Cooperative Communications
Lecture 9

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May 19, 2011

Outline

- Today, Lecture 9
- Interference
  - Impact
- Channel modeling of distributed channels including interference
  - Empirical
  - Geometry-based stochastic

Interference – Strategies

Treat interference as noise

- Uncorrelated interference can be interpreted as increasing the noise floor
- Correlated interference → correlated noise (beware!)

Treat as part of the signal

- Nullforming
- Successive interference cancellation
- Cooperative strategies (helping other nodes)

Interference metrics

Power

- SIR / SINR
  - Influenced by path loss, shadowing, shadow correlation

Channel

- Autocorrelation of interference (correlated noise)
- Interference alignment

System performance

- Capacity under interference
- Throughput / BER / BLER under interference
  - Additionally influenced by small scale fading correlation, MIMO subspace alignment

What Should Channel Models for Distributed Channels Actually Take Care Of ?

Channel models for cooperative/distributed networks

- Most signal processing techniques have been developed
  - For i.i.d. Rayleigh channels
  - Possibly with path-loss accounted for (SNR on each link depends on the Tx-Rx distance)
  - Often without shadowing and/or shadowing correlation
- However in real-world
  - **Shadowing** is present and may be a correlated variable (impact on network ?)
  - Shadowing and fast fading **cannot be easily separated**
  - **Both link ends can be mobile**

Important to note

- **When modelling the multi-user channel correctly, also interference is modelled correctly**

Distributed Channel Modeling

Goals are to model

- Shadowing correlation properly
- Fading statistics for MS-MS channels

Different approaches can be used

- **Empirical models**
  - Very direct if measurements are available
  - General enough ?
- **Stochastic models**
  - Very general
  - Too simple ?
- **Geometry-based models** (COST, WINNER)
  - Intermediate solution in terms of generalization
  - Complex models

Empirical Channel Models

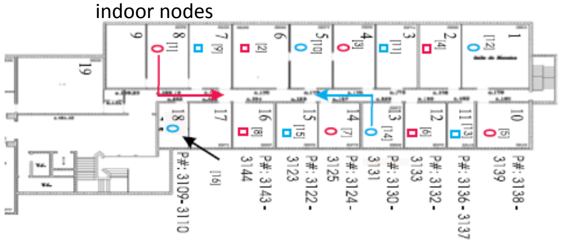
Deriving statistical relations from measurements

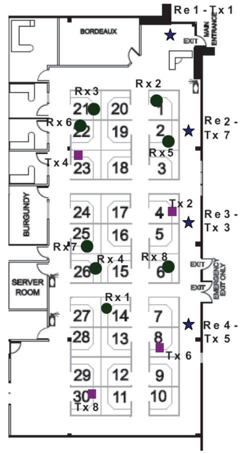
- Path loss vs. distance
- Large-scale fading (shadowing)
  - Static vs. dynamic
  - Correlation of shadowing(!)
- Small-scale fading
  - Strong dependence on mobility
  - Channel correlation for multi-antenna nodes

Empirical Models of Distributed Channels (2)

Stanford and FTW- UCL measurement campaigns

- Several types of experiments
  - Indoor-to-Indoor (I2I) static nodes
  - I2I single-mobile (Rx <u>or</u> Tx moving) and double-mobile (Tx <u>and</u> Rx moving)
  - O2I from a BS to distributed static or moving indoor nodes





Modeling Path Loss and Static Shadowing

- Path loss is deterministic and distance-dependent
- Static (= time constant) shadowing expresses that received powers between links with the same range vary over different locations
  - By different levels of **obstruction** (constant over frequency/space)
  - By constructive/destructive interference of static multipaths if nodes are stationary (**frequency/space selectivity**)
- Resulting implementation

$$L = L_0 + 1.75 \cdot 10 \log_{10}\left(\frac{d}{d_0}\right) + \bar{S}_o - 20 \log_{10} \bar{s}_s$$

- Reference path loss L_0
- Reference distance d_0
- Obstruction shadowing $\bar{S}_o$
- Spatial fading $\bar{s}_s$

is LogN distributed, $\sigma_{\bar{S}_o}$ = 4.4 dB

is Rayleigh distributed in *nomadic* cases

is = 1 in *mobile* cases

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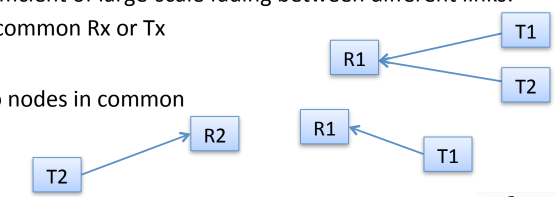
Modeling Dynamic Shadowing

Dynamic shadowing is the variation of the received power **over a** (longer) **time interval caused by the large-scale motion of terminals and obstacles**

- It is a zero-mean lognormal variable

We model

- Standard deviation of dynamic shadowing
- Dynamic shadowing auto-correlation over time
- Correlation coefficient of large-scale fading between different links:
  - Links with a common Rx or Tx
  - Links with no nodes in common



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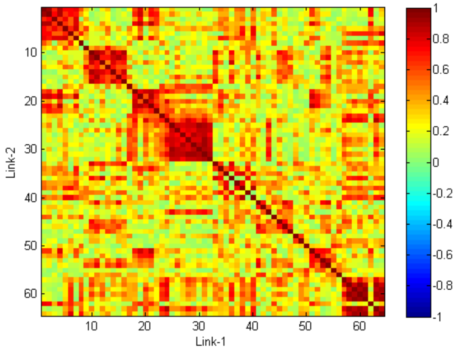
Dynamic Shadowing Correlation



Scenario	Subset	Mean
I2I static	all	0.00
I2I double mobile	all	0.16
	Rx	0.29
	Tx	0.29
	Rx-Tx	0.29
	disjoint	0.06
I2I single mobile (Rx)	all	0.05
	Rx	0.47
	Tx	-0.01
	Rx-Tx	0.23
	disjoint	0.00
I2I single mobile (Tx)	all	0.05
	Rx	0.00
	Tx	0.37
	Rx-Tx	0.19
	disjoint	0.01

64 links – pairwise correlation

subset – joint Rx, joint Tx, joint Rx or joint Tx, disjoint no link jointly

High correlation if joint node is mobile

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Modeling Small-Scale Fading

Small-scale fading is the quick amplitude variations of the received signal over time due to constructive/destructive interference of multipaths

In fixed-station to fixed-station links

- **Ricean-distributed fading** (K-factor)

is LogN distributed, std = 6 dB

$$K|_{\text{dB}} = 16.90 - 5.25 \log_{10}\left(\frac{d}{d_0}\right) + \sigma'_K$$

In mobile links

- **Second Order Scattering Fading (SOSF)**
  - Models smooth trade-off between Ricean and Double-Rayleigh fading (also including Rayleigh fading)
  - Characteristic parameters are distributed following hybrid pdfs
- **Some results**
  - One node moving: more Rice – Rayleigh
  - Both nodes moving: more towards **double-Rayleigh!**

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Small-Scale Fading for Multi-Antenna Nodes: Analytical Channel Models

Analytical channel models focus on **modelling only the spatial structure** (up to now)

- Number of antennas is **predetermined**
- Well suited for **testing signal processing algorithms**
- The spatial structure is represented by the **channel correlations matrix**
  - Can be estimated from measurements!

Analytical Channel Models – Overview

Correlation-based models

- Full-correlation model:

$$\mathbf{H} = \mathrm{unvec}\left(\mathbf{R}_{\mathbf{h}}^{1/2}\mathrm{vec}(\mathbf{G})\right)$$

- Weichselberger model:

$$\mathbf{H} = \mathbf{U}_{\mathsf{Rx}}(\tilde{\mathbf{\Omega}}_{\mathsf{WB}} \odot \mathbf{G})\mathbf{U}_{\mathsf{Tx}}^{T}$$

- Kronecker model:

$$\mathbf{H} = c \cdot \mathbf{R}_{\mathsf{Rx}}^{1/2}\mathbf{G}(\mathbf{R}_{\mathsf{Tx}}^{1/2})^{T}$$

- iid model ("canonical model"):

$$\mathbf{H} = \mathbf{G}$$

more parameters

G ... iid Gaussian Matrix R

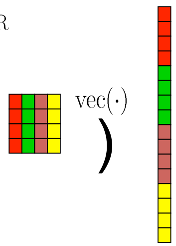
Channel Correlation Matrix

The **channel correlation matrix**

$$\mathbf{R}_{\mathbf{h}} = \mathrm{E}\{\mathbf{h}\mathbf{h}^{H}\}, \quad \text{with} \quad \mathbf{h} = \mathrm{vec}(\mathbf{H})$$

sufficiently characterizes the spatial structure of the channel. Size of $\mathbf{R}_{\mathbf{h}}$: $M_{\mathrm{T}}M_{\mathrm{R}} \times M_{\mathrm{T}}M_{\mathrm{R}}$

Note: The $\mathrm{vec}(\cdot)$ operator stacks the columns of a matrix into a vector



Underlying assumption: Rayleigh fading channel

$$\mathbf{h} \sim \mathcal{CN}(\mathbf{0}, \mathbf{R}_{\mathbf{h}})$$

If this assumption is not fulfilled, all the following models will inevitably fail!

$\mathcal{CN}(\boldsymbol{\mu}, \mathbf{R})$... distributed circular symmetric complex gaussian with mean $\boldsymbol{\mu}$ and covariance $\mathbf{R}$

Correlation-Based Analytical Models

Full-correlation model
- Very complex
- Most accurate

Weichselberger model
- Good approximation
- Good performance-complexity compromise

Kronecker model
- "Separates" channel into Tx and Rx sides
- Very limited validity

iid model
- Most simple
- No physical relevance

Full-Correlation Model

Synthetic **channel realizations** consistent with channel correlation matrix $\mathbf{R_h}$ can be generated by

$$\mathbf{H} = \mathrm{unvec}\left(\mathbf{R_h}^{1/2}\mathbf{g}\right), \quad \text{with} \quad \mathbf{g} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}),$$

where $\mathbf{g}$ is an iid white Gaussian random vector

Can be interpreted as a **noise-coloring process**:

$$\mathbf{g} \longrightarrow \boxed{\mathbf{R_h}^{1/2}} \xrightarrow{\mathbf{h}} \boxed{\mathrm{unvec}(\cdot)} \longrightarrow \mathbf{H}$$

iid Model

All elements of the channel matrix $\mathbf{H}$ are

- complex Gaussian
- independent identically distributed (iid)) uncorrelated

Channel correlation matrix is modelled as

$$\mathbf{R_h} = \rho \cdot \mathbf{I}$$

Channel realizations can be generated by

$$\mathbf{H} = \sqrt{\rho} \cdot \mathbf{G}, \quad \text{with} \quad \mathbf{G} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$$

Implications:

- no spatial structure is modelled
- only valid for (very) rich scattering environments

BUT

- Never observed in measurements – not even in those with strong scattering

Kronecker Model – Definition

Full-correlation matrix has too many parameters

➔ treat correlation independently at Tx and Rx:

- Transmit correlation matrix: $\mathbf{R}_{\mathrm{Tx}} = \mathrm{E}\{\mathbf{H}^H\,\mathbf{H}\}$
- Receive correlation matrix: $\mathbf{R}_{\mathrm{Rx}} = \mathrm{E}\{\mathbf{H}\,\mathbf{H}^H\}$

Channel correlation matrix is modelled by

$$\mathbf{R_h} \approx \frac{1}{\sqrt{\mathrm{tr}\{\mathbf{R}_{\mathrm{Rx}}\}}} \mathbf{R}_{\mathrm{Rx}} \otimes \mathbf{R}_{\mathrm{Tx}}^T$$

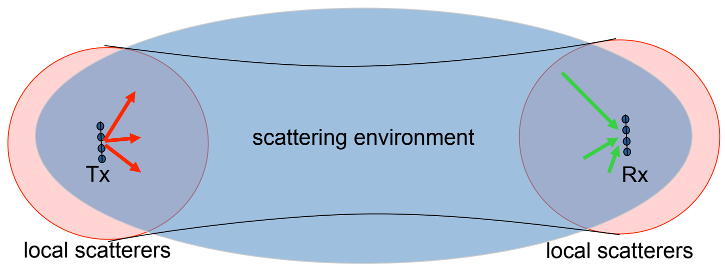
$\otimes$ … Kronecker matrix product

Channel realizations can be generated by

$$\mathbf{H} = c \cdot \mathbf{R}_{\mathrm{Rx}}^{1/2}\,\mathbf{G}\,\mathbf{R}_{\mathrm{Tx}}^{1/2}, \quad \text{with} \quad \mathbf{G} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$$

Kronecker Model – Implications

- Kronecker model holds true only if channel can be separated into Tx side and Rx side
- Rx directions are independent of Tx directions
- Only satisfied for few antennas or large antenna spacing



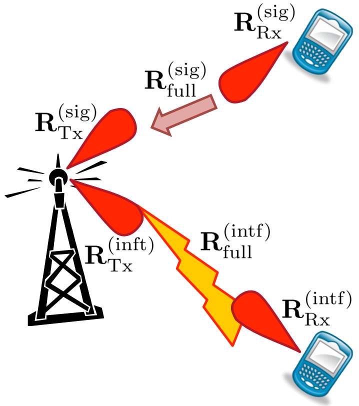
Example of Analytically Modeling Spatial Interference

Can we model

$\mathbf{R}_{\mathrm{Tx}}^{(\mathrm{inft})}$

given

$\mathbf{R}_{\mathrm{Tx}}^{(\mathrm{sig})}$?



Impact of Channel Subspace Alignment

MIMO system model including interference

$$\mathbf{y} = \mathbf{H}_0\mathbf{x}_0 + \sum_{i=1}^{N_i} \mathbf{H}_i\mathbf{x}_i + \mathbf{n}$$

$$\mathbf{R}_0 = \mathbf{H}_0\mathbf{H}_0^{\mathrm{H}} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^H$$

$$\mathbf{R}_I = \sum_{i=1}^{N_i} \mathbf{H}_i\mathbf{H}_i^{\mathrm{H}} = \mathbf{V}\mathbf{\Gamma}\mathbf{V}^H$$

Rate under interference:

$$\begin{aligned} &I(\mathbf{R}_0, \mathbf{R}_I, \sigma_N^2) \\ &= \log_2 \det\left(\mathbf{I} + \mathbf{R}_0(\mathbf{R}_I + \sigma_N^2\mathbf{I})^{-1}\right) \\ &= \log_2 \det\left(\mathbf{I} + \mathbf{\Lambda}\boxed{\mathbf{U}^{\mathrm{H}}\mathbf{V}}(\sigma_N^2\mathbf{I} + \mathbf{\Gamma})^{-1}\boxed{\mathbf{V}^H\mathbf{U}}\right) \end{aligned}$$

Expectations lead to a METRIC rather than a rate

Metrics

MIMO capacity under interference metric

$$\begin{aligned} &I(\mathbf{R}_0, \mathbf{R}_I, \sigma_N^2) \\ &= \log_2 \det\left(\mathbf{I} + \mathbf{R}_0(\mathbf{R}_I + \sigma_N^2\mathbf{I})^{-1}\right) \end{aligned}$$

- Metrics has a unique minimum for $\mathbf{V} = \mathbf{U}$ and maximum for $\mathbf{V} = \overleftarrow{\mathbf{U}} = [\mathbf{u}_D \ \cdots \ \mathbf{u}_1]$

→ **How to model points lying in between?**

Multi-User MIMO Channel Model

What we assume as given:

- $\mathbf{R}_0 = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^H$ from any suitable channel model
- $\mathbf{\Gamma}$ (SV profile of the interference)
- σ_N^2

→ specific $I^{(\mathrm{target})}$, $I^{(\mathrm{min})} \leq I^{(\mathrm{target})} \leq I^{(\mathrm{max})}$

What we model:

- $\mathbf{V}$ to reach $I^{(\mathrm{target})}$

Deterministic Subspace Model

- We know that $I^{(\min)} \le I^{(\text{target})} \le I^{(\max)}$ for $(\mathbf{V}=\mathbf{U})$ $(\mathbf{V}=\overleftarrow{\mathbf{U}})$

- To model any target value in between, we need a smooth transition from $\mathbf{U}$ to $\overleftarrow{\mathbf{U}}$

- Smooth unitary projector from $\mathbf{U}$ to $\overleftarrow{\mathbf{U}}$ can be expressed by

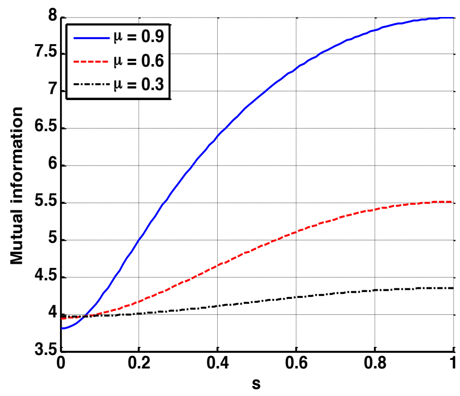
$$\boxed{\mathbf{V}(s) = (\overleftarrow{\mathbf{U}}\mathbf{U}^H)^s\,\mathbf{U}}$$

- By that,

$$I(s) = I(\mathbf{R}_0, \mathbf{V}(s)\boldsymbol{\Gamma}\mathbf{V}(s)^H)$$

→ Find S for $I^{(\text{target})}$ by bisection

Results: Capacity



- High correlation brings huge gains!
- Average correlation already significantly matter
- Low correlation have almost no impact

Geometry-Based Stochastic Modeling of Distributed Channels

What are geometry-based stochastic models ?

- Double-directional MIMO channel models
- Based on clusters of interacting objects stochastically located in the simulated environment
- Clusters are assigned
  - a direction with respect to the BS and the MS
  - spreads in the angular and delay domains

Such models are

- Antenna-independent
- Parameterized by measurements in canonical environments (urban, suburban, etc.)
- **Much more complex than empirical stochastic ones!**

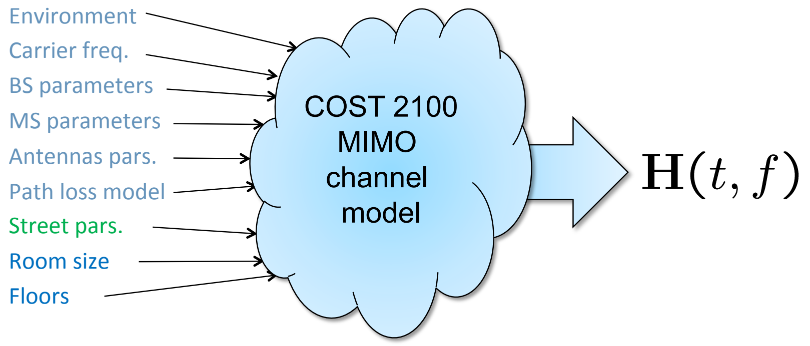
The COST 2100 MIMO channel model

Model properties

- A geometry-based stochastic multi-user MIMO channel model for **system simulation**
- Smoothly time variant, frequency selective
- A *generic* all-rounder:
  - 4 Main environments
  - 22 specified scenarios

- Not yet fully parametrised (specified ≠ parametrised)
- Not yet fully implemented
- Not yet widely used (because of above reasons)

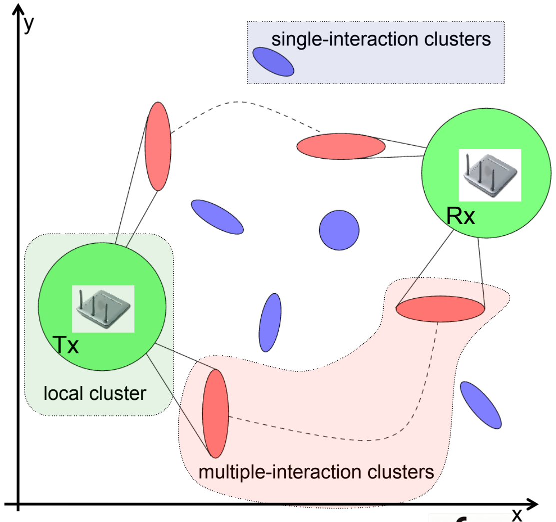
COST 2100 model overview



→ All-inclusive model,
only few parameters to set manually!

Three Kinds of Clusters

- Cluster types:
  - Local clusters
  - Single-interaction clusters
  - Multiple-interaction clusters ("twin-clusters")
- Time-variance by
  - MT movement
  - **visibility regions**



Local Cluster(s)

Effect

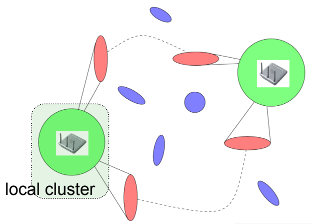
- Large angular spread around the respective station

Occurrence

- Around the Mobile: ALWAYS
- Around the "other" station:
  - Base station: only in certain environments
  - Peer-to-Peer: always
  - Ad hoc: always

Implementation

- Single scattering only



Single-interaction clusters

Effect

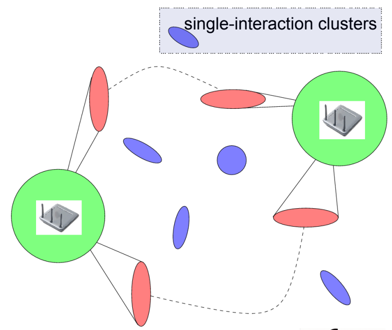
- Far cluster (as in COST 259)
- Directive component in the channel

Occurrence

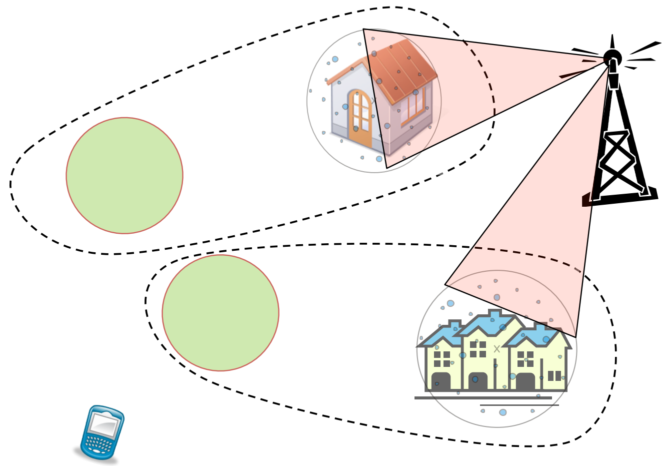
- All scenarios

Implementation

- Single scattering
- Angular position: Gaussian distributed
- Distance from BS: Exponentially distributed
- Active/Inactive: Visibility region



Visibility region?

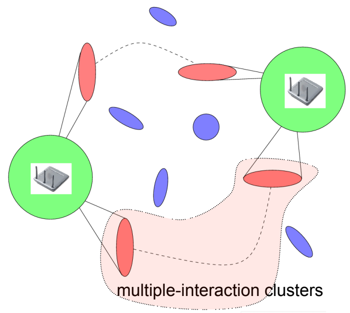


Multiple-interaction clusters

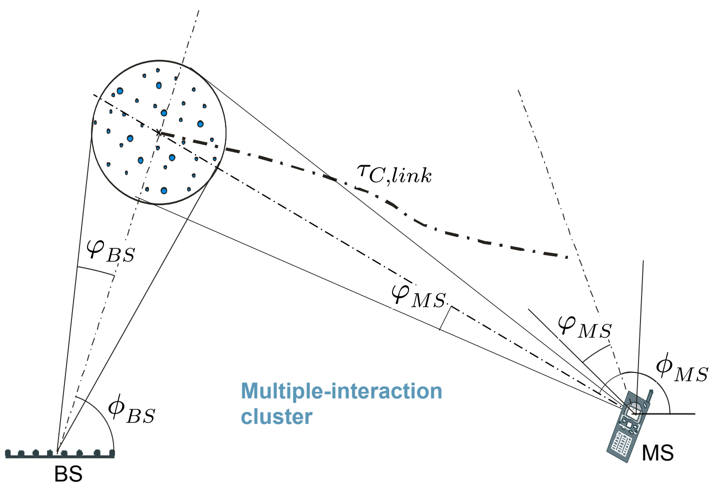
Effect
- Covers double or multi-bounce scattering
- Able to represent directional links not covered by single scattering

Occurrence
- Indoor and Ad-hoc scenarios… … but not really specified.

Implementation
- 2 Approaches:
  - Angular spectrum approach
  - "Twin-cluster" approach



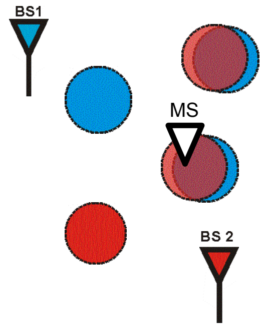
„Twin cluster"



Modeling Multiple Users

Common cluster approach
- Some clusters are defined as common to different BS
- When the MS moves into the visibility of a common cluster, a link to each BS is established via the common cluster
- Shadowing correlation is therefore realized intrinsically

→ Path loss, dynamic shadowing, and small-scale fading are intrinsically modelled.

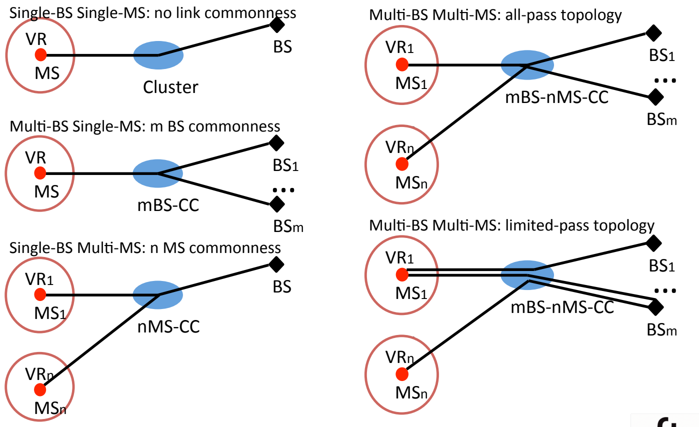


Circles are visibility regions of clusters

if overlapped clusters can be seen by both BS

Different Types of Common Clusters

Common cluster approach



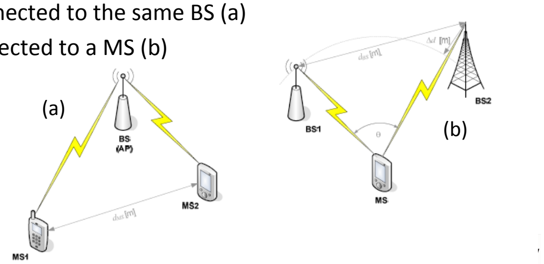
WINNER Multi-Link Channel Models

The WINNER model is a **cluster-oriented drop-based model**, each drop corresponding to a random location of the MS

- 13 parameterised environments (indoor, outdoor, O2I, LOS/NLOS)
- Over a given area, the large-scale parameters (LSPs) are defined as constant

Large-scale parameters are correlated
→ Inherent modelling of shadowing correlation!

- Different MS connected to the same BS (a)
- Different BS connected to a MS (b)

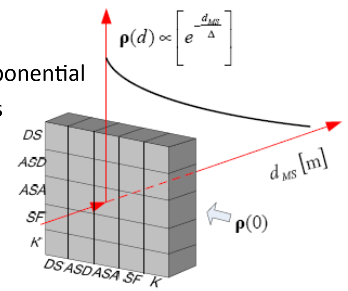


WINNER Multi-Link Channel Models (2)

Multi-user channel

- Correlation of LSPs is modeled as an exponential decay wrt to the distance between users

(LSP large scale parameters)



Multi-cell channel

- Although some degree of correlation has been measured, the model fixes the multi-cell LSP correlations to zero

Multi-hop channel

- Can be simulated using a combination of WINNER scenarios (e.g. cellular + feeder)

Summary

Empirical models

- Based on parameter estimation from **measurements**
  - Fixed bandwidth, fixed antenna patterns, …
- Model features
  - Path loss
  - Shadowing (dynamic/static, correlated)
  - Fast fading (distribution, multi-antenna properties)

Geometry-based stochastic models

- Models a randomly generated propagation environment
- Bandwidth, antenna patterns can be adjusted
- Need proper calibration with measurements (which is quite difficult)
- Two representative models: COST2100, WINNER