Cooperative Communications
Lecture 8

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Outline

Today, Lecture 7

- Wireless channel between distributed nodes
  - Measuring the distributed channel
  - Channel models

Channel Measurements

1. Principles of channel sounding
   - Switched-array channel sounders
   - Hardware-Testbeds as channel sounders
   - Network analyzer
2. Sounding Techniques
   - Single-sounder sequential measurements
   - Single-sounder multi-node measurements
   - Multi-sounder (transceiver) measurements
3. Planning channel measurements
4. Measurement campaigns and what we learned from them
   - Multi-node measurements (Lund, Aalto)
   - PAN measurements (Lund)
   - O2I / I2I multi-user MIMO (FTW, UCL, Stanford)
   - O2O base-station to relay (Bristol)
   - Outdoor multi-user MIMO (Eurecom)
   - Multi-BS measurements (Ilmenau / HHI / Ericsson)

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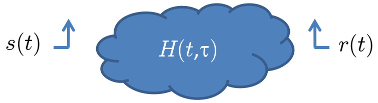
Channel Sounding

Principle of channel sounding



$$r(t) = \int H(t,\tau)s(t-\tau)d\tau + n(t)$$
$$= H(t,\tau) * s(t) + n(t)$$

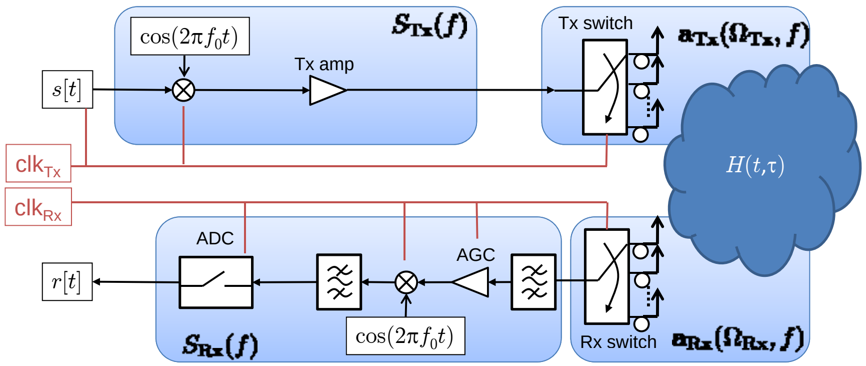
$$r(t,f) = H(t,f)s(t,f) + n(t,f)$$

- Transmit a known signal $s(t)$
- Estimate the channel from the received signal $r(t)$

Challenges

- How to cope with RF effects of the equipment?
- How to sound multiple antennas at Tx and Rx?
- Design of the transmit signal
- Fast AGC and signal sampling at the receiver
- Synchronization of Tx and Rx

State-of-the-art Channel Sounder (Block Diagram)



- Needs a joint clock!
  - **Phase and frequency** synchronization
- Every part of the system has its own impulse response!
  - "End-to-end" calibration of the equipment
  - Antenna calibration for directional estimation

Tackling the Challenges (1)

Transmit signal design criterion

- Broadband signal, BUT
- Low peak-to-average power ratio (PAPR) for optimal Tx amplifier usage
- Flat spectrum preferrable

Solutions

- OFDM training sequences (may not have good PAPR)
- Chirp signals → Overshoot at spectral edged (Gibbs phenomenon)
- PN sequence → specific spectral shape (as used by Elektrobit sounder)
- **"Engineered" chirp** → pre-amplifying of cable losses, flat spectrum, low PAPR
  (as used by RUSK MEDAV sounders)

Tackling the Challenges (2)

Fast AGC and signal sampling

- For high bandwidths, ADCs have only low resolution (typically 8 bits)
- Sampling the received signal over a wide dynamic range → fast AGC
  - Particularly challenging for **distributed** nodes!
- Requires a great deal of hardware know-how
  (that's what you pay for when you buy a sounder)

Phase synchronization of Tx and Rx

- Rubidium (^{87}Rb) does the trick
- Phase drift is small (though it may become significant over longer time!)
- Phase noise is some times problematic

Hardware Testbed as a Sounder

Testbeds can easily be "pimped" to act as channel sounder

- Use a long known transmit sequence
- Estimate your channel at the receiver

Challenges

- Proper synchronization (over the air does NOT ensure phase sync!)
- Proper calibration and (temperature) stability of the device
- Usually only limited bandwidth available
- Accurate fast AGC usually not implemented in testbeds

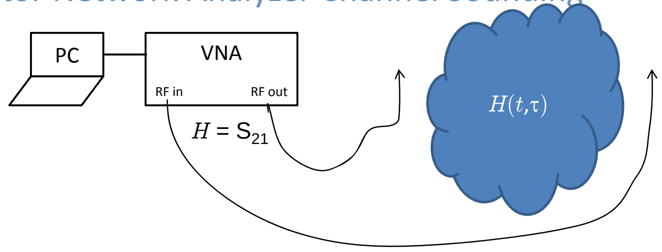
When to use a testbed

- To get a quick glimpse on **system performance**

When NOT to use a testbed

- Directional estimation, High-SNR channel characterization

Vector Network Analyzer Channel Sounding



A vector network analyzer is (intrinsically) a channel sounder

- Slow channel acquisition rate
- Transmitter and receiver are both in the same device (no real mobility except when using long cables)
- Low-cost solution (compared to commercial sounders)

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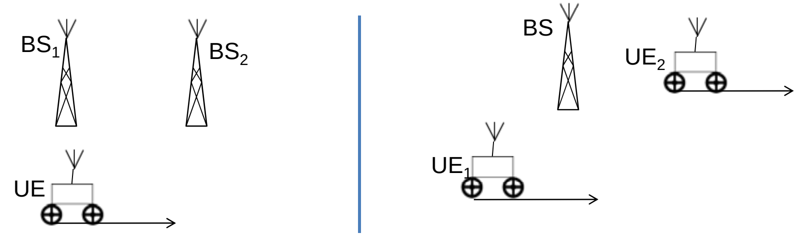
Single-Sounder Sequential Measurements



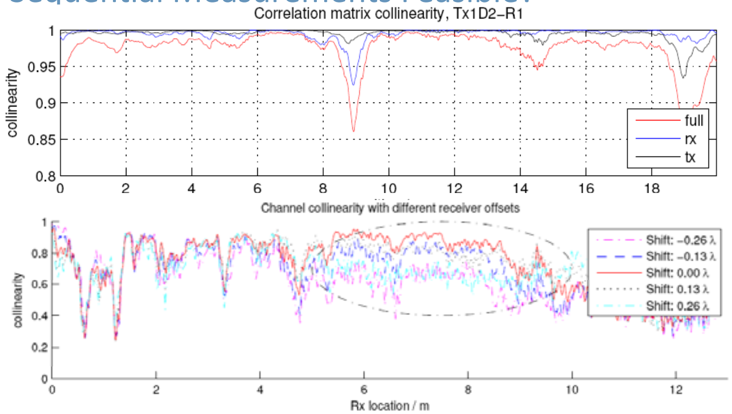
Sequential measurements bear risks

- Environment may have changed during the second "run"
- Equipment / calibration has changed (phase drift!)

→ Phase-synchronized multi-user measurements are impossible

- Is phase synchronization necessary for the evaluations planned?

Are Sequential Measurements Feasible?



Measure a route twice and compare with distance metric

- Here: using channel collinearity (correlation matrix distance)
- Applied to correlation matrices and channel matrices

→ **Environment must stay constant!**

Single-Sounder Multi-Node Measurements

Switched-array sounder + long cables = multi-node measurements

Long RF cables

- Cable loss is high
  - low-loss cables: ∼0.2dB/m @ 2.5 GHz
- Cable movement
  - introduces phase jitter
  - RF plugs tend to get unplugged…

Optical RF

- Expensive but useful!
- Allows for long distances (multi-point transmission)
- Calibration must be done for every cable (because of RF/optical crossconnectors)

Multi-Sounder (Transceiver) Measurements

Using multiple channel sounders is best practice

- Typically single transmitter, multiple receivers
- Multi-transmitter, single receiver possible with accurate synchronization and/or intelligent transmit signal design

Challenges

- Getting two **compatible** channel sounders is quite an effort
- Maintaining synchronization of multiple clocks

→ Beware of combining channel sounders of different make (For more experience on that ask Lund & Aalto experts)

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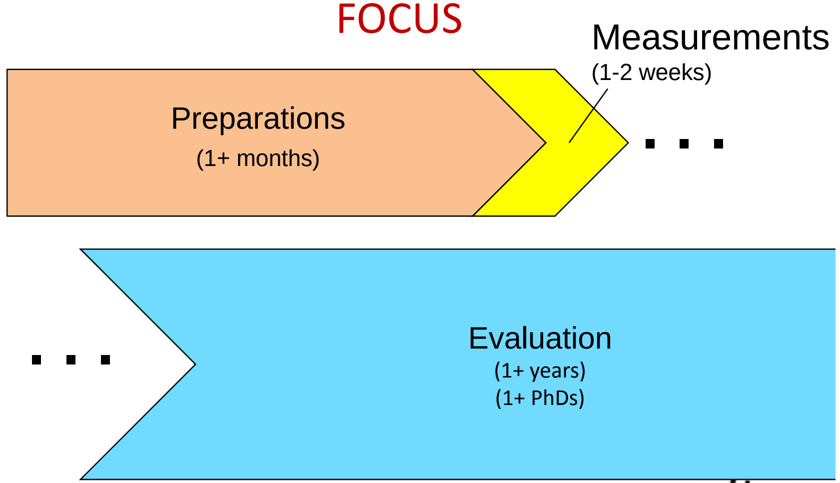
Planning Measurements

Every measurement campaign needs a

FOCUS



Preparations for Channel Measurements

Equipment
- Take care that the whole equipment will be available
  - Sounder, Antennas, Batteries
  - Documentation equipment: Camera, field notes sheets, …
- Define measurement parameters
  - Test sequence length, repetition rate, …
  - Antennas: elements, switching patterns, …
- Get radio test license from authorities!

Scenarios
- Get floorplans /maps and decide on scenarios
- Plan measurement routes
  - Calculate link budget
  - Prioritize measurements – there is never enough time to measure all routes that are planned

People
- Helping hands
- Observers

Don't forget Murphy's Law, always have a backup plan!

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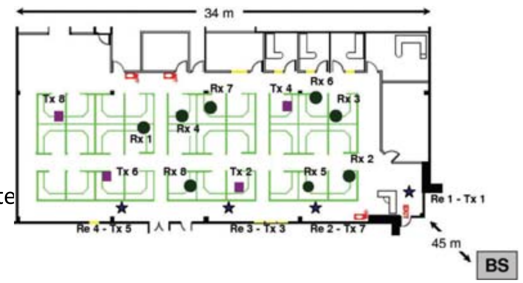
Cubicle-Style: O2I/I2I Distributed Nodes

Modeling the O2I and I2I cooperative channel



Equipment
- RUSK Stanford sounder
- Long RF cables for distributed measurements

Environment
- Large office building, cubicles
- Antennas distributed within the room
- "Relays" along one wall (close to the BS)

Measurement practice
- O2I static measurements
- I2I static and mobile measurements

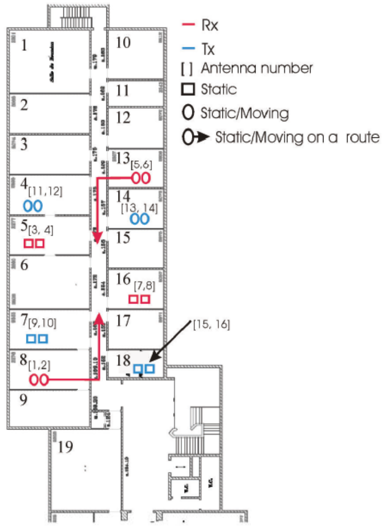
Office-Style: O2I/I2I Distributed MIMO

Modeling the cooperative channel (2)

Equipment
- Elektrobit Propsound CS
- Long RF cables
- Omni-directional Rx antennas

Environment
- Brick-wall building
- Some rooms separated by brick walls, others by plaster-board walls
- Measurements with 1/2/4 antennas peer-to-peer

Measurement practice
- Static and mobile measurements
- I2I, O2I



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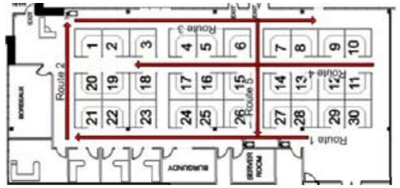
Cubicle-Style: O2I Multi-User MIMO

Interference in MU-MIMO channels

Equipment
- RUSK Stanford sounder
- 2 WiMAX BS antennas (2-pol) lifted to 25m height
- UE: WiMAX user equipment antennas

Measurement practice
- BS outdoor looking into different directions
- Indoor routes repeated with meticulous accuracy for all BS positions



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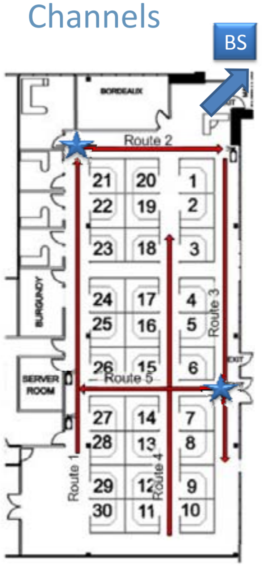
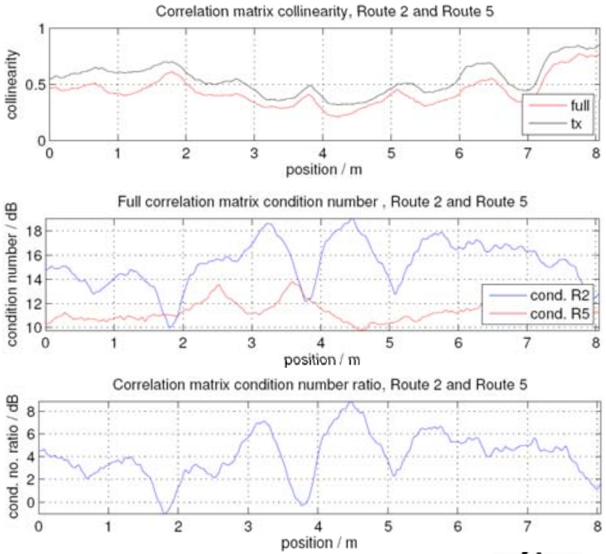
Result: Spatial Separation of Multi-User MIMO Channels





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Sequential Multi-BS O2O Measurements

Investigations of the cooperative multi-point MIMO channel

Four (!) recent campaigns
- TU Berlin campus (EASY-C project)
- Berlin city (EASY-C project)
- Dresden city (EASY-C project)
- Ilmenau town center (TU Ilmenau)

Equipment
- RUSK MEDAV channel sounder
- GPS and odometer to obtain high position accuracy

Measurement practice
- All routes are measured for each BS position

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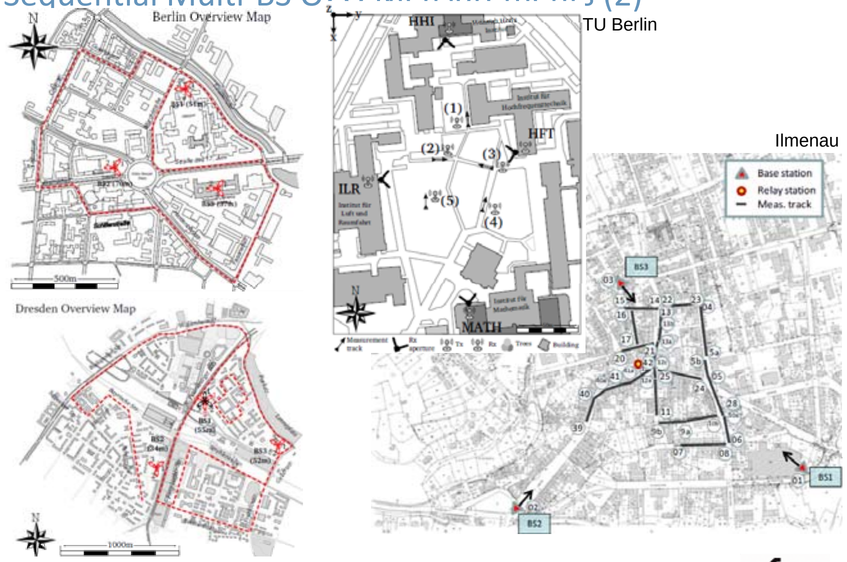
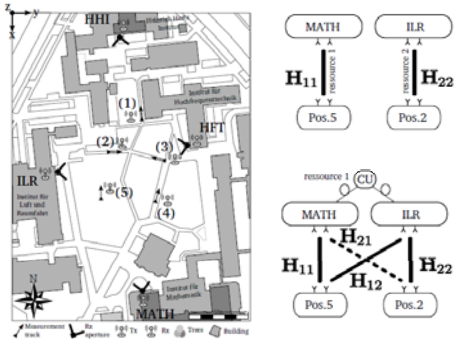
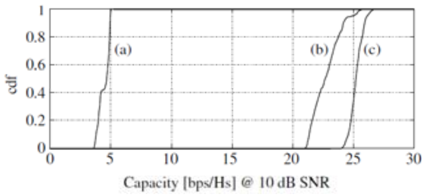
Sequential Multi-BS O2O Measurements (2)



Result: Capacity using Multi-Cell Cooperation





Comparison of achievable sum-rate capacity using cooperative multi-point transmission

(a) TDMA

(b) Mean capacity of isolated cells

(c) Base station cooperation

Outdoor MU-MIMO with a Testbed

Performance of MU-MIMO cellular systems

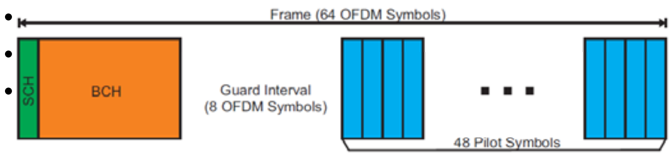
Equipment:

- Eurecom OpenAir testbed
- Single transmitter, multiple receivers
- Receivers use a specific pilot structure to synchronize to the transmitter

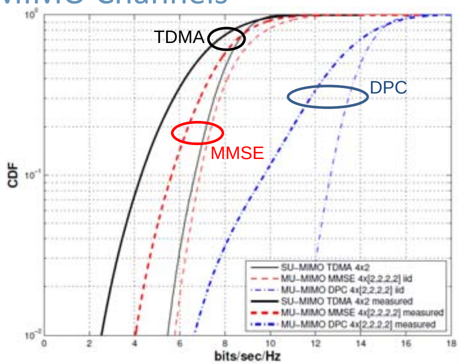
Advantages:

- Low-cost (compared to unsing multiple channel sounders)
- Flexible in usage (can also test algorithms)

Shortcomings:



Result: Capacities for MU-MIMO Channels



Comparing TDMA with multi-point transmission schemes:

- DPC clearly outperforms MMSE and TDMA schemes
- MMSE clearly outperforms TDMA in real channels
- Real channels are not Gaussian i.i.d!

Channel Measurements – Conclusions

To do channel measurements you need
money, time, friends, good equipment, good organization, and lots of patience

Multi-link measurements create additional challenges:

- Different methods to measure distributed links
  - Single-sounder sequential measurements
  - Single-sounder multi-node measurements
  - Multi-sounder (transceiver) measurements

→ Each has their advantages and shortcomings

Data from some of the presented campaigns are publicly available!

"Nobody believes simulations (except the one who does them), but everybody believes measurements (except the one who does them)."

Distributed Channel Modeling – Overview

1. **Relay channels**
   - Analysis of the global relay channel
   - Focus on fading statistics
2. **Distributed/cooperative/virtual MIMO channels**
   - Different approaches
     - Empirical models
     - Geometry-based models (COST, WINNER)
     - Stochastic models

Relay Channels

Relay channels are a particular case of cooperative channels

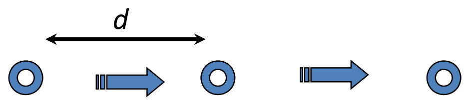
- It is possible to characterize a relay channel as a global channel MS ↔ Relay ↔ BS
- The analysis considers half-duplex schemes

Various relaying methods

- Amplify & Forward
- Classical Regenerative Multihop
- Decode & Forward
- […] & Forward

A Very Simple Model of Relay Channels

Many information theory papers have used the following model for relay channels



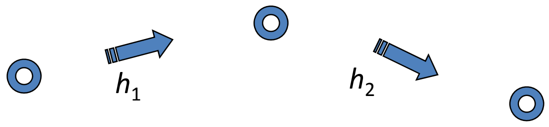
$h_1 = g_1 / d^{\eta}$ $\qquad$ $h_1 = g_1 / [1-d]^{\eta}$

- Using the relative distance from Tx to Relay (full Tx-Rx distance is 1)
- Based on i.i.d. Rayleigh fading
- No shadowing included
- Same path-loss exponent on both links

Amplify & Forward Relay Channel

AF relay channel is made of two successive channels

- Two-hop model



$$y = h_2 A \left[h_1 \sqrt{E_s} c + n_1 \right] + n_2$$

- Global channel is the multiplication of Tx-Relay and Relay-Rx channels, with amplification factor A
  - h_1 and h_2 are Rayleigh fading channels with energy $2\sigma_1^2$ and $2\sigma_2^2$
  - n_1 and n_2 are noise contributions of power N
  - P_1 and P_2 are the transmit powers of nodes 1 and 2

Amplify & Forward Relay Channel (2)

Amplification factor

- Fixed gain (depends on the CDIT of h_1)

$$A = \sqrt{\frac{P_2}{2P_1\sigma_1^2 + N}}$$

- Variable gain (depends on the CSIT of h_1)

$$A = \sqrt{\frac{P_2}{P_1 |h_1|^2 + N}}$$

AF Relay Channel Statistics

Overall relay channel is expressed as $h_{AF} = h_1 A h_2$

For fixed relay gain (A arbitrarily fixed to 1) channels

- Envelope PDF ($s = |h|$) for independent fading channels is **Double-Rayleigh**

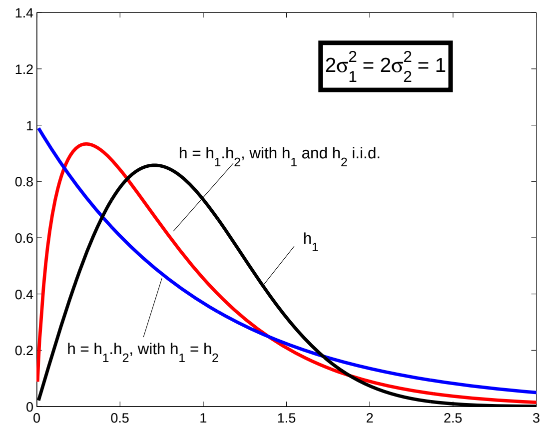
$$p_s(s) = \frac{s}{\sigma_1^2 \sigma_2^2} K_0 \left[\sqrt{\frac{s^2}{\sigma_1^2 \sigma_2^2}} \right]$$

AF Relay Channel Statistics (2)

Overall relay channel is expressed as $h_{AF} = h_1 A h_2$

For fixed relay gain (A arbitrarily fixed to 1) channels

- Envelope PDF depends strongly on the correlation between both channels



What Should Cooperative Channel Models 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**

Distributed Channel Modeling

Goals are to model

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

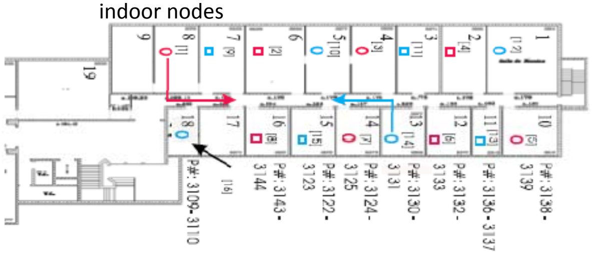
Different approaches can be used

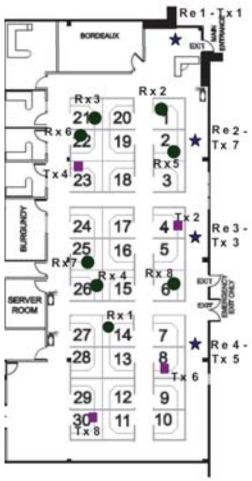
- **Empirical models**
  - Very direct if measurements are available
  - General enough ?
- **Stochastic models**
  - Very general
  - Too simple ?
- **Geometry-based models** (COST, WINNER)
  - Intermediate solution in terms of generalization
  - Complex models

Empirical 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)
  - I2I 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 $\bar{S}_o$ — is LogN distributed, $\sigma_{\bar{S}_o}$ = 4.4 dB
- Spatial fading $\bar{s}_s$ — is Rayleigh distributed in *nomadic* cases; is = 1 in *mobile* cases

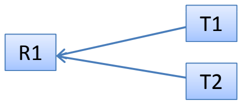
Modeling Dynamic Shadowing

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

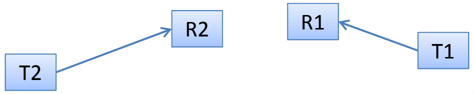
- It is a zero-mean lognormal variable

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

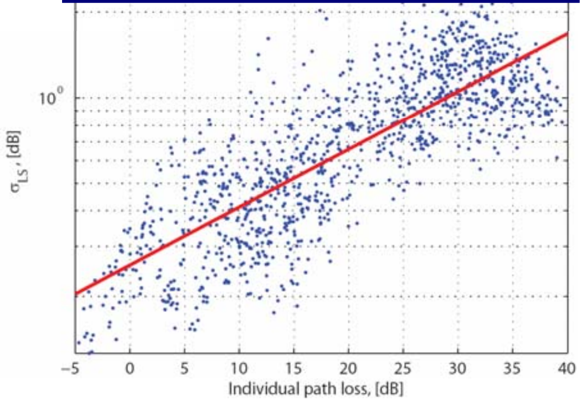


Standard Deviation of Dynamic Shadowing

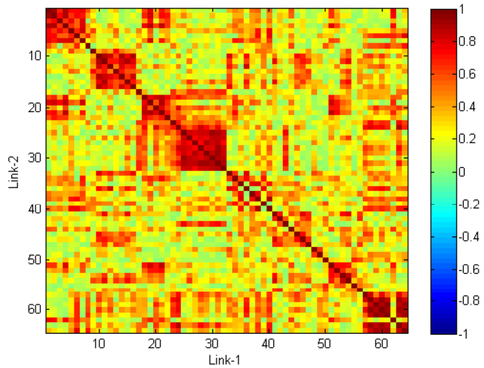
Dynamic shadowing standard deviation in **stationary environment**

Larger path loss → Stronger dynamic shadowing !

$$\log_{10}(\sigma_{\tilde{S}}) = \log_{10}(1.85) + 0.2\log_{10} d + \sigma'_{\sigma_{\tilde{S}}}$$



Dynamic Shadowing Correlation



Scenario	Subset	Mean	Std.	Max	Min
I2I static	all	0.00	0.27	0.94	-0.90
I2I double mobile	all	0.16	0.39	0.97	-0.90
	Rx	0.29	0.36	0.89	-0.40
	Tx	0.29	0.42	0.97	-0.74
	Rx-Tx	0.29	0.39	0.97	-0.74
	disjoint	0.06	0.36	0.81	-0.90
I2I single mobile (Rx)	all	0.05	0.38	0.99	-0.91
	Rx	0.47	0.41	0.99	-0.79
	Tx	-0.01	0.35	0.80	-0.83
	Rx-Tx	0.23	0.45	0.99	-0.83
	disjoint	0.00	0.34	0.90	-0.91
I2I single mobile (Tx)	all	0.05	0.41	0.99	-0.93
	Rx	0.00	0.36	0.81	-0.82
	Tx	0.37	0.50	0.99	-0.84
	Rx-Tx	0.19	0.47	0.99	-0.84
	disjoint	0.01	0.37	0.87	-0.93

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 FS-FS links

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

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

is LogN distributed, std = 6 dB

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!**

Stochastic Modeling of Distributed Channels

The main goal of this approach is the modeling of shadowing correlation by means of spatial random fields

- In [Agrawal 2009], shadowing between any two nodes is modeled as the weighted line integral of a spatial loss field
- Spatial variation are modeled as a wide sense stationary Gaussian random field

Comments

- This model always produces a positive shadowing correlation, while measurements also show negative shadowing correlation for some links

[Agrawal 2009] P. Agrawal and N. Patwari, "Correlated link shadow fading in multi-hop wireless networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, pp. 4024–4036, Aug. 2009

Geometry-Based Modeling of Distributed Channels

What are geometry-based models ?

- Double-directional MIMO channel models
- Based on clusters of interacting objects stochastically located in the simulated cell
- Clusters are assigned
  - a direction wrt 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.)

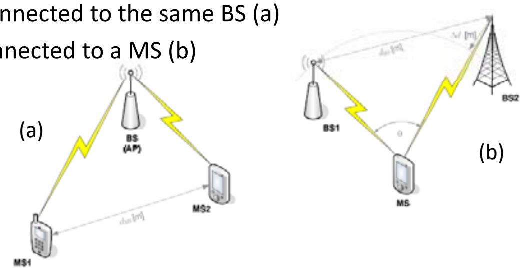
WINNER Multi-Link Channel Models

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

- Over a given area, the large-scale parameters (LSPs) are defined as constant

LSPs are correlated

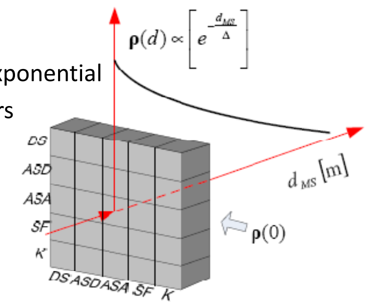
- Different MS connected to the same BS (a)
- Different BS connected to a MS (b)



WINNER Multi-Link Channel Models (2)

Multi-user channel

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



Multi-cell channel

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

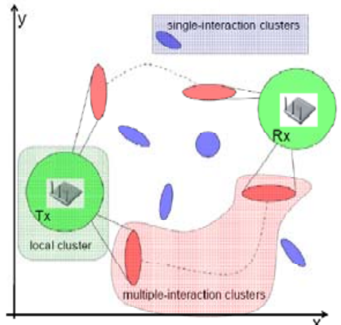
Multi-hop channel

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

COST 2100 Multi-Link Channel Model

COST 2100 approach

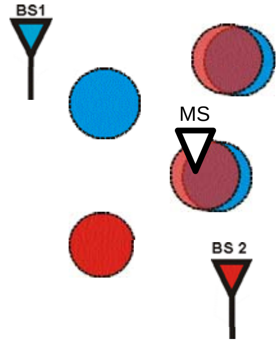
- Geometry-based model using 3 types of clusters
- Time variation is introduced by the motion of MS into visibility regions associated with each cluster
- Originally developed as a single-link simulation model



COST 2100 Multi-Link Channel Model (2)

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



Summary – Distributed Channel Modeling

Static shadowing

- Results from different levels of obstruction OR from interference between static multipaths

Dynamic shadowing

- is different from shadowing in stationary scenarios
- is **correlated across links**!

Small-scale fading

- Advanced model provides a smooth transition between Double-Rayleigh fading, Rayleigh fading and Rician fading
- Simple random number generator