Tutorial 5

From Network based Location Estimation to Location Aided Communications

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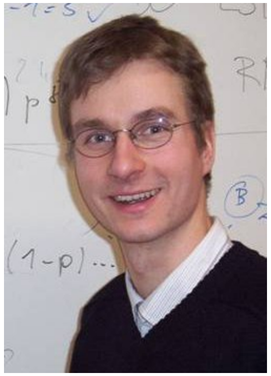
T5: From Network based Location Estimation to Location Aided Communications

Part 1:

a. Satellite based Global Positioning Systems
b. Wireless Network based Localization Techniques



Part 2:

c. Radio maps: Location-aware Learning and Completion
d. Location-aided Channel Prediction
e. Location-aided Communications: Anticipation

Part 3:

f. Non Line-of-Sight Positioning Techniques
g. Location-aided Communications: Multi-Antenna Systems
h. More Location-aided Communications

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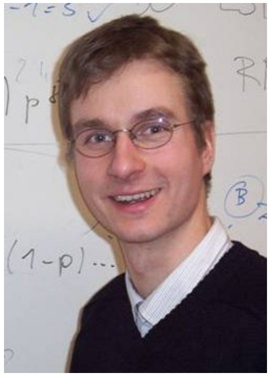
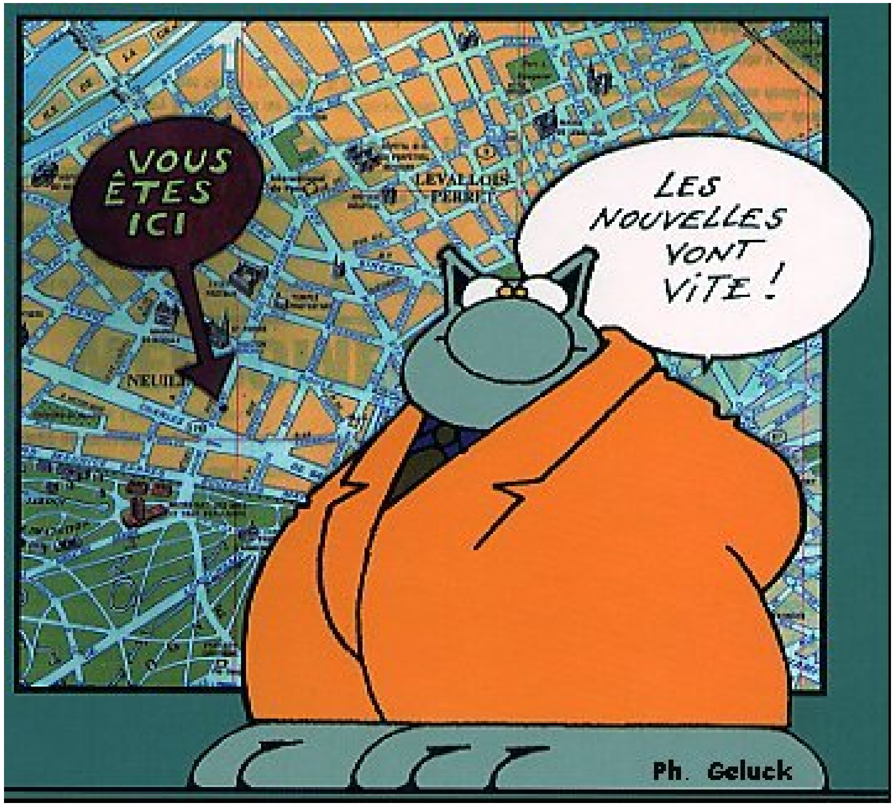


Part III: Presentation Outline

- Non Line of Sight (NLoS) geo-location estimation techniques
  - Single bounce channel models
  - Power Delay Profile (PDP) fingerprinting
- Location aided Communications
  - basic PHY techniques
  - Cellular Systems
  - MANET (Mobile Ad Hoc Networks), VANET (Vehicular)
  - Cognitive Radio

Wireless Network based Localization now in LTE-A

- Enhanced Cell Id
  - Cell Id + RSS (received signal strength)
- O-TDoA (Observed Time Difference of Arrival)
- AoA (Angle of Arrival at BS)



Part II: Presentation Outline

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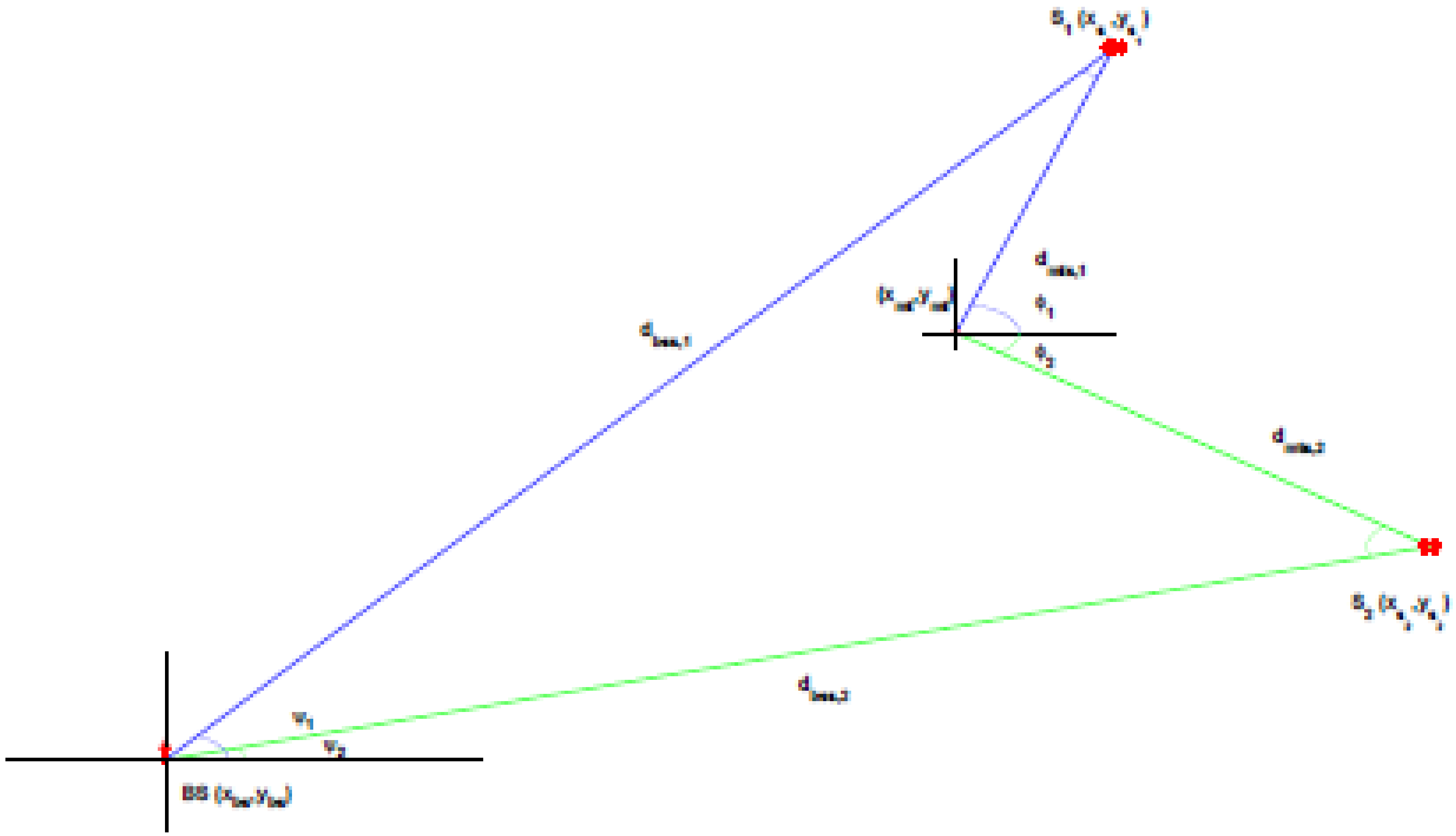
Introduction - Motivation

- "Traditional" geometrical localization methods can not achieve sufficient accuracy in Non-Line-of-Sight (NLoS) environments.
- NLoS localization methods that introduce some errors due to NLoS propagation and try to mitigate them, require at least some LoS paths and/or some knowledge about the errors (eg. statistics).
- NLoS localization methods that utilize geometrical channel and mobility models result in high performance algorithms.

Introduction - Motivation

- In choosing the right geometrical and mobility model, we are faced with a performance-complexity-applicability trade-off.
- The **Single-Bounce Model** (SBM) can achieve a good trade-off, since it enables mobile terminal (MT) localization with high accuracy in numerous NLoS environments.
- The SBM can be integrated with a mobility model in order to exploit the information in the time-variation of the location-dependent parameters (LDP). Exploiting this new dimension has great advantages in terms of performance and identifiability.

Geometrical Channel Models: Single-Bounce Model



Single-Bounce Model: Unique Invertible Mapping Between p and θ

$$\phi_j = \frac{\pi}{2}(1 - sgn\{x_{s_j} - x_{mt}\}) + \tan^{-1}\frac{y_{s_j} - y_{mt}}{x_{s_j} - x_{mt}}$$

$$\psi_j = \frac{\pi}{2}(1 - sgn\{x_{s_j} - x_{bs_j}\}) + \tan^{-1}\frac{y_{s_j} - y_{bs_j}}{x_{s_j} - x_{bs_j}}$$

$$d_j = d_{mts,j} + d_{bs,j}$$

$$d_{mts,j} = \sqrt{(y_{s_j} - y_{mt})^2 + (x_{s_j} - x_{mt})^2}$$

$$d_{bs,j} = \sqrt{(y_{s_j} - y_{bs_j})^2 + (x_{s_j} - x_{bs_j})^2} \quad .$$

ToA/AoA/AoD Hybrid Localization: WLS Solution

$$\underbrace{\begin{bmatrix} -\mathbf{C}_{\psi}\mathbf{1} & \mathbf{0} & (\mathbf{C}_{\phi}+\mathbf{C}_{\psi}) & \mathbf{O} \\ \mathbf{0} & -\mathbf{S}_{\psi}\mathbf{1} & \mathbf{O} & (\mathbf{S}_{\phi}+\mathbf{S}_{\psi}) \\ -\mathbf{S}_{\psi}\mathbf{1} & \mathbf{0} & \mathbf{S}_{\psi} & \mathbf{C}_{\phi} \\ \mathbf{0} & -\mathbf{C}_{\psi}\mathbf{1} & \mathbf{S}_{\phi} & \mathbf{C}_{\psi} \end{bmatrix}}_{=\mathbf{A}} \underbrace{\begin{bmatrix} x_{mt} \\ y_{mt} \\ \mathbf{x}_s \\ \mathbf{y}_s \end{bmatrix}}_{=\mathbf{p}} = \underbrace{\begin{bmatrix} (\mathbf{D}\mathbf{C}_{\psi}+\mathbf{X}_{bs})\mathbf{C}_{\phi}\mathbf{1} \\ (\mathbf{D}\mathbf{S}_{\psi}+\mathbf{Y}_{bs})\mathbf{S}_{\phi}\mathbf{1} \\ (\mathbf{D}\mathbf{S}_{\psi}+\mathbf{Y}_{bs})\mathbf{C}_{\phi}\mathbf{1} \\ (\mathbf{D}\mathbf{C}_{\psi}+\mathbf{X}_{bs})\mathbf{S}_{\phi}\mathbf{1} \end{bmatrix}}_{=\mathbf{b}}$$

$$\hat{\mathbf{p}}_{WLS} = (\mathbf{A}^t\mathbf{C}_{\mathbf{b}}^{-1}\mathbf{A})^{-1}\mathbf{A}^t\mathbf{C}_{\mathbf{b}}^{-1}\mathbf{b}.$$

Identifiability

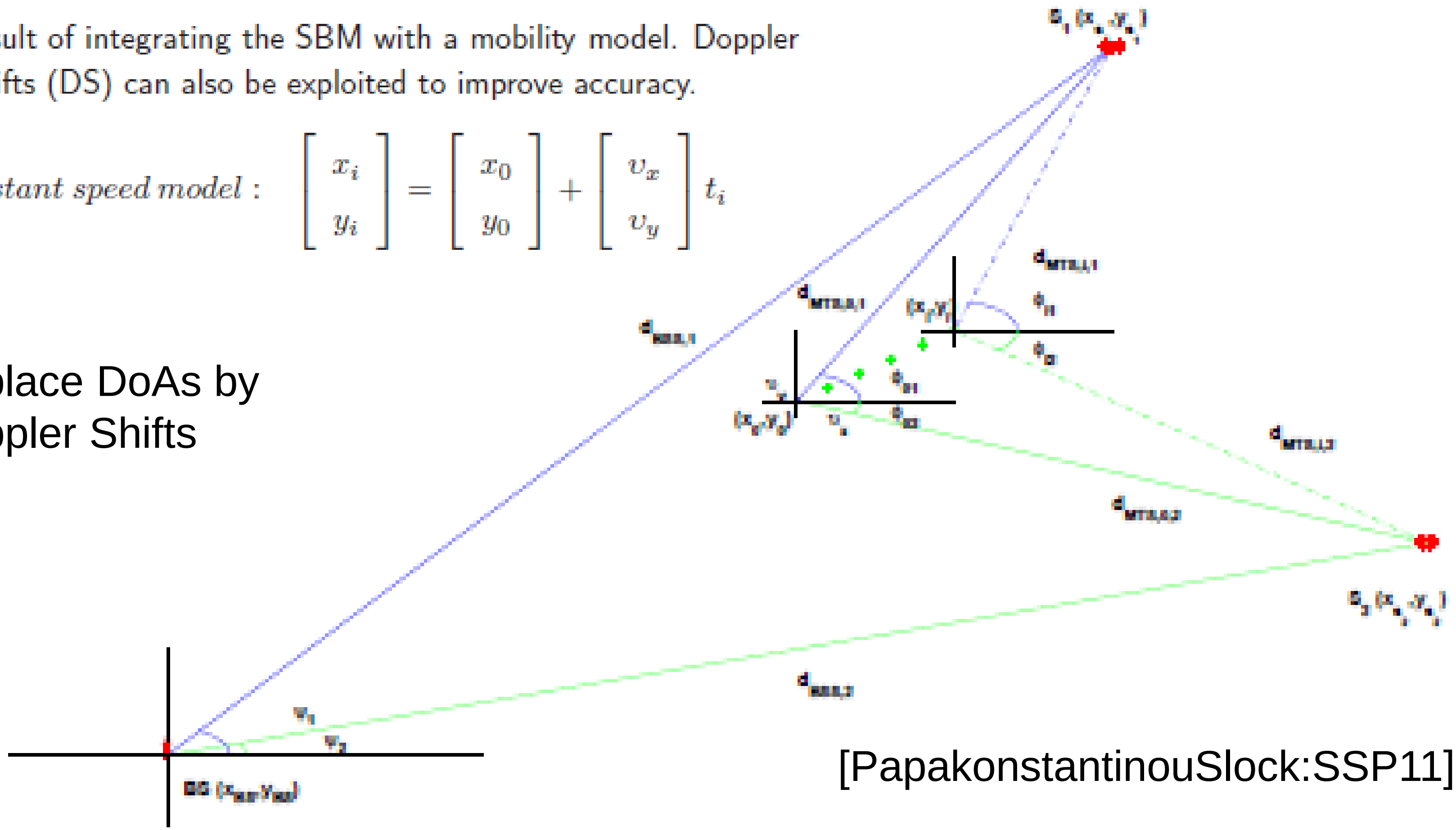
$$3N_s \geq 2N_s + 2 \Leftrightarrow N_s \geq 2$$

If less than 3 LDP per scatterer are available, the MT location is not identifiable independently of the richness of the channel.

Geometrical Channel Models: Dynamic Single-Bounce Model

It's the result of integrating the SBM with a mobility model. Doppler Shifts (DS) can also be exploited to improve accuracy.

$$\textit{Constant speed model}: \begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \begin{bmatrix} v_x \\ v_y \end{bmatrix} t_i$$



Replace DoAs by Doppler Shifts

[PapakonstantinouSlock:SSP11]

Multi-bounce between known walls

- (unknown) scatterer positions now replaced by (known) position of walls.
- Hence can even handle multi-bounce!
- Get identifiability much more easily.
- However, assumes room to be empty.

- M. Froehle, E. Leitinger, P. Meissner, K. Witrisal, “Cooperative Multipath-Assisted Indoor Navigation and Tracking (Co-MINT) Using UWB Signals”, ICC 2013. Also icc 2012.
- P. Setlur and N. Devroye, ``Multipath Exploited Bayesian and Cramer-Rao ´ Bounds for Single Sensor Target Localization," EURASIP JASP, 2013. Also icassp2013.

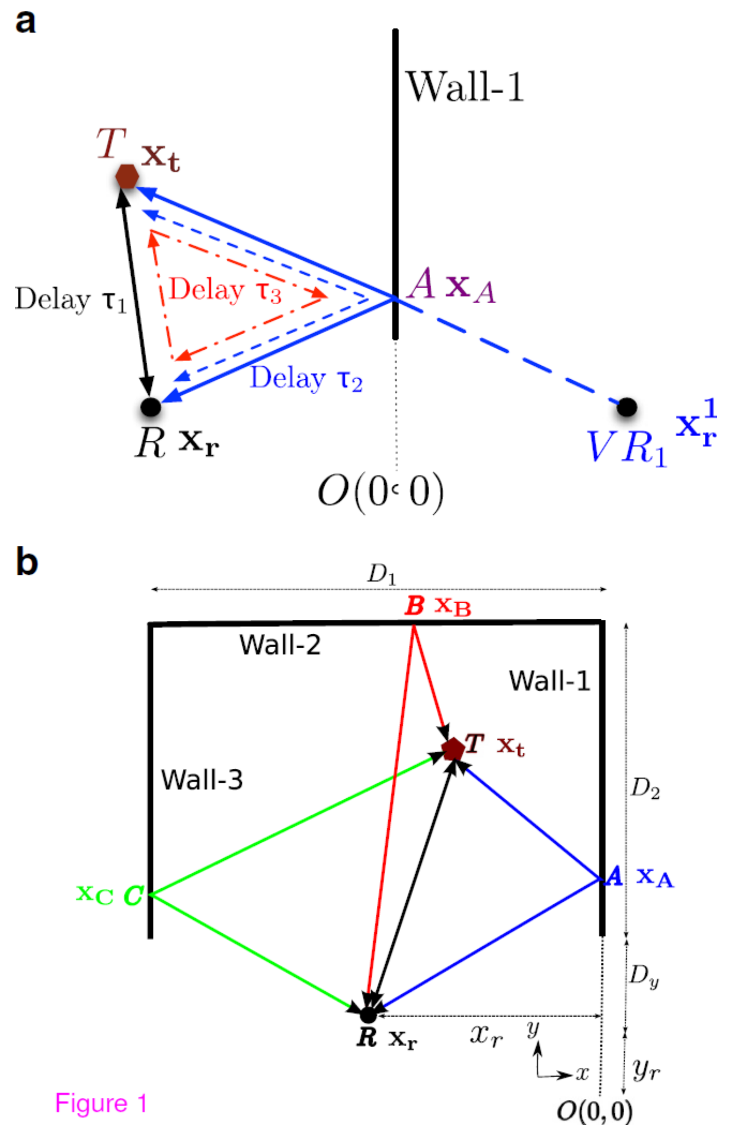


Figure 1

Part II: Presentation Outline

- Non Line of Sight (NLoS) geo-location estimation techniques
  - Single bounce channel models
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- Location aided Communications
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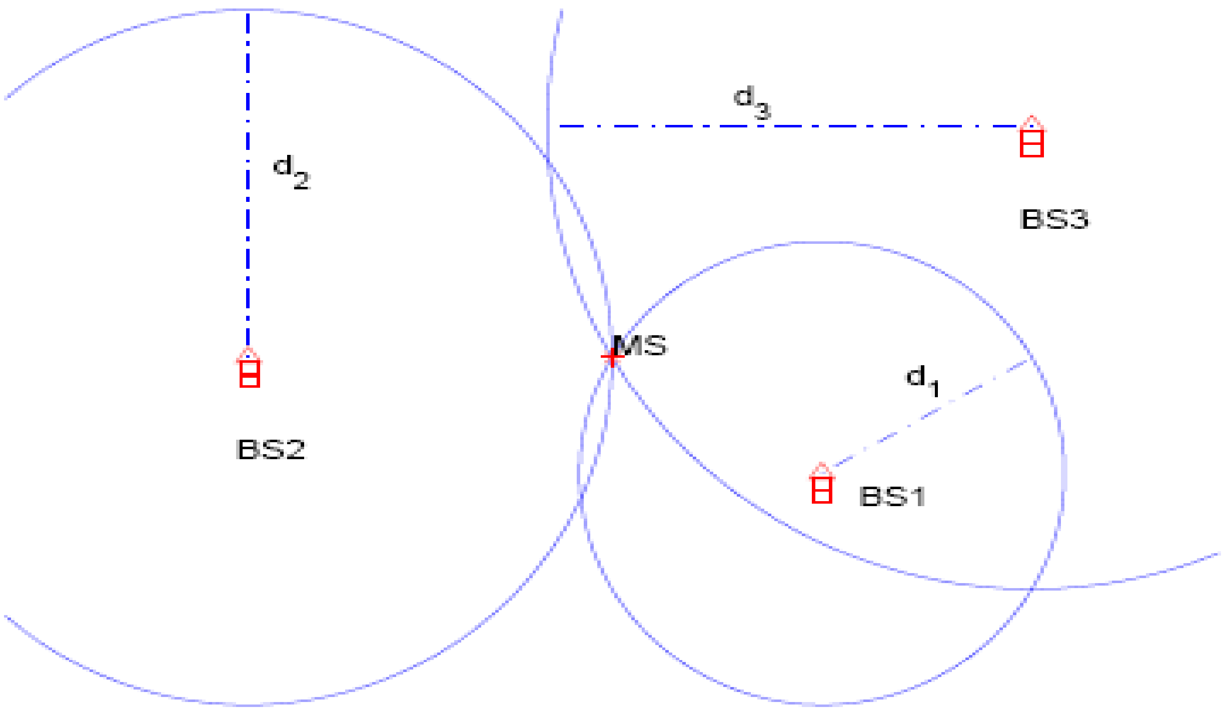
Fingerprinting based Localization Methods

- Fingerprinting based positioning: **fingerprint = RSS usually** (Received Signal Strength)
- Location fingerprinting (LF) (introduced by U.S. Wireless Corp. of San Ramon, Calif.) relies on signal structure characteristics
- LF may exploit the multipath nature of the channel hence the NLOS conditions
- By using multipath propagation pattern, the **LF exploits a signature unique to a given location**
- The position of the mobile is determined by matching measured signal characteristics from the BS-MT link to an entry of the database
- The location corresponding to the highest match of the database entry is considered as the location of the mobile
- For LF, it may be enough to have only one BS-MT link (multiple BSs are not required) to determine the location of the mobile
- Also LF is classified among Direct Location Estimation (DLE) techniques
- Power Delay Profile Fingerprinting (PDP-F) works by matching with the position dependent Power Delay Profiles (PDPs) in a database

Classical ToA based Positioning

LOS: 1 ToA to 1 BS => 1 circle



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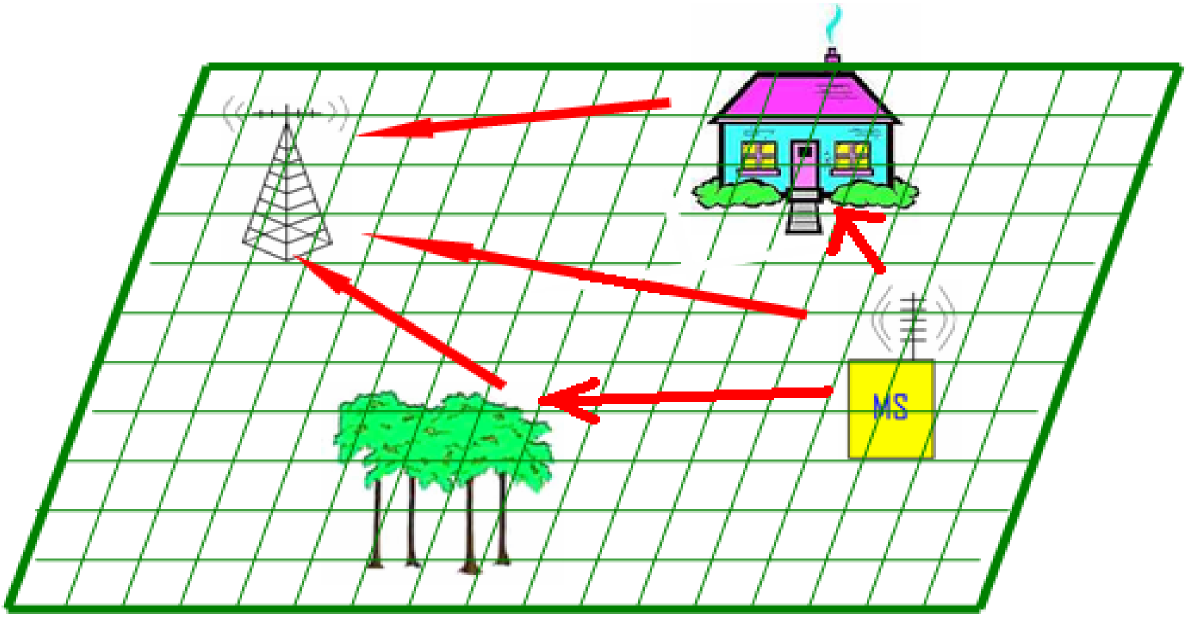
Localization in Multipath Environments

Multipath: Curse or Blessing?

- Curse:
  - LOS: hampers estimation of LOS ToA and other parameters
  - NLOS: introduces bias on LOS ToA
- Blessing:
  - richer LDP information ⇒ may allow single anchor based localization!
  - each path providing as much info as a separate anchor in LOS only case.

Mobile Terminal Localization

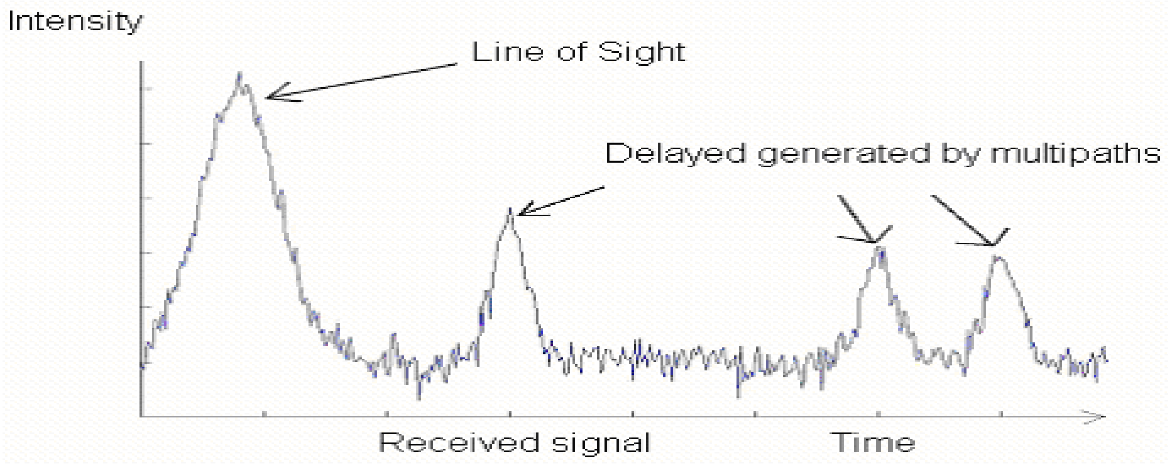
- Exploit (instead of suffer) Multipath Diversity
  & be able to work in NLOS case
  Power Delay Profile Fingerprinting



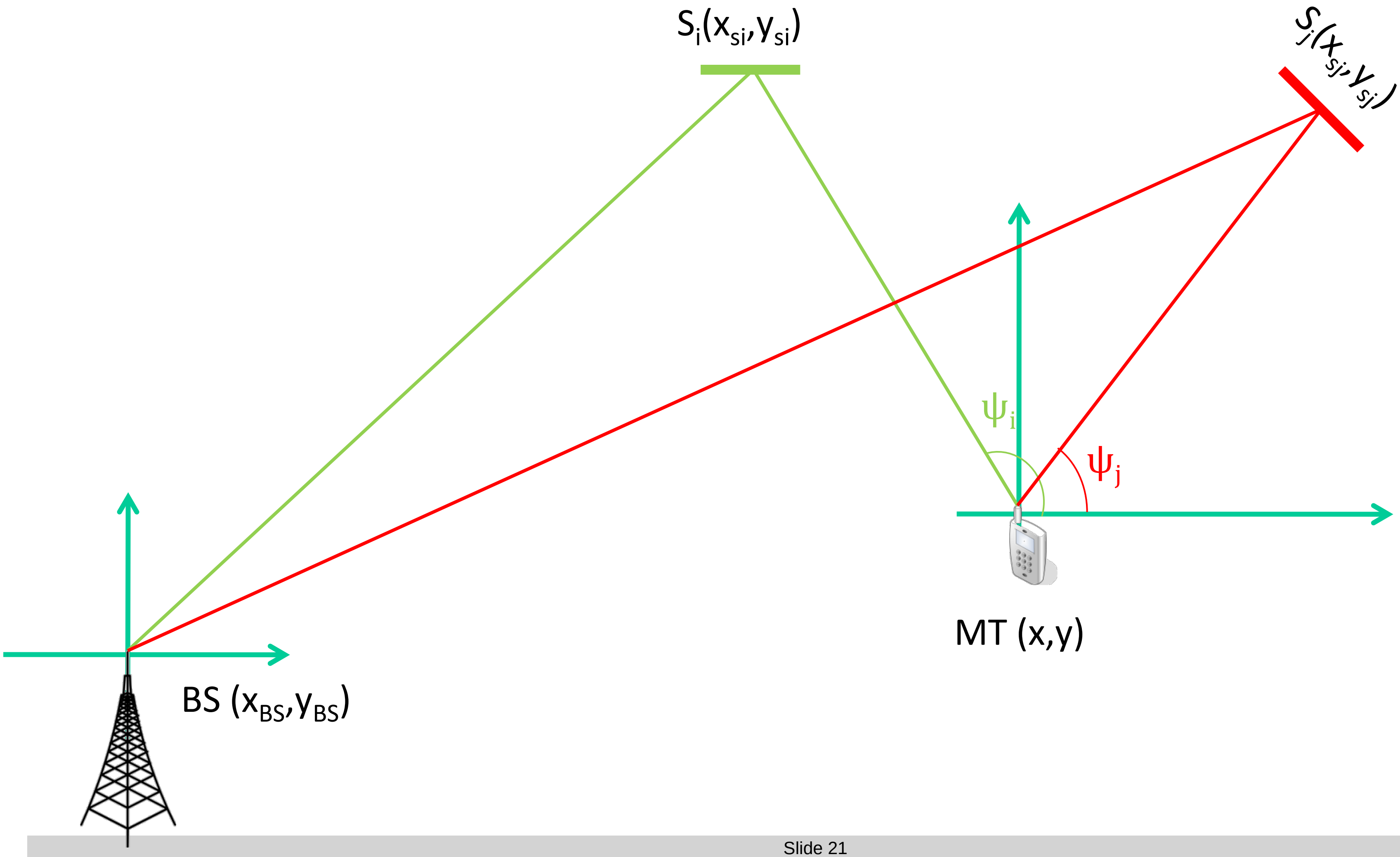
PDP Fingerprinting
(with time reference)

- In the case of a synchronous network,
  - The first peak of the measured PDP determines the ToA of the line-of-sight path
  - The PDP exploits the ToA of the reflected paths

➡ Multi-point signal reception is not required



BS-MT Geometry



PDP Fingerprinting – unsynchronized case

Classical TDoA vs unsynchronized PDP-F

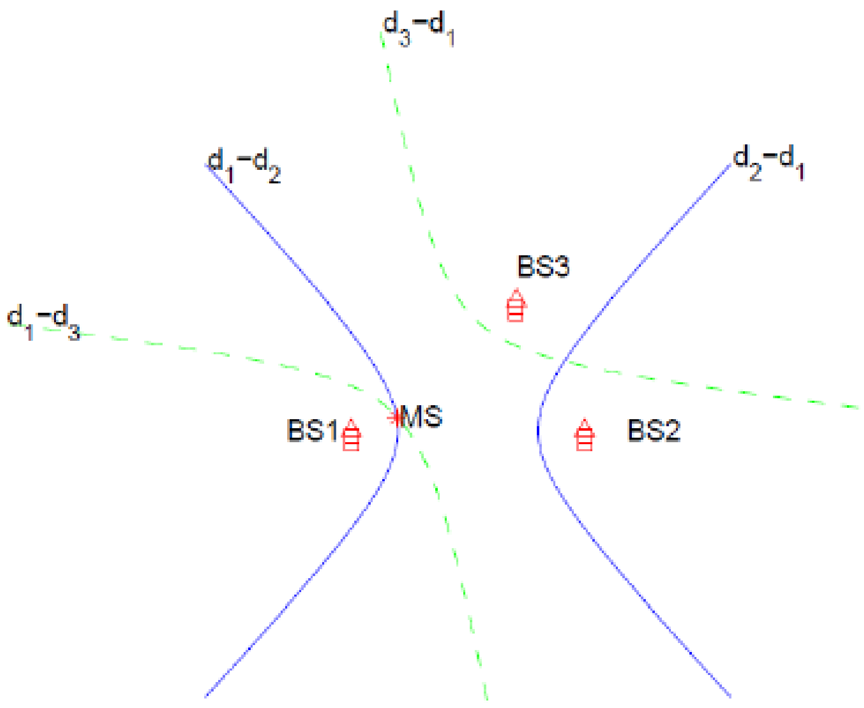
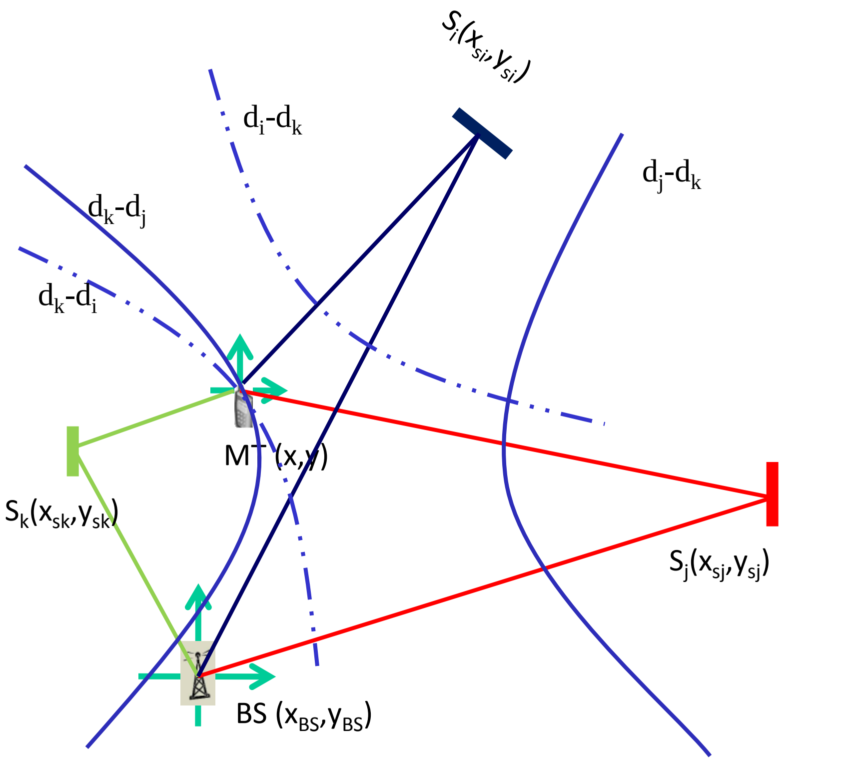


Figure 3.3: TDoA Localization with 3 base stations



Unsynchronized PDP-F with 2TDoA of 3 NLOS paths

Conventional location techniques

- Two step procedure
  - Measure given physical parameters of the transmitted signal (ToA, TDoA, AoA, signal strength...)
  - Combine multiple measurement from a convenient number of BSs to estimate the mobile position

✓ The localization parameters are estimated separately and independently at each BS

✓ The approach ignores the constraint that all measurements must correspond to the same source

→ Suboptimal !!!

Nonlinearities in Classical Indirect Approach

- Classical indirect approach, e.g. ToA based, computes position as intersection of circles
- Nonlinearities introduce breakdown behavior at low SNR
- Rx signal
  - channel impulse response
  - path parameters (ToA, DoA, amplitude,…)
  - position locus per parameter
  - intersect position loci

Direct Position Determination

- One step procedure
  - Introduced by Anthony Weiss (eg: [spawc07])
  - Each BS transfers the observed signal to a central processing unit.
  - ➔ The position is computed as the best match to all the data simultaneously.

- Not robust to
  - Multipath propagation
  - Non line-of-sight conditions

PDP Fingerprinting

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- The received CIR between a MS and the BS:

$$h(t,\tau) = \sum_{l=1}^{L} A_l(t)\, e^{j\varphi_l(t)}\, p(\tau - \tau_l(t))$$

  - ✓ The path delay $\tau_l(t)$ and fading amplitude $A_l(t)$ vary slowly with the position.
  - ✓ The fading phase $\varphi_l(t)$ varies rapidly.

- The PDP is obtained by averaging the squared CIR magnitude over the path phases (assumed uncorrelated!), i.e.,

$$PDP(\tau) = E_{\varphi}\left|h(t,\tau)\right|^2 = \sum_{l=1}^{L} A_l^2 p^2(\tau - \tau_l)$$

PDP Fingerprinting (2)

- Classically, the PDP is estimated by averaging the square of the CIR taps, i.e.,

$$\widehat{PDP}(\tau) = \frac{1}{T}\sum_{t=1}^{T}\left|\widehat{h}(t,\tau)\right|^2$$

✓ If the mobile moves slowly and/or some paths are not resolvable

➔ Poor PDP estimation and location accuracy.

➡ Exploiting the prior information of the channel structure to enhance the PDP estimation

Moving Away from Classical PDP Fingerprinting

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- Improving PDP estimation accuracy
  - ✓ Classical PDP estimate is non-parametric
  - ✓ Improve PDP estimate accuracy by introducing a pathwise parametric model
  - ✓ Estimate path parameters

  However, in moving from non-parametric to parametric, should not forget the Direct approach (and the diffuse components act as estimation error)

- Other issue: fingerprinting criterion: should reflect the sources of inaccuracy
  - ✓ A least-squares PDP fingerprinting criterion would mean that the PDP inaccuracy is additive white Gaussian noise in the PDP estimate
  - ✓ Instead, the additive white Gaussian noise is in the channel estimate(s)

$$\mathcal{LL} \propto -\ln\left(\det\left(\mathbf{C}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}\right)\right) - \operatorname{tr}\left(\hat{\mathbf{C}}\mathbf{C}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}^{-1}\right) \quad \text{where } \hat{\mathbf{C}} = \frac{1}{T}\sum_{i=1}^{T}\left(\hat{\mathbf{h}}_{\mathbf{i}} - \mu\right)\left(\hat{\mathbf{h}}_{\mathbf{i}} - \mu\right)^{H}$$

Specular Channel Model

- The channel imulse response is

$$h(t,\tau) = \sum_{i=1}^{N_p} A_i(t)\ p(\tau - \tau_i(t))$$

where N_p = number of paths (rays), $p(t)$ is the convolution of the transmit and receive filters (pulse shape), $\tau_i(t)$, $A_i(t)$ denote delay and complex attenuation coefficient (amplitude and phase of the ray) of the i^{th} path respectively.

- sampling the CIR with period of τ_s leading to N_τ samples:

$$\mathbf{h}(t) = \begin{bmatrix} h(\tau_s, t) \\ h(2\tau_s, t) \\ \vdots \\ h(N_\tau \tau_s, t) \end{bmatrix} = \sum_{i=1}^{N_p} A_i(t)\, \mathbf{p}_{\tau_i}, \text{ where } \mathbf{p}_\tau = \begin{bmatrix} p(\tau_s - \tau) \\ p(2\tau_s - \tau) \\ \vdots \\ p(N_\tau \tau_s - \tau) \end{bmatrix}$$

- with channel estimation noise:

$$\hat{\mathbf{h}}(t) = \underbrace{\left[\mathbf{p}_{\tau_1} \cdots \mathbf{p}_{\tau_{N_p}}\right]}_{\mathbf{P}_\tau} \underbrace{\begin{bmatrix} A_1(t) \\ \vdots \\ A_{N_p}(t) \end{bmatrix}}_{\mathbf{a}(t)} + \mathbf{v}(t).$$

where $\mathbf{v}(t)$ is the complex additive white Gaussian noise vector with covariance matrix $\sigma_v^2 \mathbf{I}$. The PDP, being another vector having the

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same length as the CIR, could be estimated as:

$$\widehat{\mathbf{PDP}} = \frac{1}{T}\sum_{t=1}^{T}\left|\hat{\mathbf{h}}(t)\right|^2$$

where T is the number of channel observations, and for a vector argument, $|.|^2$ is to be interpreted element-wise.

- For the path amplitudes, there can be two possibilities:
  - deterministic model: $A_i(t)$ deterministic unknowns
  - Gaussian model: $A_i(t)$ Gaussian with zero mean, characterized by a power (variance) i.e. $var(A_i) = \sigma_i^2$, which corresponds to Rayleigh fading for the magnitudes.

As we are interested in investigating the robustness of PDP fingerprinting to fading channel elements, we shall consider the Rayleigh model.

PDP Fingerprinting

- Local Performance Analysis:
  - Cramer-Rao Bound, local identifiability, GDoP
- Global Performance Analysis:
  - Pairwise Error Probability (PEP), diversity order

Power Delay Profile Fingerprinting (PDP-F)

- PDP: attempting to localize with 1 fingerprint
  - With Power Delay Profile-Fingerprinting (PDP-F) technique, it is possible to do mobile localization in multipath and even in NLoS environments
  - One of the Direct Location Estimation (DLE) methods
  - We consider a specular PDP with a finite number of paths.
  - We provide Cramer-Rao bounds (CRBs) and local identifiability analysis for position estimation

Local Identifiability Concept

- To explain the notion of identifiability, consider an example: Time of Arrival (ToA) based localization
  - At least 3 BSs are required for a ToA system to uniquely identify (global identifiability) the location of the MT in 2D
  - If only signals from 2 BSs are available, the intersection of two circles will result in two possible candidates for the MT position. In this case it is clear that there is no global identifiability. However local identifiability is achieved
  - No global identifiability in presence of local identifiability means that there remain discrete (not continuous) ambiguities
  - No local identifiability means that there are continuous ambiguities left

Local Identifiability Theoretical Definition

- To achieve local identifiability of the position vector r, it is required that the LDP Fisher Information Matrix (FIM) be full rank (rank 2 for 2D localization)
- The Elements of the FIM for a general complex Gaussian pdf is given as:

$$[\mathbf{J}_\theta]_{ij} = tr\left(\mathbf{C}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}^{-1}\frac{\partial \mathbf{C}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}}{\partial \theta_\mathbf{i}}\mathbf{C}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}^{-1}\frac{\partial \mathbf{C}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}}{\partial \theta_\mathbf{j}}\right) + 2\Re\left(\left[\frac{\partial \mu}{\partial \theta_\mathbf{i}}\right]^H \mathbf{C}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}^{-1}\left[\frac{\partial \mu}{\partial \theta_\mathbf{j}}\right]\right)$$

where **θ** is here the vector of LDPs $\theta = \left[\tau_1,\ \tau_2,\ \cdots\ \tau_{N_\mathrm{p}},\ \sigma_1^2,\ \sigma_2^2,\ \cdots\ \sigma_{N_\mathrm{p}}^2\right]^T$

Local Identifiability Theoretical Definition Cont.

- Transformation of the FIM from LDP θ to position r is carried out by:

$$\mathbf{J}_{\mathbf{r}} = \mathbf{F}\mathbf{J}_{\theta}\mathbf{F}^{H}$$

where Jacobian

$\mathbf{F} = \frac{\partial \theta}{\partial \mathbf{r}}\Big|_{\mathbf{r}=\mathbf{r}_0}$ ($\mathbf{r}_0 = [x_0, y_0]^T$ being the true position of the mobile)

$$\mathbf{F} = \left[\begin{array}{cccccc} \frac{\partial \tau_1}{\partial x} & \cdots & \frac{\partial \tau_{N_p}}{\partial x} & \frac{\partial \sigma_1^2}{\partial x} & \cdots & \frac{\partial \sigma_{N_p}^2}{\partial x} \\ \frac{\partial \tau_1}{\partial y} & \cdots & \frac{\partial \tau_{N_p}}{\partial y} & \frac{\partial \sigma_1^2}{\partial y} & \cdots & \frac{\partial \sigma_{N_p}^2}{\partial y} \end{array} \right] \Bigg|_{x=x_0, y=y_0}$$

Modeling of the Path Amplitudes

- The complex path amplitudes $A_i(t)$ might be modeled in a couple of different ways
  1. Zero mean complex Gaussian random variables with variance σ_i^2 which corresponds to Rayleigh fading case
  2. Deterministic unknowns
  3. Having both a fading and non-fading component which corresponds to Rician fading

- Another interesting characteristic of the path amplitudes (or variances) is being either Isotropic (only delay dependent) or anisotropic (a genuine function of position)

Assumption about the Delays

- A great simplifying assumption in analyzing results comes from the non-overlapping pulse assumption, i.e., pulse contributions corresponding to different paths do not overlap with each other

- Also the simple case of 2 overlapping pulses has been investigated
- Lack of synchronization (Delay offset) has also been investigated

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CRB comparison: Gaussian vs deterministic path amplitudes

- Gaussian case:

$$SNR_i = \sigma_i^2 e_p / \sigma_v^2$$

$$CRB_{\tau_i} = \frac{1}{2W^2 SNR_i}\left(1 + \frac{1}{SNR_i}\right)$$

$$CRB_{\sigma_i^2} = \sigma_i^4\left(1 + \frac{1}{SNR_i}\right)^2$$

- Deterministic case:

$$SNR_i = a_i^2 e_p / \sigma_v^2$$

$$CRB_{\tau_i} = \frac{1}{2W^2 SNR_i}$$

$$CRB_{a_i} = \frac{a_i^2}{2SNR_i}$$

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Interpretation of Local Identifiability Results

- For anisotropic case, local identifiability can be accomplished with just 1 path both for Rayleigh fading and Deterministic modeling
  - For the case of 2 overlapping pulses, local identifiability is still possible
- For isotropic case, at least 2 paths are required to achieve the local identifiability of the position vector
- The results are parallel with the ToA based systems which requires signals from 2 BSs to achieve local identifiability
- The difference between the isotropic and anisotropic stems from the fact that in the first case we have only 1 distinct information about position. However in the second case we have 2 distinct information about position which makes the local identifiability possible

Local Identifiability with a Delay Offset

- In case of a delay offset, local identifiability is not possible with 1 path. At least 2 paths are required for the anisotropic case, and 3 for the isotropic case.

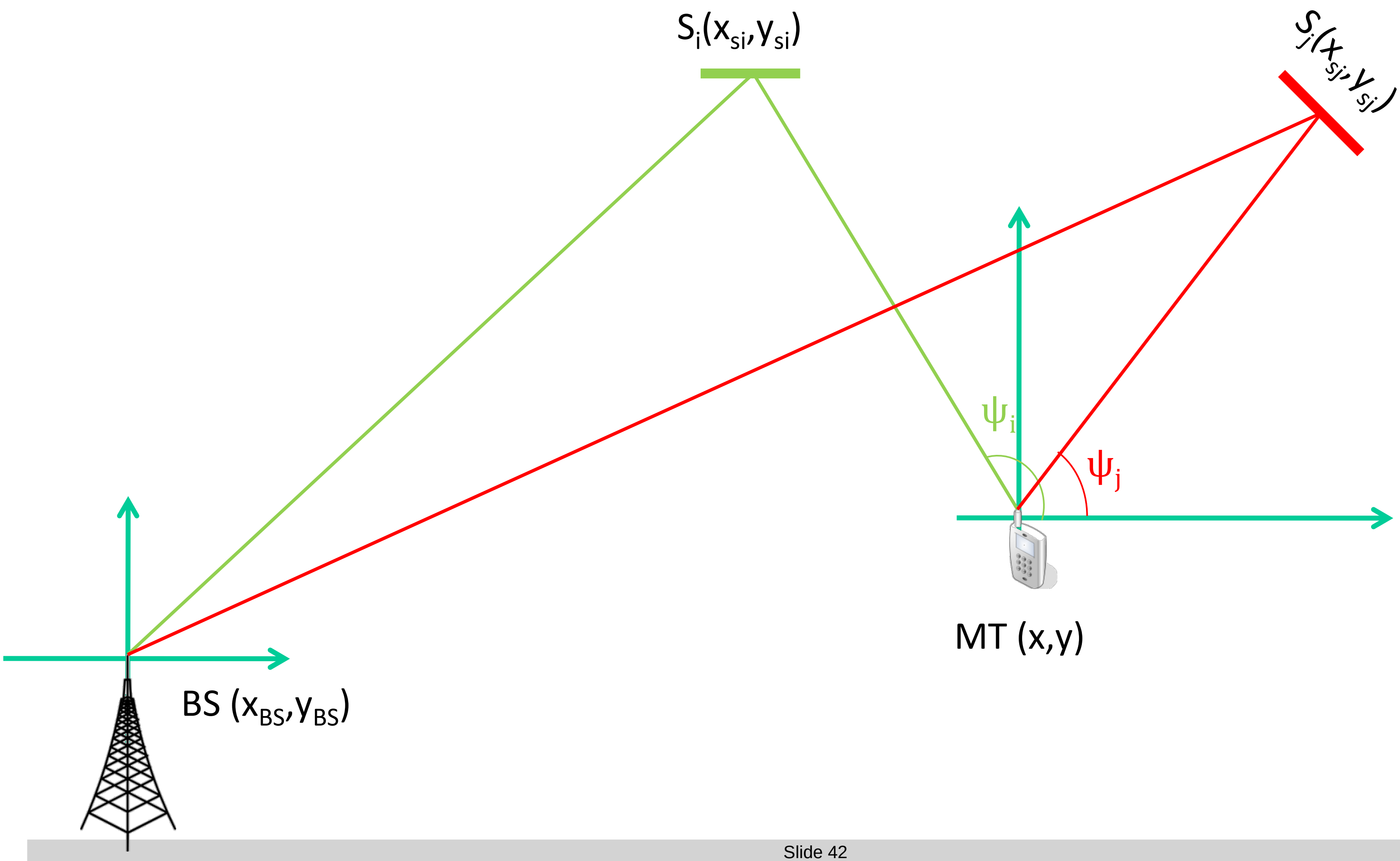
$$\mathbf{F} = \begin{bmatrix} \mathbf{f1} & \mathbf{f2} & -\mathbf{f1} \end{bmatrix} \qquad \mathbf{J}_{\theta} = \begin{bmatrix} \mathbf{J}_{\tau_{10},\tau_{10}} & 0 & \mathbf{J}_{\tau_{10},\tau_{10}} \\ 0 & \mathbf{J}_{\sigma_1^2,\sigma_1^2} & 0 \\ \mathbf{J}_{\tau_{10},\tau_{10}} & 0 & \mathbf{J}_{\tau_{10},\tau_{10}} \end{bmatrix} \qquad \mathbf{J}_{\mathbf{r}} = \mathbf{J}_{\sigma_1^2,\sigma_1^2}\mathbf{f2}\,\mathbf{f2}^H$$

where

- True delay of path i: τ_i
- Measured delay of path i: τ_{i0}
- Synchronization offset: τ_0
- Parameter vector augmented with: τ_0

$$\tau_{i0} = \tau_i + \tau_0$$

Geometric Dilution of Precision (GDoP)



GDoP analysis

For the deterministic case with deterministic phases for $N_p \geq 2$:

$$E\|\mathbf{r}-\hat{\mathbf{r}}\|^2 = \frac{c^2}{8\pi^2 W^2} \frac{\sum_{i=1}^{N_p} SNR_i}{\sum_{i=1}^{N_p-1}\sum_{j=i+1}^{N_p} SNR_i\, SNR_j \sin^2(\psi_i - \psi_j)}$$

$$= \frac{c^2}{8\pi^2 W^2} \frac{\sum_{i=1}^{N_p} SNR_i}{2\left(\sum_{i=1}^{N_p} SNR_i^2 - \left|\sum_{i=1}^{N_p} SNR_i e^{-j2\psi_i}\right|^2\right)}$$

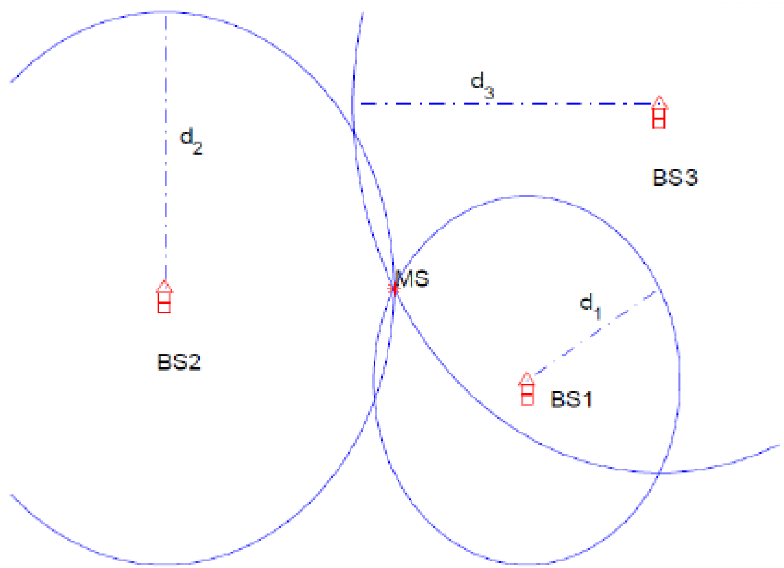
Need to max

$$= \left|\sum_{i=1}^{N_p} SNR_i e^{j2(\psi_1-\psi_i)}\right|^2$$

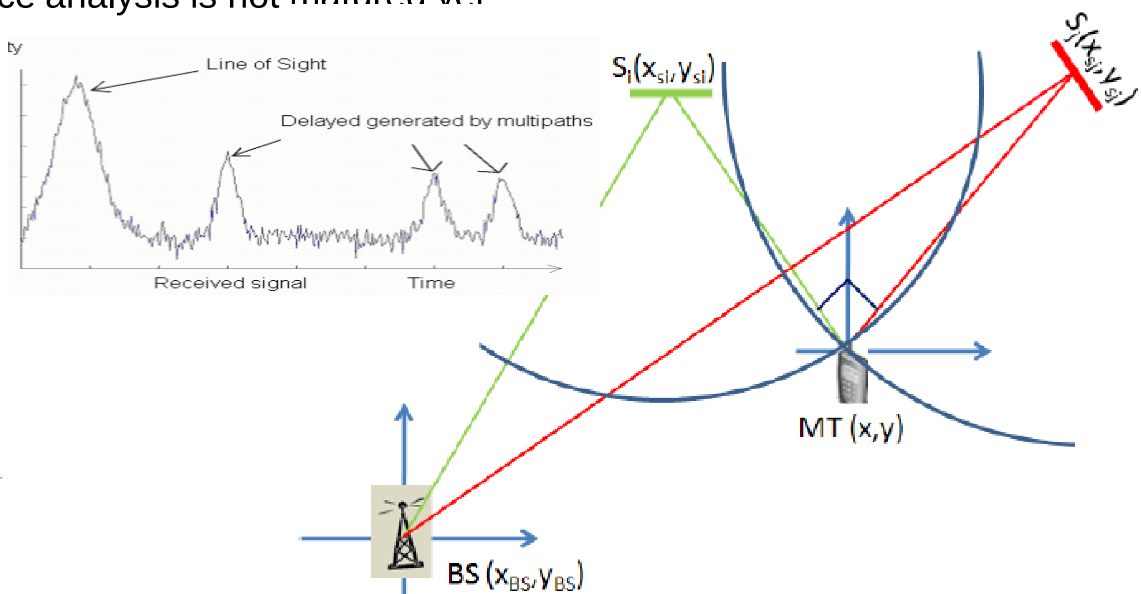
which leads (for uniform SNRs) to uniformly spaced DoAs:

$$\psi_i = \alpha + i\pi / N_p, i = 1, \dots, N_p$$

- Position accuracy analysis of Power Delay Profile fingerprinting (PDP-F), bridging the gap between fingerprinting approaches and classical triangulation
  - With Power Delay Profile-Fingerprinting (PDP-F) technique, it is possible to do mobile localization in multipath and even in NLoS environments
  - Although many algorithms for position fingerprinting have been developed, analytical investigation about their performance analysis is not matured yet



Classical triangulation (ToA)



PDP-F 2 NLOS paths

Concluding Discussion

- PDP is a rich fingerprint
- May lead to single-link position identifiability
- (an)isotropic behavior of path power is an issue
- In particular the path scenario dependent Geometric Dilution of Precision is illustrated.
- CRB corresponds to local performance

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PSDP fingerprinting paper inspired from our work

Single-Site Emitter Localization via Multipath Fingerprinting

Evgeny Kupershtein, Mati Wax, and Israel Cohen

Abstract—A novel method enabling single-site localization of wireless emitters in a rich multipath environment is presented. The localization is based on a novel fingerprinting technique leveraging the spatial-temporal characteristics of the multipath signals, captured by the base station antenna array. The test results, with both simulated and real data, demonstrate localization accuracy of about 1m in typical indoor environments.

Index Terms—antenna array, indoor localization, multipath fingerprinting, signal subspace.

location, i.e., that a fingerprint can be extracted from the received signals and serve as a unique identifier of the location. The problem is casted as a pattern recognition problem, namely, a database of fingerprints is pre-collected in the desired coverage area, and the location is determined by matching the extracted fingerprint to the fingerprints' database.

Two types of fingerprinting techniques have been developed about the same time. One, developed by Wax et al. [3]-[6] and further investigated by Nezafat and Kaveh [7]-[9], is based on using the multipath characteristics, derived from the signals

IEEE Trans. Signal Processing, Jan. 2013

[11] M. Triki and D. T. M. Slock, "Mobile terminal positioning via power delay profile fingerprinting: reproducible validation simulations", *Proc. of IEEE VTC*, pp. 1-5, Sep. 2006.

[12] M. Triki and D. T. M. Slock, "Mobile localization for NLOS propagation", *Proc. of IEEE PIMRC*, pp. 1-4, Sep. 2007.

[13] T. Oktem and D. T. M. Slock, "Power delay Doppler profile fingerprinting for mobile localization in NLOS", *Proc. of IEEE PIMRC*, pp. 876-881, Sep. 2010.

Paper highlights

- Uses **Power** Space Delay Profile characteristics, from SIMO UL channel, from single antenna UE to multi-antenna AP
- Pulse shape issues circumvented by actually working with the received signal during a training signal (not estimated channel impulse response). (assumes stability of Tx/Rx filters)
- Does not assume knowledge of path amplitudes and phases (hence is robust to UE antenna diagram variations and unknown orientation)

$$x(t) = Ay(t) + n(t) \qquad A = \left[a(\theta_1) \otimes s(t-\tau_1), \ \cdots \ , a(\theta_q) \otimes s(t-\tau_q)\right]$$

Antenna array responses from DoAs , delayed training signals

- Position identifiability investigation
- Position estimation by subspace matching (column space of A)
- Original: use of vector of fingerprint match criterion values to the whole database as a new meta fingerprint
- No path amplitude exploited => somewhat sensitive to estimate of number of paths

Paper: Ray Tracing Simulation/Evaluation Results

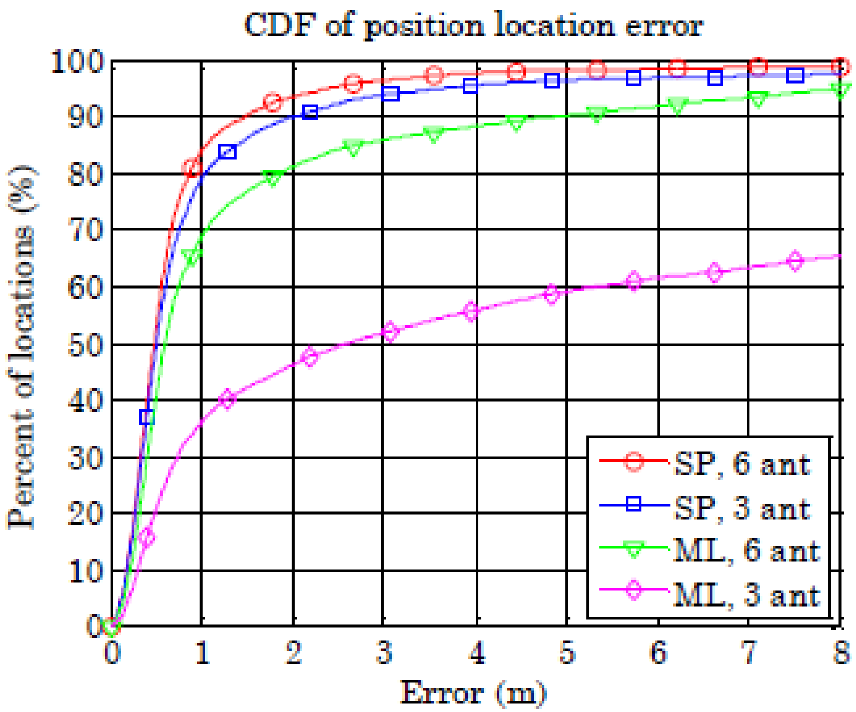


Fig. 6. Performance of the SP and ML techniques for different number of antennas. The number of taps per sensor was $N = 8$ and the signal bandwidth BW=20MHz, while the number of signal snapshots used for each database and test location was $L = 60$ and $M = 55$, respectively.

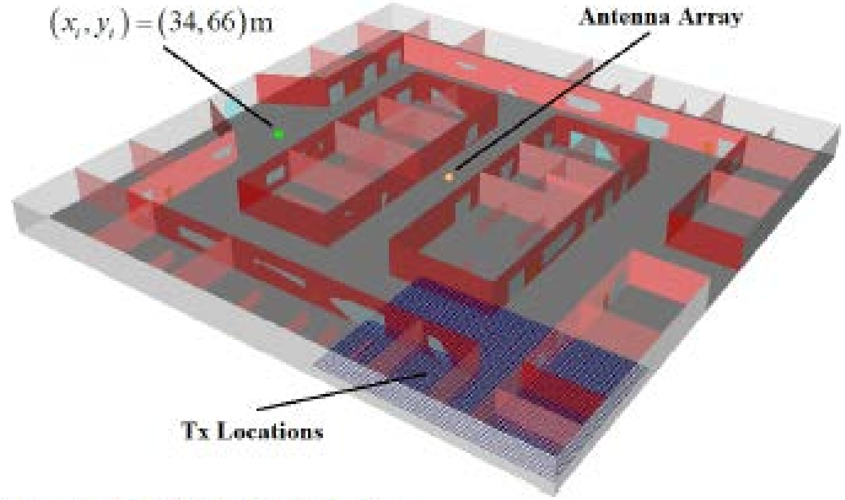


Fig. 3. The simulation environment.

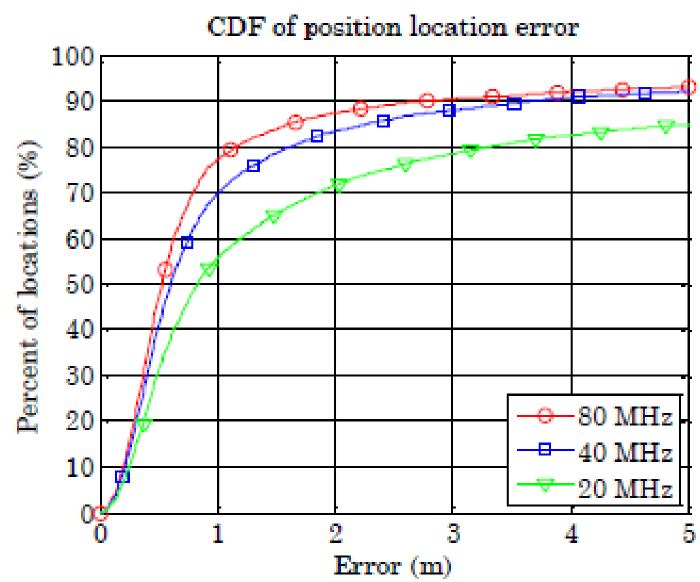


Fig. 12. Performance of the SP technique for different BWs. The number of antennas was $p = 3$ and the number of taps $N = 8$. The number of database and test point snapshots was $L = 60$ and $M = 10$, respectively.

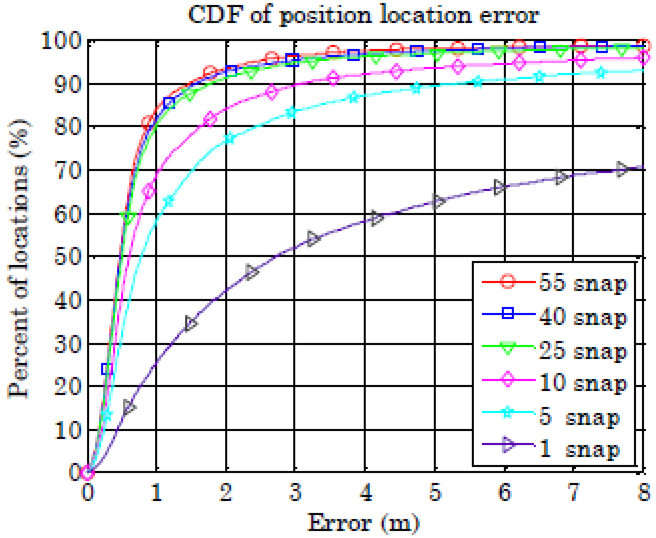


Fig. 8. Performance of the SP technique for different number of test point snapshots. The number of taps $N = 8$ and BW=20MHz, the number of antennas was $p = 6$ and the number of database snapshots $L = 60$.

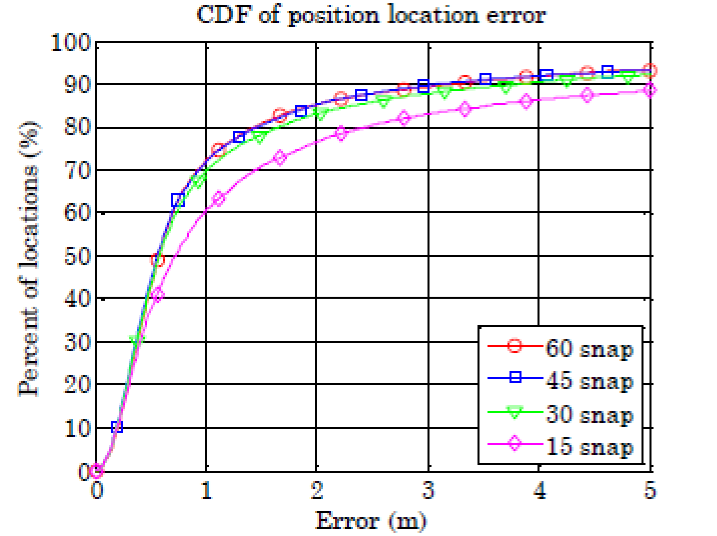


Fig. 9. Performance of the SP technique for different number of database snapshots. The number of taps $N = 8$ and BW=20MHz, the number of antennas was $p = 3$ and the number of test point snapshots $M = 25$.

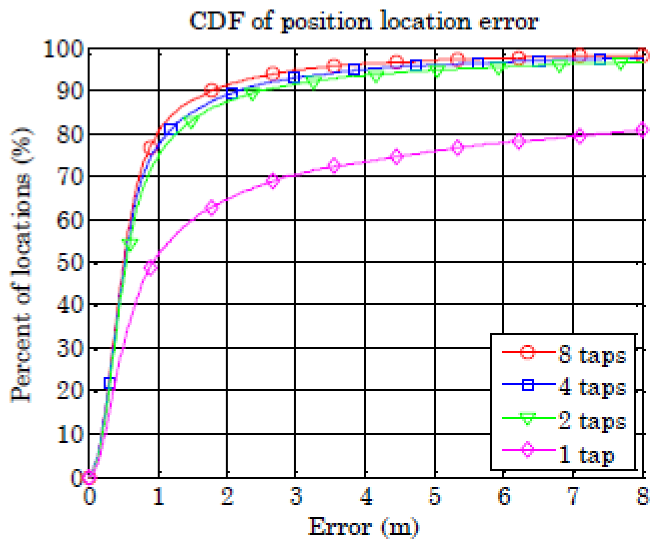


Fig. 10. Performance of the SP technique for different number of taps. The number of antennas was $p = 6$ and BW=20MHz. The number of database and test point snapshots was $L = 60$ and $M = 25$, respectively.

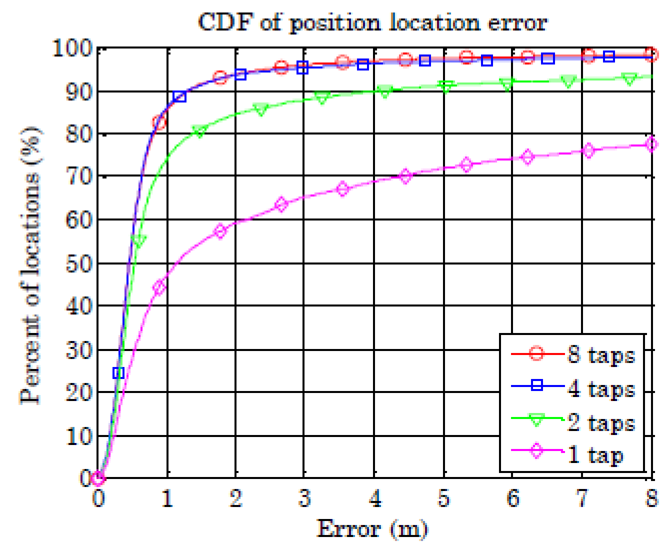


Fig. 11. Performance of the SP technique for different number of taps. The number of antennas was $p = 6$ and BW=80MHz. The number of database and test point snapshots was $L = 60$ and $M = 25$, respectively.

Paper: Evaluation on Real Data

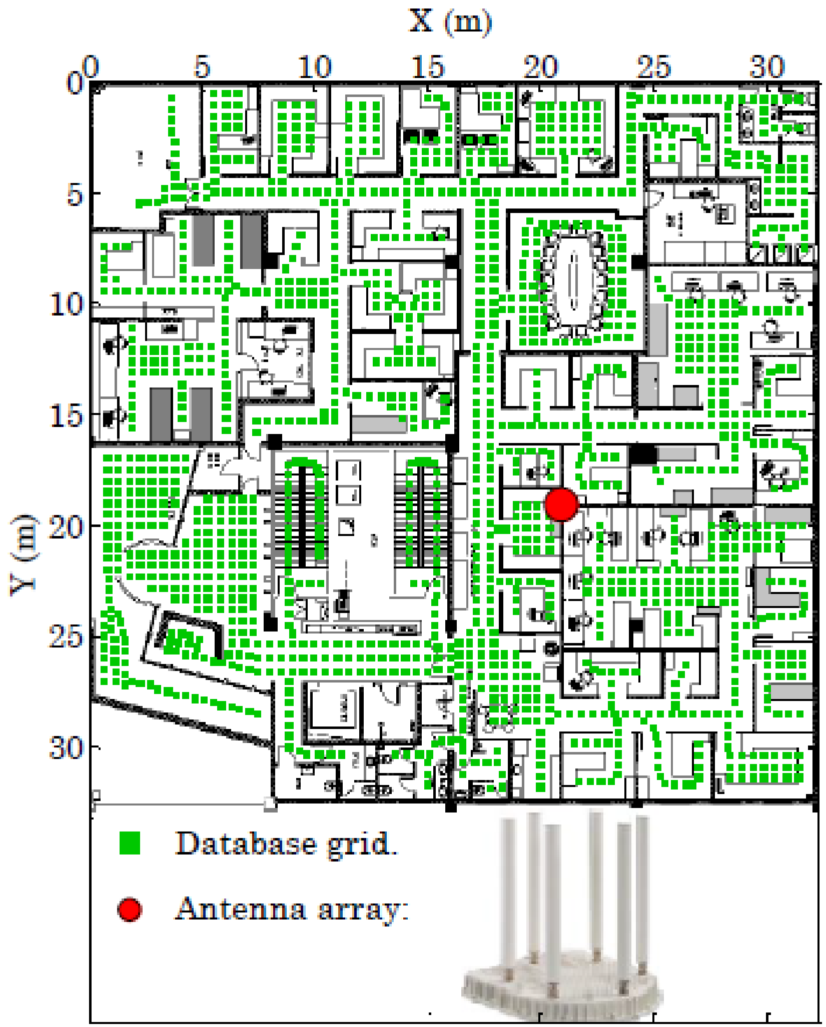


Fig. 13. The office floor wherein the real data experiment was conducted.

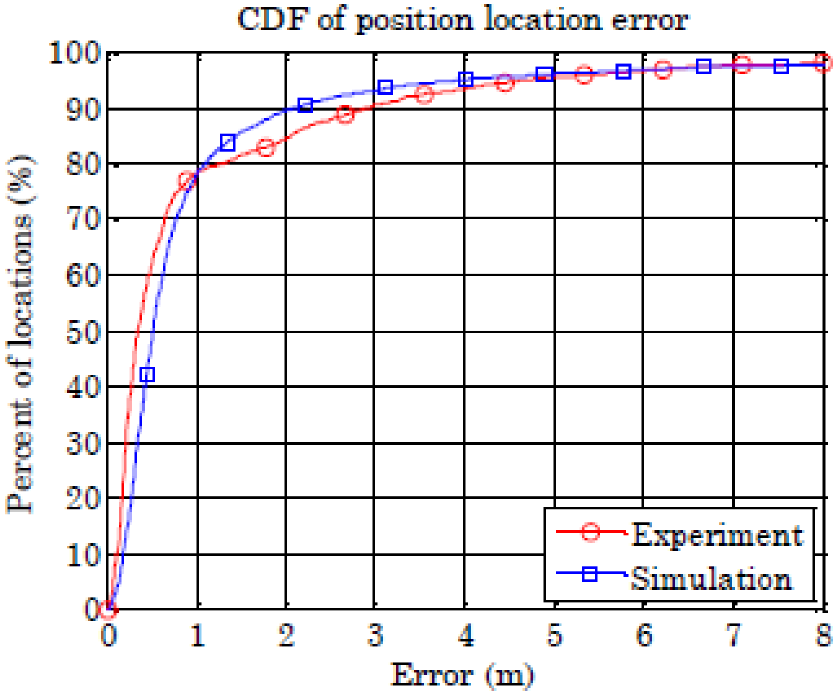


Fig. 14. Performance of the SP technique for real data compared to that of simulated data. In both the experiment and simulation we used $p = 6$ antennas, BW of 20MHz, $N = 8$ taps, and $L = 30$ for the database and $M = 25$ for the test points.

Our ongoing work on this

- Pursue our Gaussian path modeling approach (Rayleigh fading)
  - Avoids determination of number of dominant paths
  - Allows to handle diffuse channel portions

- Extend our PDP fingerprinting analysis to PSDP (possibly MIMO iso MISO):
  - CRB, identifiability, GDoP
  - PEP diversity order

- Investigate further:
  - training Rx signal based vs channel impulse response estimate based
  - Optimal weighting, accounting for database error, position error also

PEP Analysis

- The Gaussian loglikelihood for T i.i.d. channel estimates $\widehat{\mathbf{h}}_t$ at a given position with channel estimate covariance matrix $\mathbf{C}_{\widehat{\mathbf{h}}_t\widehat{\mathbf{h}}_t}$ is

$$\mathcal{LL} \propto -\ln\left(\det\left(\mathbf{C}_{\widehat{\mathbf{h}\mathbf{h}}}\right)\right) - tr\left(\widehat{\mathbf{C}}\,\mathbf{C}^{-1}_{\widehat{\mathbf{h}\mathbf{h}}}\right)$$

where $\widehat{\mathbf{C}} = \frac{1}{T}\sum_{t=1}^{T}\widehat{\mathbf{h}}_t\widehat{\mathbf{h}}_t^H$ is the sample covariance matrix.

- So we have an error when the loglikelihood for a false position is larger than that for the true position:

$$\mathrm{PEP} = \Pr\left\{\mathcal{LL}_T < \mathcal{LL}_F\right\}.$$

Hence,

$$\mathrm{PEP} = \Pr\left\{tr(\widehat{\mathbf{C}}\,\mathbf{A}) < \ln\det(\mathbf{C}_T\,\mathbf{C}_F^{-1})\right\}$$

where $\mathbf{A} = \mathbf{C}_F^{-1} - \mathbf{C}_T^{-1}$.

PEP analysis (3)

- Consider the specular path model with $\widehat{\mathbf{h}} = \mathbf{P}_T\,\mathbf{a} + \mathbf{v}$ with covariance matrix

$$\mathbf{C}_T = \mathbf{P}_T \mathbf{D}_T \mathbf{P}_T^H + \sigma_v^2 \mathbf{I}$$

where the columns of $\mathbf{P}_T$ contain the delayed pulse shapes for the true channel, and the $N_p \times N_p$ diagonal $\mathbf{D}_T$ contains the N_p path powers for the true channel.
Assume here that the pulse shape is energy normalized and that the path delays are well separated so that $\mathbf{P}^H\mathbf{P} = \mathbf{I}_{N_p}$.
SNR in the channel estimates $\rho = tr\{\mathbf{D}_T\}/\sigma_v^2$.

$$\mathbf{C}_T^{-1} = \frac{1}{\sigma_v^2}\mathcal{P}^{\perp}_{\mathbf{P}_T} + \mathbf{P}_T(\mathbf{D}_T + \sigma_v^2\mathbf{I})^{-1}\mathbf{P}_T^H$$

where $\mathcal{P}_{\mathbf{X}} = \mathbf{X}(\mathbf{X}^H\mathbf{X})^{-1}\mathbf{X}^H$ nd $\mathcal{P}^{\perp}_{\mathbf{X}} = \mathbf{I} - \mathcal{P}_{\mathbf{X}}$ denote the orthogonal projection matrices onto the column space of $\mathbf{X}$ (which is assumed here to be of full column rank), and its orthogonal complement respectively.

- For the false position hypothesis, let the channel estimate covariance matrix $\mathbf{C}_F$ be structured similary, $\mathbf{C}_F = \mathbf{P}_F \mathbf{D}_F \mathbf{P}_F^H + \sigma_v^2 \mathbf{I}$ with a possibly different number of again well separated paths (σ_v^2 is assumed to be estimated separately, so σ_v^2 can be taken to be the same in $\mathbf{C}_T$ and $\mathbf{C}_F$).
- Now let $\mathbf{C}_F$ have N_c path delays in common with $\mathbf{C}_T$, with the remaining number of path delays being different. Then we can write

$$\mathbf{P}_T = [\mathbf{P}_1 \;\; \mathbf{P}_2]$$

where the N_c columns of $\mathbf{P}_2$ are in common with $\mathbf{P}_F$. We have a corresponding split in $\mathbf{D}_T = \text{blockdiag}\{\mathbf{D}_1, \mathbf{D}_2\}$. We then get up to first order in SNR:

$$\begin{aligned} \mathbf{C}_T \mathbf{C}_F^{-1} &= \frac{1}{\sigma_v^2} \mathbf{P}_T \mathbf{D}_T \mathbf{P}_T^H \mathcal{P}_{\mathbf{P}_F}^{\perp} + \mathcal{O}(\rho^0) \\ &= \frac{1}{\sigma_v^2} \mathbf{P}_1 \mathbf{D}_1 \mathbf{P}_1^H + \mathcal{O}(\rho^0) \, . \end{aligned}$$

so that we get at high SNR ρ

$$\text{PEP} = \text{E}_{\mathbf{h}}\, Q\left(\sqrt{\frac{T}{2\sigma_v^2}}\,\|\mathbf{a}_1\|\right) .$$

Now exploiting the Gaussian distribution of $\mathbf{a}_1$, this leads to

$$\text{PEP} \;=\; \frac{c}{\det(T\,\mathbf{D}_1)\;\rho^{N_p - N_c}}$$

(for some constant c) which exhibits the well-known diversity behavior of probability of error for digital communication over fading channels.

- Again, $N_p - N_c$ are the number of path delays in which the mistaken PDP differes from the true PDP. Clearly, the richer the multipath, the smaller the PEP is likely to be, esp. at high SNR.

Concluding Remarks

- In this contribution we derived approximate analytic expressions for the Pairwise Error Probability (PEP) for Power Delay Profile Fingerprinting (PDP-F).
- In the non-ergodic case, the diversity present in the channel impulse response leads to the same SNR diversity order for PDP-F PEP as for probability of error in digital communications over fading channels.
- In communications, the diversity order is determined by the rank of the channel covariance matrix, regardless of whether the channel is specular or diffuse. In PDP-F on the other hand, the specularity of the channel may play a more determining role in the resulting performance. In the local performance analysis corresponding to the CRB [OktemSlock:icassp11], the diffuse portion of the channel plays the same role as channel estimation error, of which the power does not go down with increasing SNR though.

Part II: Presentation Outline

- Non Line of Sight (NLoS) geo-location estimation techniques
  - Single bounce channel models
  - Power Delay Profile (PDP) fingerprinting

- Location aided Communications
  - basic PHY techniques
  - Cellular Systems
  - MANETs
  - Cognitive Radio

Some generalities on position based information that can be exploited

- **Slow fading channel characteristics** of various links:
  - LOS/NLOS
  - Attenuation
  - Delay spread, frequency selectivity
  - Angular spreads, MIMO channel characteristics
  - Speed, direction of movement, acceleration (predictibility of movement)

  Some of these aspects may require the use of databases (containing these characteristics as a function of position), compatible with cognitive radio setting.

  Compared to feedback based approaches: some of these characteristics can not easily be determined from isolated channel estimates, or not predicted at all (e.g. slow fading prediction).

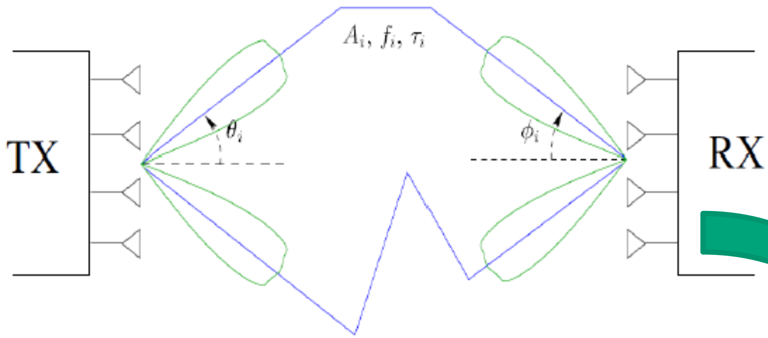
- Can **not** be inferred on basis of position: **fast fading** state, instantaneous channel response

location aided communications : thoughts at the end of WHERE

Impact of position information on channel estimation.

- On the receiver side:
  - position information can lead to information about the channel statistics via a database, which can be used to improve channel estimation. This could be compared to learning of the channel statistics from previous channel estimates (which is not possible though in short packet mode!)
- On the transmitter side:
  - one could consider adapting the (OFDM) Cyclic Prefix (CP) and pilot structure on the basis of environment parameters. This would lead to minimized overhead and would avoid to design for the worst case.
- MCSS'11 Artist4G session, Nokia-Siemens presentation: database of channel impulse responses themselves!! (stable over 40' in some measurements), to overcome problem of delay in channel feedback (FB). Considered combined FB + location aided approaches as realistic.

Location and database aided channel estimation/prediction



$$\underline{\mathbf{A}}[k] = \mathbf{F}[\mathbf{p}[k], k]\, \underline{\mathbf{A}}[k-1] + \mathbf{Q}^{\frac{1}{2}}(\mathbf{p}[k], k)\, \mathbf{w}[k]$$
$$\underline{\hat{\mathbf{h}}}[k] = \mathbf{H}[\mathbf{p}[k], k]\, \underline{\mathbf{A}}[k] + \underline{\tilde{\mathbf{h}}}[k]$$

Integrated
position tracking (PKF) and
channel tracking (KF)

$\underline{\mathbf{A}}[k]$: fast fading complex path gains

$\mathbf{H}[\mathbf{p}[k], k], \mathbf{F}[\mathbf{p}[k], k], \mathbf{Q}[\mathbf{p}[k], k]$: slow fading position-dependent parameters

For fast fading channel estimation and short-term prediction, the channel dynamics components H,F,Q can be

(1) learned from consecutive channel estimates, but knowledge will often come a bit late in this way, or

(2) determined from position information + database, leading to instantaneous knowledge & extended (short-term) channel prediction range.

(2) Allows furthermore longer-term prediction, but of channel statistics only.

Future work: what if database content is limited?

location aided communications : thoughts at the end of WHERE

Position based Adaptive Modulation and Coding (AMC).

- (Position information leads to) Environment information which in turn leads to information on the channel diversity structure, on the channel frequency selectivity and would allow to adapt frequency allocation/interleaving.

- Information on the MIMO channel richness allows to adapt the spatial multiplexing and the (linear) space-time coding.

- Information on the mobility provides temporal diversity information, which can be used to adapt interleaving in time.

- All these adaptations can take into account channel non-Rayleigh aspects (e.g. LOS/NLOS, LOS leads to reduced or no fading).

HIGHTS
High precision positioning for Cooperative-ITS

location aided communications : thoughts at the end of FP7 WHERE

Location aided Resource Allocation.

- A transversal aspect is also that location tracking can lead to **location prediction**. This leads in turn to **slow fading predictibility** (and not just fast fading prediction, which can in principle be done also from past channel response estimates). Another aspect is that **user selection** (multi-user diversity) potentially leads to an **explosion of CSIT requirements** and associated overhead. Location based covariance CSIT might offer a (partial) solution.
- **Single user aspects**:

  the environment (profile) and mobility information can be exploited to aid (time,frequency) allocation in OFDMA.
- **Multi-user MIMO**:

  Use environment information to preselect users, to limit channel feedback to a reduced set of preselected users. The user preselection can e.g. involve: users with similar RSS, users with rank 1 MIMO channels (close to LOS), ...
- **Multicell aspects** (interference coordination) or for **Cognitive Radio** (interference from secondary systems to primary systems):

  the interference level can be predicted from position based information.

From WHERE to WHERE2 for Location aided Communications

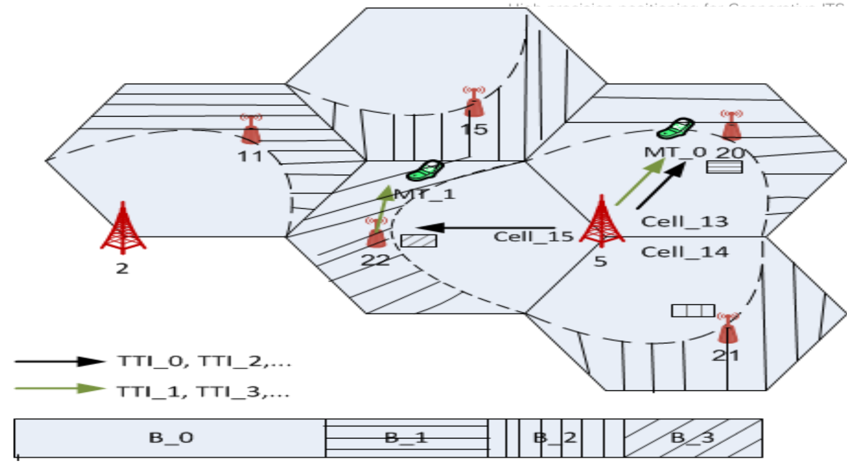
- In WHERE: mostly single-user link, some single-cell SDMA, and some intercell interference coordination (ICIC) started.

  In WHERE2: study of relays, multicell approaches, macro-femto coexistence.

- More emphasis on the cooperative aspect in WHERE2. Appearance of security issues also.

- Significant emphasis on cognitive radio.

Upgrading Wireless Communications to Location Aided Systems (1/3)



- **T3.1 - Coordination and Cooperation between Network Nodes**
- Partners
  - **EUR, DLR, IT, MER, MTN, UniS, PTIN, OTE**
- Subtasks
  - T3.1.1: Fixed Relays for Cellular Systems (LTE-Advanced)
  - T3.1.2: Location-aided Multi-cell Processing
  - T3.1.3: Femtocell based Communications

- Enablers
  - Location information permeating (e.g. LTE): smart phones, or WP2 !
    - Hence communication overhead for obtaining location info not an issue (but may want info for many nodes)
  - Network based radio environment databases
- Communication System Paradigms/Characteristics
  - Broadcast Channel, Interference Channel, Interfering Broadcast Channel, ...!
  - Macro cells, relays, femto cells, HetNets
  - Power Control, Resource Allocation, Green radio
  - Celll edge/cell center, (fractional) frequency reuse
  - LOS/NLOS, static/mobile

T3.1.1 – Location-aided relaying (UNIS)

- **Context & Problem**:
  - Improving the spectrum efficiency in multiple relay network. The orthogonality between source and multiple relay requires extra cost either in time or frequency which reduces the spectral efficiency
- **Principle & Novelty**:
  - Novel semi-deterministic approach is proposed for performing joint rate-adaptation and best relay selection. The selection process employs two criteria using mixed channel knowledge. Criterion I, SD link instantaneous SNR employed as threshold to compare with the average SNR of SR link to form a subset for selection. Criterion II, order the average SNR of SR link, best K relays are selected to form a subset. Then the best relay of this subset in terms of RD link instantaneous SNR will be selected to forward the message to destination.

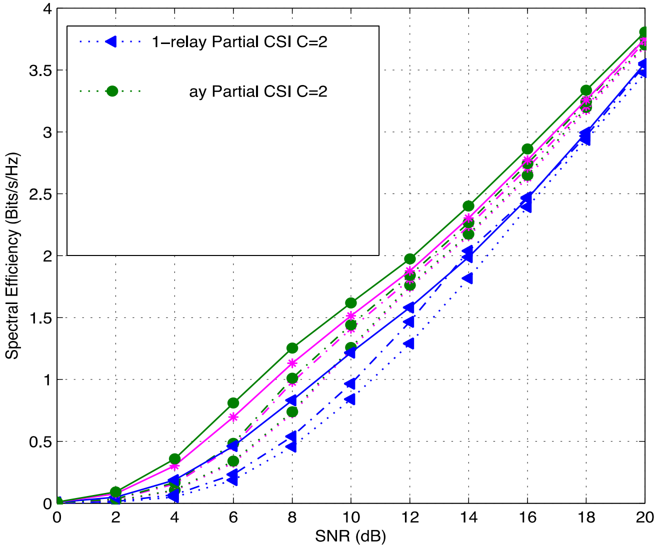
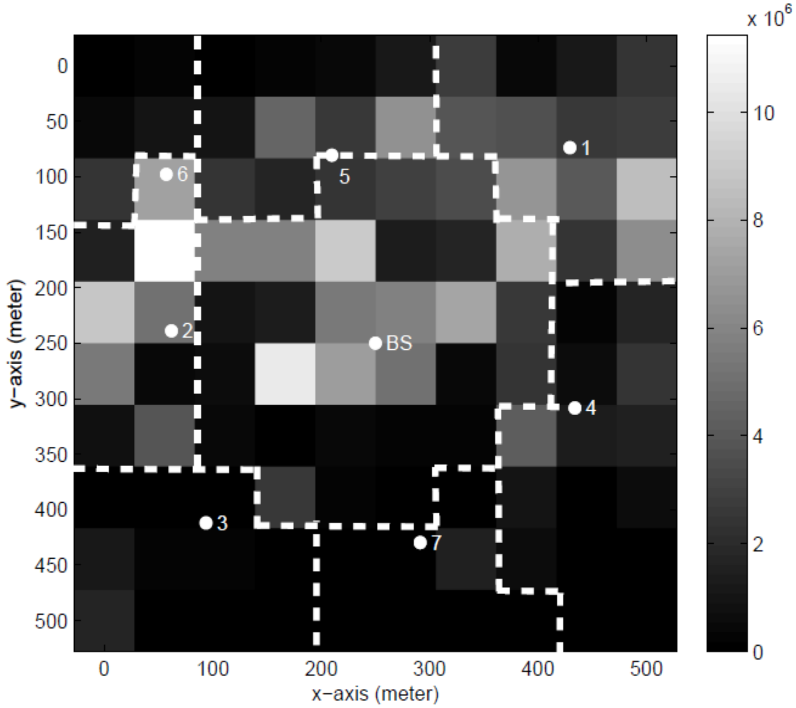


Fig.1. Spectrum efficiency of the modulation adaptive cooperation scheme with relay selection Criterion I as a function of the average SNR of SD link. The average SNR of the SR link are 6, 12, and 2.5 dB higher than the SD link respectively.

T3.1.1 – Location Aided Relay Node Planning (IT) (WCNC12 paper)

- **Context & Problem:**
  - Where are the best locations to install relay nodes , besides satisfying practical constrains such as having sufficient power supply?
  - RNs should be placed according to geographical traffic distribution over a cell area.
  - How to obtain geographical traffic distribution?
  - Conventional scheme, measuring traffic at the BS, can not provide sufficient space resolution.
- **Principle & Novelty:**
  - derive users' mobility pattern from their historical location information, derive users' comm. pattern from measurement, so as to estimate geographical traffic distribution.
  - propose an optimization algorithm for RN location selection.
- **Recent Achievements:**
  - IEEE WCNC, April 2012
  - ISCCSP, May 2012: location-aided cooperative adaptive beam-forming
  - IEEE CAMAD, Sept. 2012: location-aided round-robin scheduling.



The estimated traffic (denoted by color) over a 500*500 (m^2) area. 7 locations (white dots) are selected over 44 candidate places . The RN coverage area is represented by dotted line. Number 1 to 7 represents decreasing order of importance in terms of bandwidth reduction.

T3.1.1 – Location-aided Round-Robin Scheduling for Fractional Frequency Reuse (FFR) LTE-A Relay Network (IT) (CAMAD12 paper)

- **Context & Problem**:
  - Freqency band deployed at the relay nodes (RN) and at the eNodeB are mutual different. (Fig.1)
  - As a result, the co-channel interference from relays in adjacent cells are miminized.
  - However, this frequency resouce division is static, and not stastisfy dynamic traffic load.
  - Downlink transmission is considered in this work.
- **Principle & Novelty**:
  - Principle: When the traffic load at the central exceeds its capacity, proportional freqency bands dedicated to RNs for edge_MTs are temporary allowed to be used simultaneously at the eNodeB to communicate with central_MTs.
  - Novelty:
    - derive long-term fading of RN-to-central_MTs and eNodeB-to-edge_MTs from a location-fading mapping database.
    - The MTs having the deepest fading will be allocated using the same frequency band.
    - It outperfoms CSI-aided scheme in low-mobility scenario, since not only the feedback signaling, but also the reference signaling can be reduced.
  - **Results**: The accumulated throughput of central area is enhanced. (Fig 2.)

Fig. 1

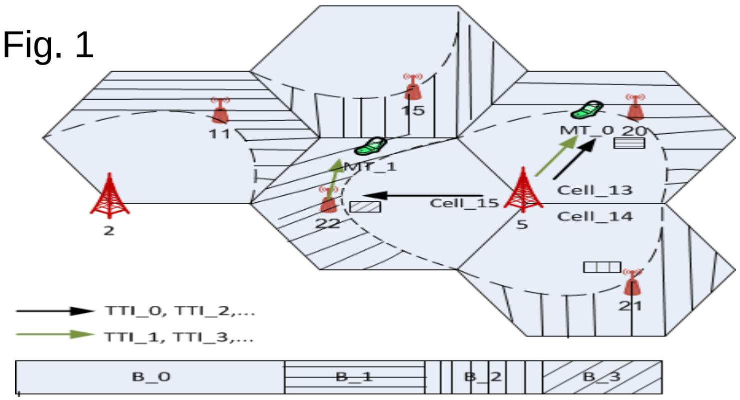
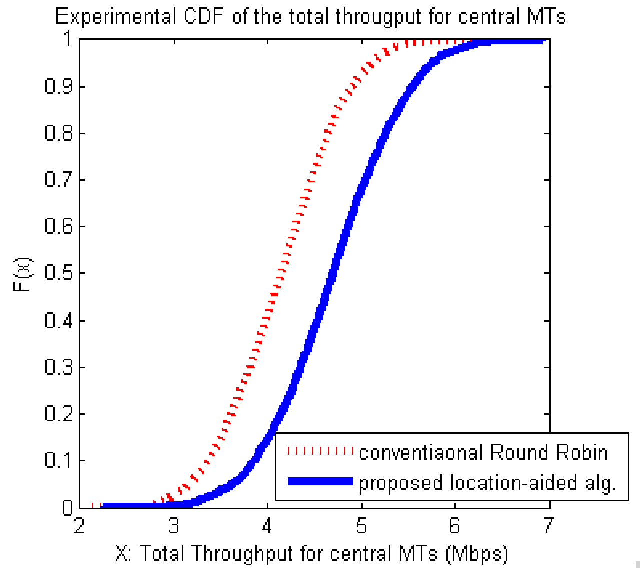
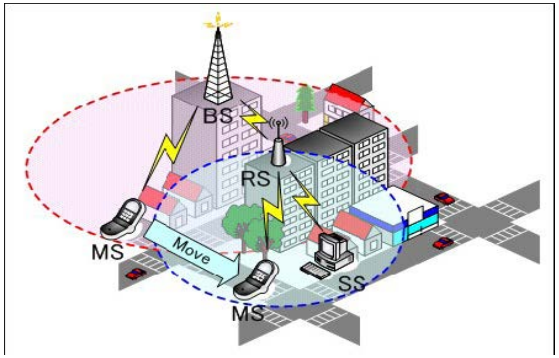


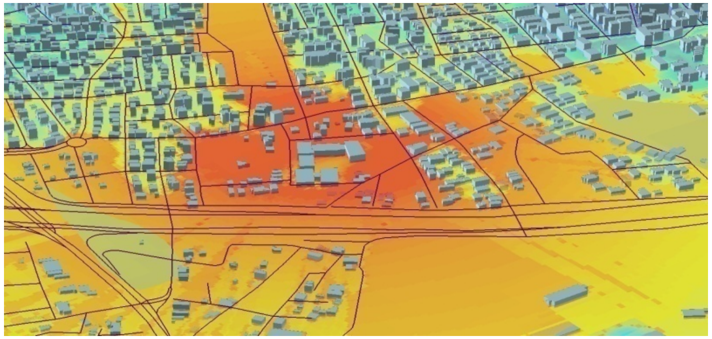
Fig. 2



T3.1.1 – Geo-location for improving the communication of a user with a network consisting of a Base station and a Relay (OTE)

- Context & Problem:
  - Acquire the geolocation of the mobile user through GPS. According to his geolocation, the CPE is handovered /attached to the nearest node (BS or RS) and the throughput, capacity of the network is improved. The energy efficiency of the network is also improved by estimating the location of a user.
- Principle & Novelty:
  - Use the position of a user acquired from GPS in a BS-RS network . The user's terminal is attached to the BS or RS node that has the least capacity and thus the capacity of the network is uniformly utilized. The energy dissipation is improved by using the location of the user and letting the node to be in a live or sleep mode depending whether the user is in close or not proximity with the reference node.
- Recent Achievements:
  - Perform a number of measurements in the surroundings of a BS-RS 802.16j network. A platform based on purl, MySQL and java scripts was monitoring the netwok online and the improved performance of the network was justified.





HIGHTS
High precision positioning for Cooperative-ITS

T3.1.1 – Geolocation aiding in the selection of a node in a network with base station and relays (OTE)

- **Context & Problem**:
  - Optimal node selection for a network with cooperative relays is of utmost importance since it can improve the performance of the network and reduce the power consumption at the network and terminal side
- **Principle & Novelty**:
  - Considered an optimization function that involves the terminal's position and the data rate between the terminal and the node.
  - Selection (Q)= max(α_1R, α_2RSSI) where R is the rate and RSSI is the signal strength
- **Recent Achievements:**
  - Development of an algorithm for optimizing the scenario where a user is in a network with base stations and relays
  - Implementation of the algorithm in a real field scenario based on a network with a base station and two relays

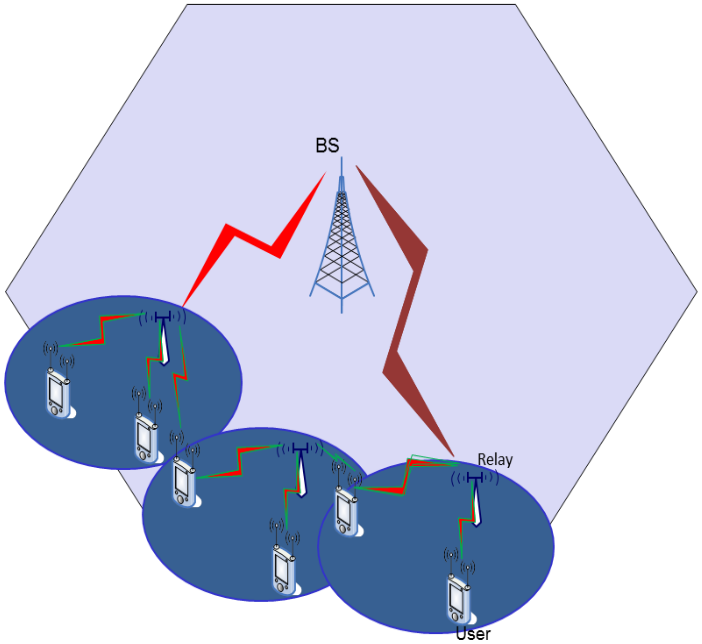


Fig. 1 Optimizing a network where a user is located between relays and a base station

T3.1.1 – Geolocation aiding in the selection of a node in a network with base station and relays (OTE)

Comparing the optimized theoretical Q values with field measurements

Compared the theoretical Q value with measured values of the RSSI and the data rate between the user and the node

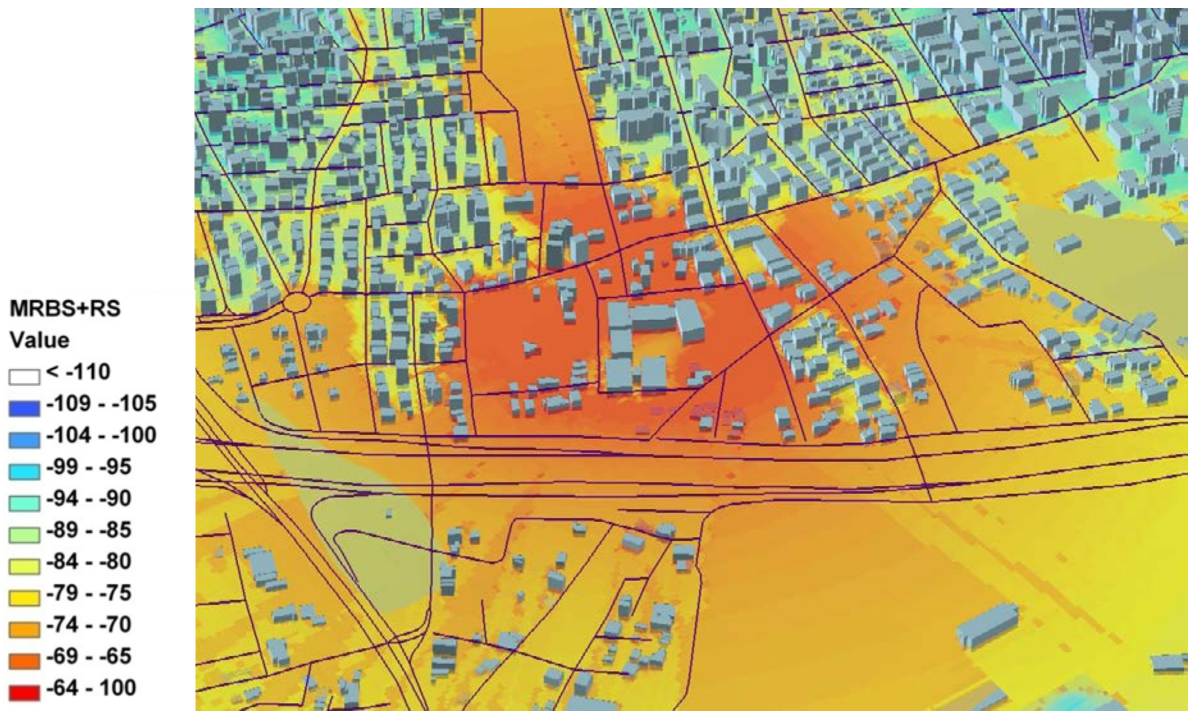


Fig. 1 Field strength values were taken in a scenario where a base station and two relays were installed

T3.1.2 Location-aided Multi-cell Processing (EUR)

- One key observation: **user selection**:
  - Requires enormous overhead: to know instantaneous channels (without delay) for a large pool of users to schedule from (so from many more users than the ones actually scheduled)
  - How far can we go with partial CSIT, typically covariance CSIT (could be location based)? E.g. spatial subspaces (multi-antenna), or PDP holes (even single antenna, see further).

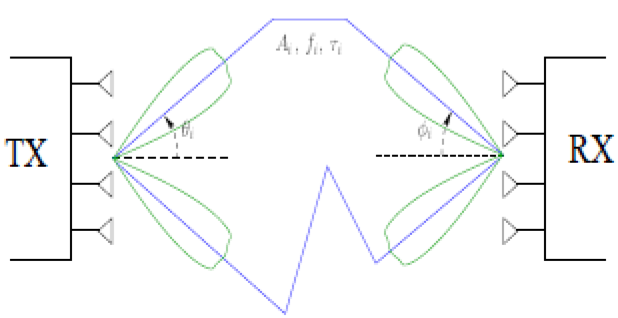
- **Single antenna**: power coordination, can fairly easily be done location-aided.

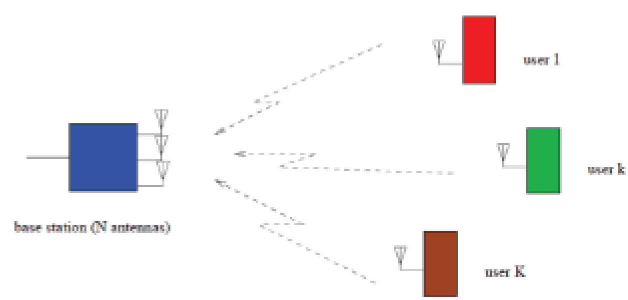
- **Multi-antenna** techniques:

  Require downlink channel knowledge, in principle of all channels at all transmitters
  - Multi-Cell coordinated beamforming (MIMO/MISO Interference Channel (IFC))
  - Network MIMO (= CoMP): requires furthermore signal distribution over the BS's

SDMA (MISO BC) considerations

- Whereas single user (SU) MIMO communications represented a big breakthrough and are now integrated in a number of wireless communication standards, the next improvement is indeed multi-user MIMO (MU MIMO).
- This topic is nontrivial as e.g. illustrated by the fact that standardization bodies were not able to get an agreement on the topic until recently to get it included in the LTE-A standard.
- MU MIMO is a further evolution of SDMA, which was THE hot wireless topic throughout the nineties.





HIGHTS
High precision positioning for Cooperative-ITS

MU MIMO key elements

- SDMA is a suboptimal approach to MU MIMO, with transmitter precoding limited to linear beamforming, whereas optimal MU MIMO requires Dirty Paper Coding (DPC).
- Channel feedback has gained much more acceptance, leading to good Channel State Information at the Transmitter (CSIT), a crucial enabler for MU MIMO, whereas SDMA was either limited to TDD systems (channel CSIT through reciprocity) or Covariance CSIT. In the early nineties, the only feedback that existed was for slow power control.
- Since SDMA, the concepts of multiuser diversity and user selection have emerged and their impact on the MU MIMO sum rate is now well understood. Furthermore, it is now known that user scheduling allows much simpler precoding schemes to be close to optimal.

MU MIMO key elements (2)

- Whereas SU MIMO allows to multiply transmission rate by the spatial multiplexing factor, when mobile terminals have multiple antennas, MU MIMO allows to reach this same gain with single antenna terminals.
- Whereas in SU MIMO, various degrees of CSIT only lead to a variation in coding gain (the constant term in the sum rate), in MU MIMO however CSIT affects the spatial multiplexing factor (= Degrees of Freedom (DoF)) (multiplying the log(SNR) term in the sum rate).

- SIMO vs MIMO case: multiple Rx antennas do not allow increase of total number of streams (sum rate), only variable # streams/user (SU MIMO)

Position Aided SDMA (= MU-MIMO)

- Context & Problem:

  Spatial Division Multiple Access = Multi-User MIMO

  SDMA (90's) unsuccessful: no user selection (user orthogonality), disregard of multipath

  Use location/multipath information to select users and reduce CSIT feedback

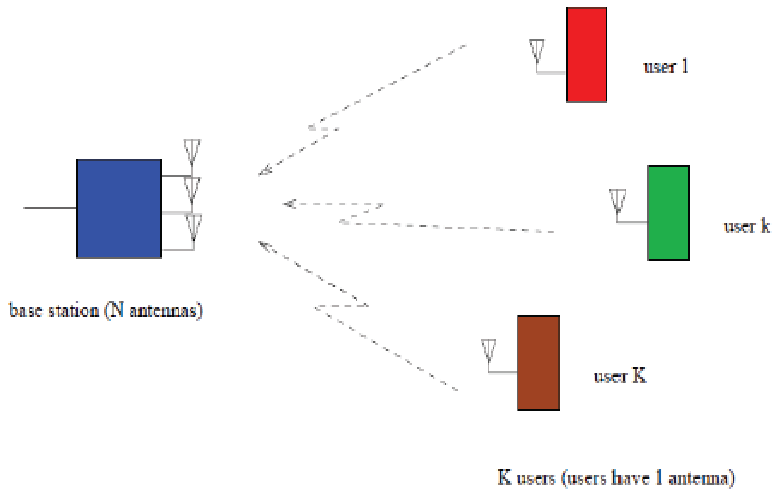
- Principle & Novelty:
  - Only select LoS/NADA users (Narrow Angle of Departure Aperture) , that go well together
  - Location aided vs DoA based:
    - More precision / better sensitivity can be obtained if BS antennas are spaced apart further (while satisfying far field assumption, or at least narrowband assumption).
    - Leads to ambiguities in DoA, which can be resolved by location info.
  - MISO->MIMO: NADA = rank 2: no DoF loss if do 2 streams/user
  - Next: MU-MIMO w single stream/user

NADA MIMO channel model

$$H = \sum_i h_r(\theta_i) h_t^T(\phi_i) = B\, A^T\,, \quad A = \left[h_t(\phi)\ \dot{h}_t(\phi) \right]$$

narrow AoD spread: $\phi_i = \phi + \Delta\phi_i$

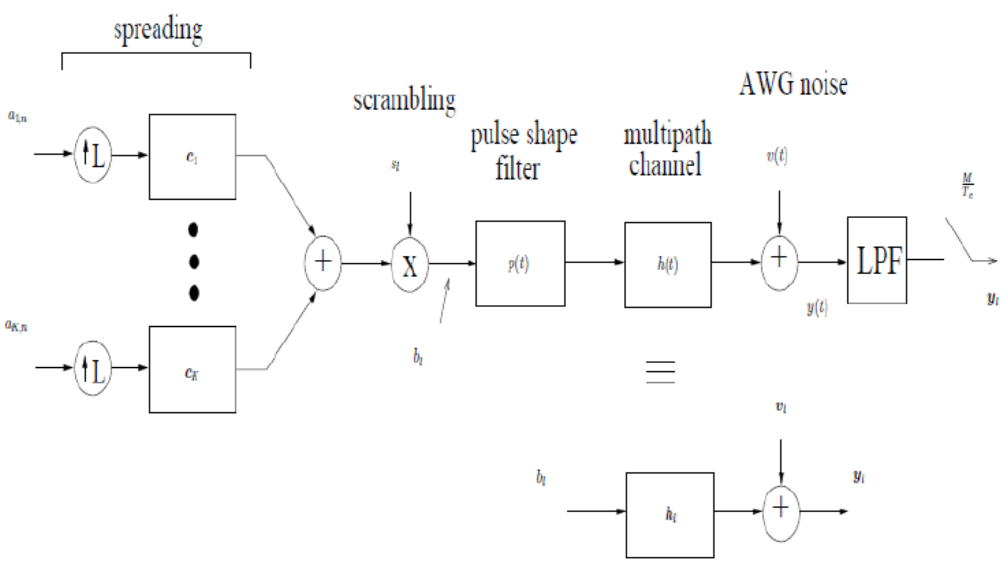
$$h_t(\phi_i) \approx h_t(\phi) + \Delta\phi_i\, \dot{h}_t(\phi)$$

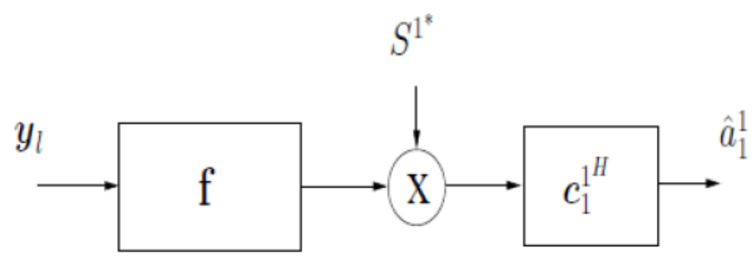


HIGHTS
High precision positioning for Cooperative-ITS

MISO -> MIMO SDMA (MU-MIMO): similarities to DL CDMA

- CDMA: synchronous downlink (DL) => simple correlator is simultaneously matched filter (max SNR) and ZF interference suppressor (max SIR)
- Multipath propagation destroys code orthogonality
- But at a terminal: all codes have passed through the same DL channel!!
- Hence suffices to (chip) equalize the channel, followed by a correlator





MIMO SDMA: incomplete CSIT sufficient (for ZF, DoF)

- Assume Tx knows only a vector in row space of MIMO channel for each user:

$$\mathbf{g}_k^H = \mathbf{c}_k \mathbf{H}_k P^{\perp}_{(\mathbf{cH})_{\overline{k}}} / ||\mathbf{c}_k \mathbf{H}_k P^{\perp}_{(\mathbf{cH})_{\overline{k}}}||$$

$$\text{where } P^{\perp}_{\mathbf{X}} = I - P_{\mathbf{X}} \text{ and } P_{\mathbf{X}} = \mathbf{X}^H(\mathbf{X}\mathbf{X}^H)^{-1}\mathbf{X}$$

- Rx signal:

$$\mathbf{y}_k = \mathbf{H}_k \, \mathbf{g}_k \, x_k + \sum_{i=1,\neq k}^{M} \mathbf{H}_k \, \mathbf{g}_i \, x_i + \mathbf{v}_k$$

- Received SIR $\mathrm{SIR}_k = \frac{|\mathbf{f}_k \mathbf{H}_k \mathbf{g}_k|^2 \sigma_k^2}{\sum_{i=1,\neq k}^{M} |\mathbf{f}_k \mathbf{H}_k \mathbf{g}_i|^2 \sigma_i^2}$ $\quad \max_{\mathbf{f}_k} \mathrm{SIR}_k = \mathrm{SIR}_k(\mathbf{f}_k = \mathbf{c}_k) = \infty$

Theorem 1: **Sufficiency of Incomplete CSIT for Full DoF in MIMO BC** In the MIMO BC with perfect CSIR, it is sufficient that the BS knows for each of the K users any vector in the row space of its MIMO channel (as long as the resulting vectors are linearly independent) in order for ZF BF to produce $\min(M, K)$ DoF.

Location based MU MIMO

- Assume BS knows (only) LoS path for each mobile terminal (MT)
- Assume BS performs ZF BF on the LoS paths.
- At a MT: interference arrives through the multipath components.

- As long as Nr > # multipath components, the MT antennas can suppress the multipath so that only the LoS path passes, on which interference has been suppressed by the BS beamformer (BF).

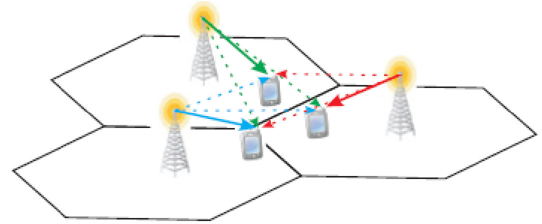
- All paths in a NADA cluster count for (only) 2 paths (rank 2).

HIGHTS
High precision positioning for Cooperative-ITS

Location-aided Multi-cell Processing

- single-cell MU-MIMO (cell center)
  - This is single-cell, but the opportunities of multiple Rx antennas in MU-MIMO are still not well understood. Here we focus on the use of Rx antennas to handle the multipath difference between NADA (angular spread) and LOS, or general NLOS, whereas the Tx handles the nominal directions (LOS). [WCNC12-W4] (Artist4G/WHERE2 SS)
- MU-MIMO with intercell interference (cell edge)
  - Like MIMO Interference Channel (IFC) but here only the Rx antennas are used to handle intercell interference. Consider LOS and then NADA.
- MIMO IFC
  - MISO IFC: maxmin SINR design via UL/DL duality [pimrc11]
  - MIMO IFC
    - [ita11]: ZF/IA feasibility, globally opt. max. sum rate via deterministic annealing
    - [asilomar11,ita12]: centralized and distributed CSI training and feedback (over the reverse IFC)
    - Currently exploring:
      - Spatial aspects: specificities for LOS, extension to NADA (location based (N)LOS info, spatial signature?)
      - Recent approaches // blind IA (BIA): interweave PDP polyphase components

Location-aided Multi-cell Processing



HIGHTS
High precision positioning for Cooperative-ITS

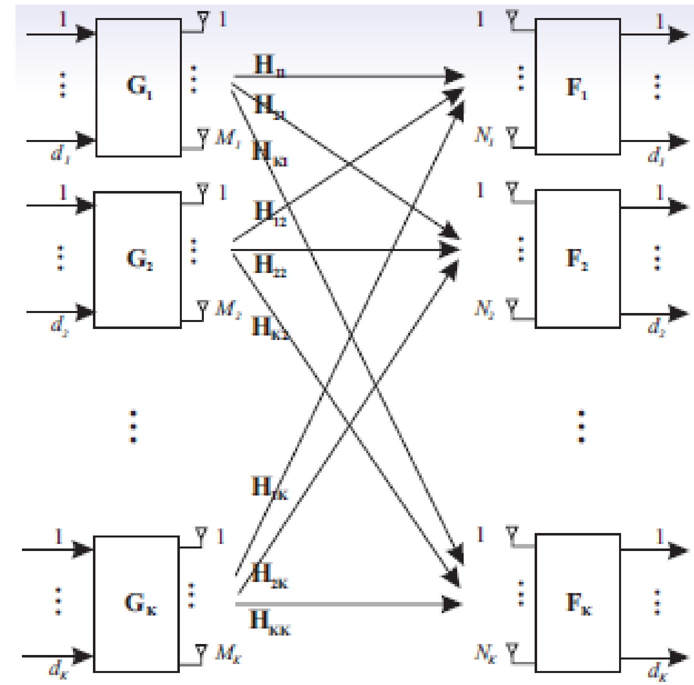
- Context & Problem:

  MIMO Interference Channel (IFC): multi-Tx coordination of BF without exchanging signals (=CoMP, NW-MIMO)

  Model for Multi-Cell, macro-femto, etc.

- Principle & Novelty:
  - Joint Tx/Rx design plagued by numerous local optima (proposed deterministic annealing for guaranteeing global optimum)
- Recent Achievements:
  - In LOS case (all rank-1 MIMO): role of Tx and Rx much clearer: repartition of ZF roles between Tx's and Rx's
  - Furthermore: design of a Tx or Rx only requires CSI of channels connected to it (local).
- Perspectives:
  - LOS -> NADA, mixed CSIT
  - Not all interfering links equally important:

    From "Generalized DoF" or "tier 1 interferers" to location (distance & propagation) dependent interference strengths



LOS: $\mathbf{H}_{ji} = \sigma_{ji}\mathbf{u}_{ji}\mathbf{v}_{ji}^H$

$\mathbf{f}_j^H\mathbf{u}_{ji}\mathbf{v}_{ji}^H\mathbf{g}_i = 0 \Rightarrow \mathbf{f}_j^H\mathbf{u}_{ji} = 0$ or $\mathbf{v}_{ji}^H\mathbf{g}_i = 0$

$$\begin{bmatrix} F_1^H & 0 & \cdots & 0 \\ 0 & F_2^H & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & F_K^H \end{bmatrix} \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1K} \\ H_{21} & H_{22} & \cdots & H_{2K} \\ \vdots & & \ddots & \vdots \\ H_{K1} & H_{K2} & \cdots & H_{KK} \end{bmatrix} \begin{bmatrix} G_1 & 0 & \cdots & 0 \\ 0 & G_2 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & G_K \end{bmatrix} = \begin{bmatrix} F_1^H H_{11} G_1 & 0 & \cdots & 0 \\ 0 & F_2^H H_{22} G_2 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & F_K^H H_{KK} G_K \end{bmatrix}$$

Interference Alignment (IA) feasibility MIMO Interference Channel (IC)

- Case of singular MIMO channels

[10]. In the full rank case with K links of $N \times M$, we have that $d_k = \frac{M+N}{K+1}$ is feasible in the not too rectangular case. In the uniform singular $K = 2$ case with $(M, N, r)^2$, $d = \min(r, \dfrac{M+N-r}{2})$ is possible (with $d_1 = d_2 = d$). For the uniform square $K = 3$ case $(M, M, r)^3$, $d = \min(r, M/2)$ is feasible. Still in the $K = 3$, $M \times M$ case with

$$r_{ik} = \begin{cases} r_0 & , i = k \\ r_1 & , i > k \\ r_2 & , i < k \end{cases} \qquad (29)$$

we get $d = \min(r_0, M - \dfrac{\min(M, r_1 + r_2)}{2})$.

Interference Alignment (IA) is joint Tx/Rx ZF BF and allows to attain the correct DoF in an IC. For d_k streams of user k, a $M_k \times d_k$ Tx filter $\mathbf{G}_k$ and a $d_k \times N_k$ Rx filter $\mathbf{F}_k$ is used. In the rank deficient case, if $0 \leq r_{ik} \leq \min(N_i, M_k)$ denotes the rank of MIMO channel $\mathbf{H}_{ik}$ then we can factor $\mathbf{H}_{ik} = \mathbf{B}_{ik}\mathbf{A}_{ik}$ for some full rank $N_i \times r_{ik}$ $\mathbf{B}_{ik}$ and $r_{ik} \times M_k$ $\mathbf{A}_{ik}$. The ZF from BS k to MT i requires

$$\mathbf{F}_i\mathbf{H}_{ik}\mathbf{G}_k = \mathbf{F}_i\mathbf{B}_{ik}\mathbf{A}_{ik}\mathbf{G}_k = 0 \qquad (28)$$

which involves $\min(d_i d_k, d_i r_{ik}, r_{ik} d_k)$ constraints to be satisfied by the $(N_i - d_i)d_i/(M_k - d_k)d_k$ variables parameterizing the row/column subspaces of $\mathbf{F}_i/\mathbf{G}_k$. The overall IA feasibility

Interference Alignment (IA) feasibility MIMO Interference Channel (IC)

- IA feasibility singular MIMO IC with Tx/Rx decoupling

In this case we shall insist that (28) be satisfied by

$$\mathbf{F}_i \mathbf{B}_{ik} = 0 \text{ or } \mathbf{A}_{ik} \mathbf{G}_k = 0 \,. \tag{30}$$

This leads to a possibly increased number of ZF constraints $r_{ik} \min(d_i, d_k)$ and hence to possibly reduced IA feasibility.

- Task of ZF of cross links now partitioned between Tx's and Rx's

In the uniform case $(M, N, r)^K$ with $d \leq r$ per user, (30) leads to

$$d \leq \frac{1}{2}(M + N - (K-1)r) \tag{31}$$

whereas the general coupled case (28) would have led to $d \leq \frac{1}{2}(M + N - (K-1)d)$. There is no loss if $d = r$, in which case $d = r \leq \frac{M+N}{K+1}$.

In the case of general rank distribution but with a single stream per user ($d_k \equiv 1$), we get

$$\sum_{i=1}^{K}(M_k + N_k) \geq 2K + \sum_{i \neq k} r_{ik} \,. \tag{32}$$

The non-decoupled case would correspond to replacing all the r_{ik} in (32) by 1.

IA feasibility singular MIMO IC with Tx/Rx decoupling: LoS: ranks = 1

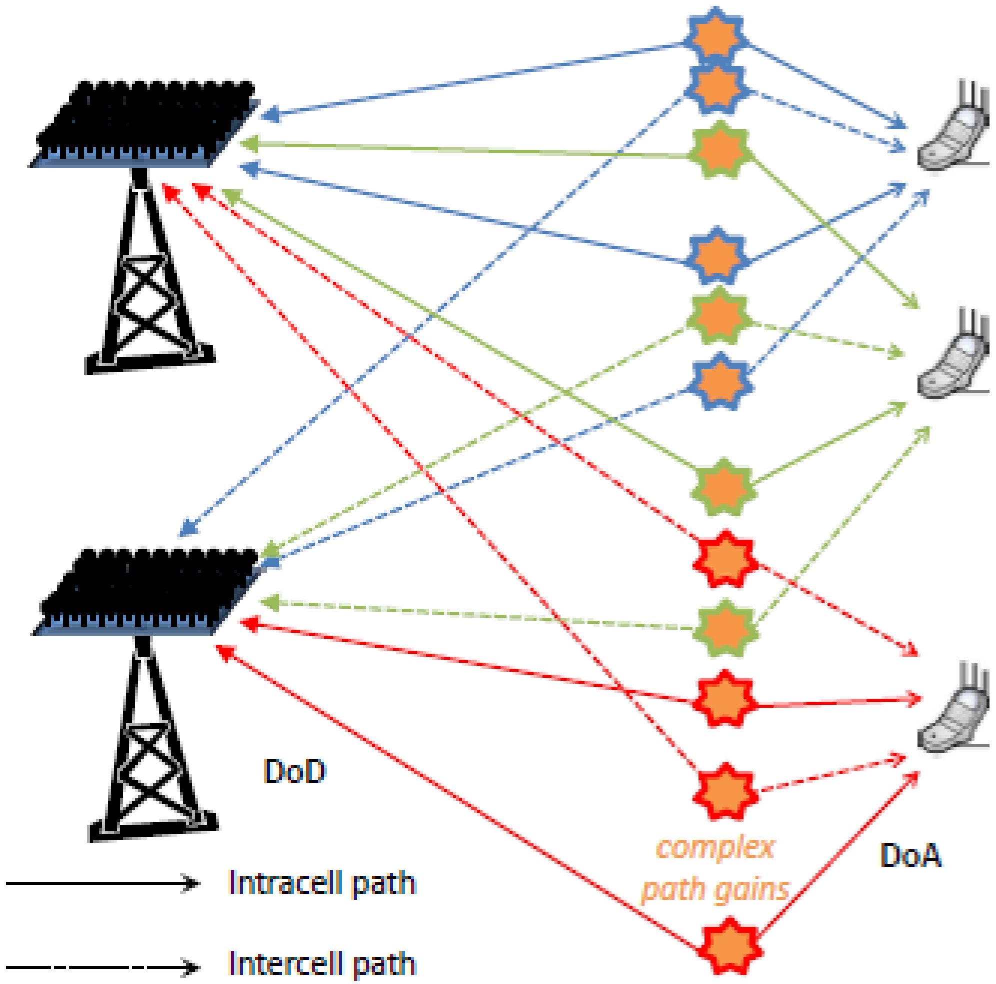
In what follows, we shall focus on the LoS limit for considerations of location based processing. This is a special case of (31) with $d = r = 1$ and leads to the requirement

$$M + N \geq K + 1 \tag{33}$$

for IA feasibility with a single stream per user. In the MISO or SIMO cases this becomes $M \geq K$ or $N \geq K$. The meaning of (33) is: $(M-1)+(N-1) \geq K-1$: that each BS performs ZF towards $M-1$ MTs. As a result, each MT still receives interference from $(K-1)-(M-1)$ cross links but with its N antennas it can ZF $N-1$ streams.

In the decoupled approach, the design of any Tx $\mathbf{g}_k$ only depends on the factors A_{ik} of the channels connected to it and in general even only on a subset of this local CSIT (e.g. in the LoS case, only $M-1$ cross link A_{ik} are required to be known for any given BS). In the LoS case, the A_{ik} are clearly only a function of the positions of the BS and MTs (and the BS antenna array response).

Pathwise Multi-User Multi-Cell



scrambler → path gains, DoAs ; DL → dual UL LMMSE

Location-aided Multi-cell Processing

HIGHTS
High precision positioning for Cooperative-ITS

Genuine location aided / Ongoing work

- Location aided beamforming (spatial signature): complementary to DoA based?
- Location aided covariance CSIT vs CSIT feedback (FB) when CSI varies too fast.

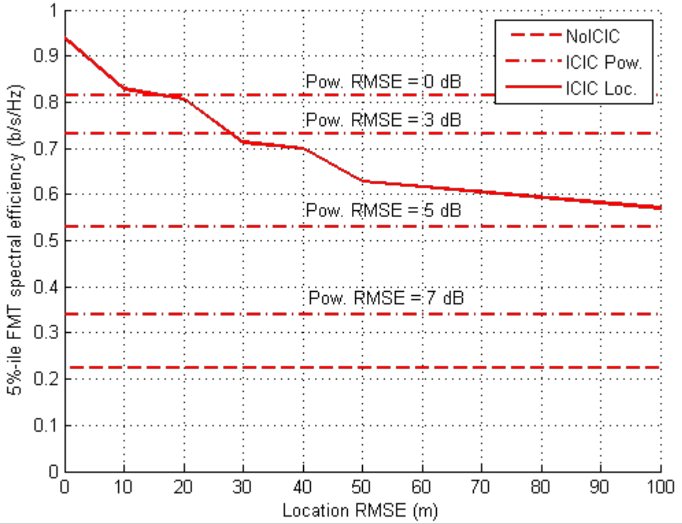
  Genuine location aided potential: trajectory based spatial signature prediction. Requires simulation/analytical comparison/combination with
  - DoA estimation and prediction?
  - or feedback based spatial signature estimation plus its prediction over realistic FB delays.
- Location aided covariance CSIT vs CSIT feedback (FB) when too many users to schedule: reducing signaling (FB) overhead.
- NADA (Narrow Angle of Departure Aperture) for IBC (Interfering Broadcast Channel)
  - LOS condition important for location aided spatial signature determination (to a lesser extent also for DoA based)
  - Position info for knowing which interference is strong, which needs to be coordinated and which can be ignored (in the noise)? Topological IA
  - Mixed CSIT: channel feedback based for some users, position based for others.
- Massive MIMO: several recent works exploit slow fading (eg spatial) subspaces

T3.1.3: Downlink ICIC in heterogeneous networks with long-term power setting **(MER)**

- **Context & Problem**
  - Macro degradation brought by a femto base station (FBS) depends on its location
  - Improvement of macro- and femto-cell-edge performance through inter-cell interference coordination (ICIC)
- **Principle & Novelty**
  - Definition of a high-interference zone (HIZ) in which the amount of interference is controlled
    - Target: Only *x*% of terminals in the HIZ have a ratio of Shannon capacities with and without FBS larger than *y*
  - For a macro terminal at position *p*, the optimum FBS transmit power PF(*p*) depends on P_M, the received power from the macro BS, and *I*, the interference plus noise level.
  - Location information: FBS obtains P_M and *I* for each *p* in HIZ from a finger-printing map, using its own location
- **Recent achievements**
  - Comparison of fixed FBS power (*NoCIC*), location based long-term power setting (*ICIC Loc*) and long-term power setting based on FBS measurements P_M and *I* at its own location (*ICICPow*)
  - With map granularity and location & measurement errors
  - *ICIC Loc* vs *ICIC Pow*: With 0dB (resp. 5dB) power RMSE at the FBS, location information provides gain with a location RMSE lower than 15m (resp. 100m)

Femto performance vs location RMSE for 10 % cellular cell-edge decrease with 125 FBS/km2

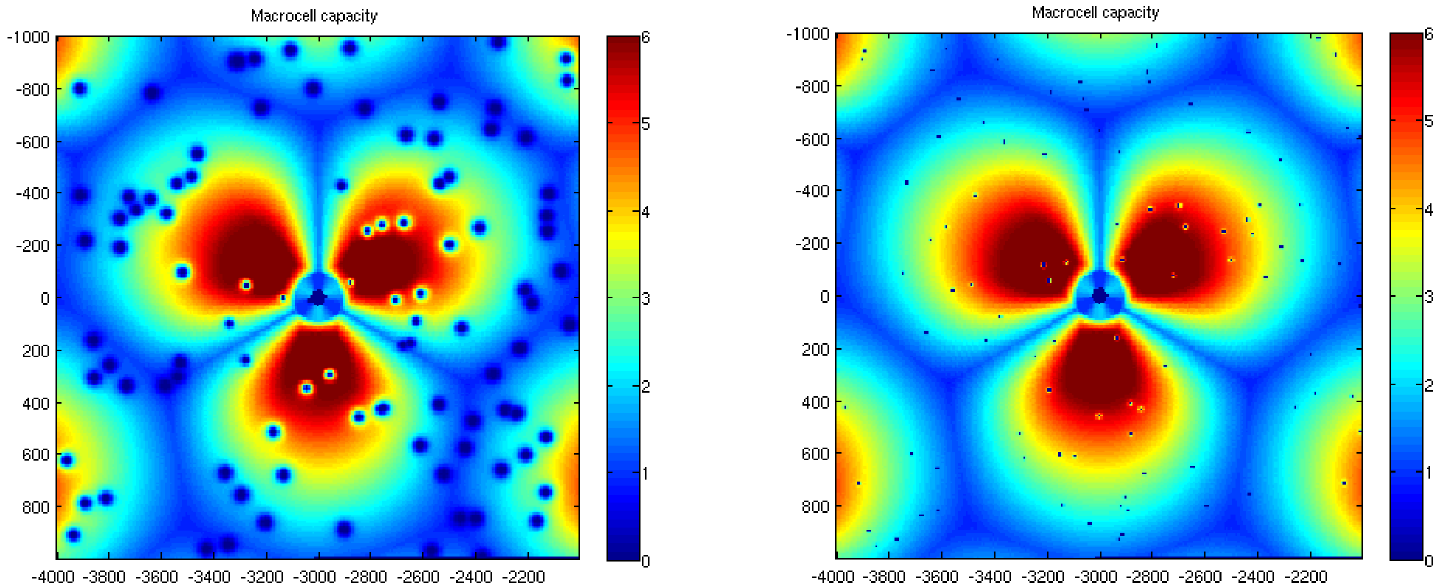
- LTE system level simulation scenario
  - 3GPP Case 3 deployment for 19 tri-sectorised macro BS
  - 10-MHz LTE, 2x2 MIMO, up to 12 b/s/Hz
  - Round-Robin scheduling
  - 10 dB wall penetration loss assumed in the algorithm
  - Map granularity: 1 mobile terminal per 10 m^2
  - Root mean square error (RMSE) on location: 0-100 m
  - RMSE on power measurement: 3 dB
  - Additional root mean square error in the FBS measurement (Power RMSE) in order to model the decorrelation between indoor and outdoor shadowing



- Heterogeneous networks
  - Deployments including femto base stations and macro base stations
  - Macro degradation brought by a femto base station depends on its location
    - Femto base stations in the macro cell-edge strongly degrade the macro UE performance
- Inter-cell interference coordination (ICIC)
  - Decentralised approach in downlink based on power setting

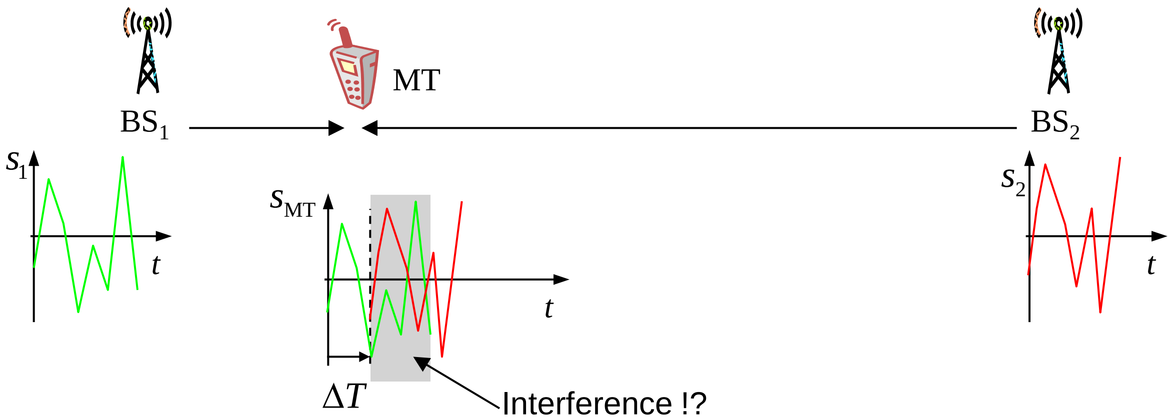
Coverage holes due to femto base stations

Without ICIC — With ICIC



T3.1.3 Synchronization in Coordinated Multipoint Transmission (DLR)

The Idea



$$\Delta\tau = \frac{d_2 - d_1}{c_0}$$ 🡐 This is the use of location information

- Common sync procedure:
  - Usage of differential or cross correlation methods for $s_1(t)$
  - ➔ Interference due to s_2 (grey backgrounded)

- ΔT depends on MT position
  - If ΔT is known $s_1(t) + s_2(t - \Delta\tau)$ can be used as reference for cross correlation methods
  - ➔ Former „interference“ becomes useful signal

T3.1.3 Synchronization in Coordinated Multipoint Transmission (DLR)

Performance compared to Single Link

TX Power: 30 dBm

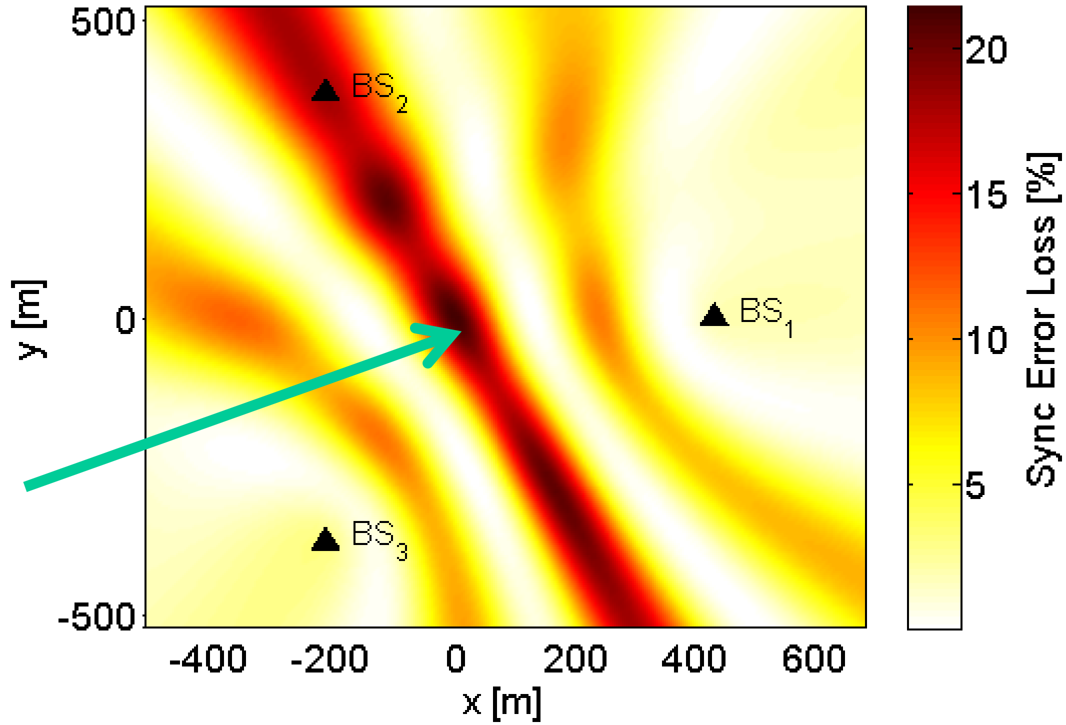
Path loss: A=35.7, B= 42.6, C=23, f_c = 2.6 GHz
Typical Urban Macro Cell
(WINNER C2, NLOS)

Signals: LTE Secondary Sync Signals
IDs 142, 411, 472

Subcarrier
Spacing: f_{sc} = 15 kHz

➔ Loss at cell edge even if we apply joint estimation algorithms

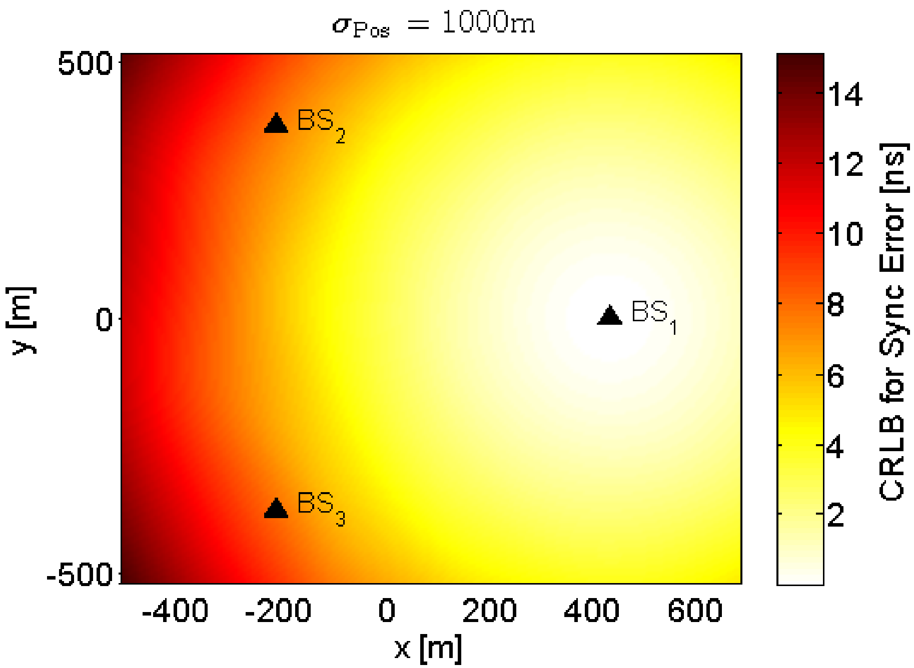
➔ By using position information, interference becomes useful signal and the performance can be expected to increase. especially in high interference regions and at cell edges

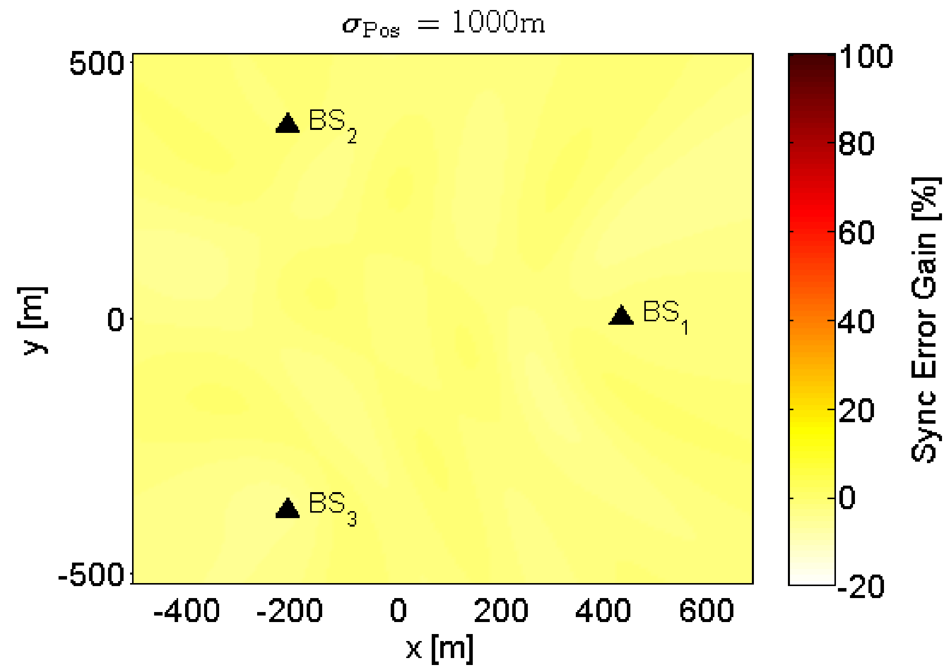


T3.1.3 Synchronization in Coordinated Multipoint Transmission (DLR)

Performance with Position Information (1)

This is approximately with no position information



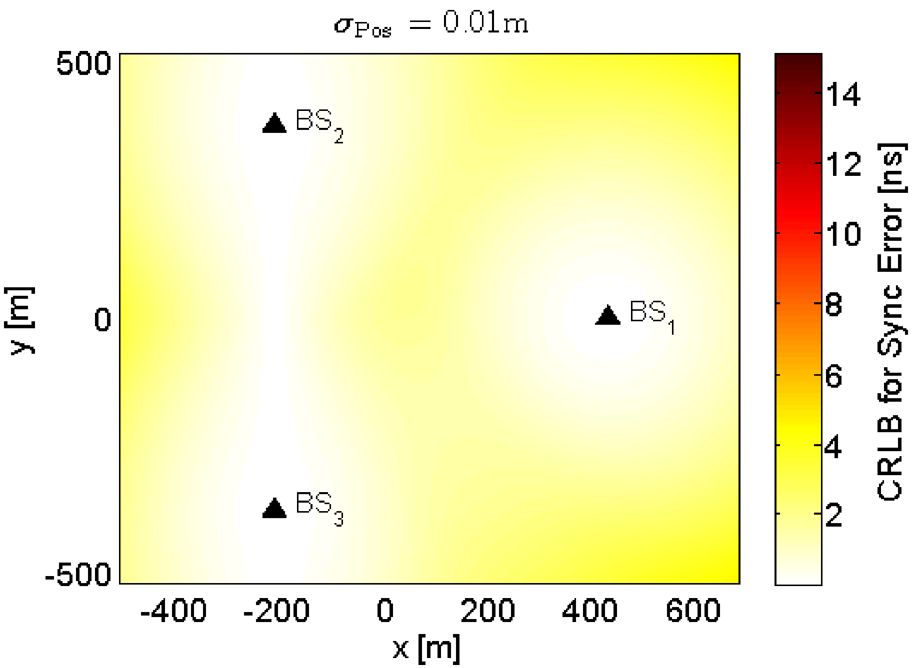


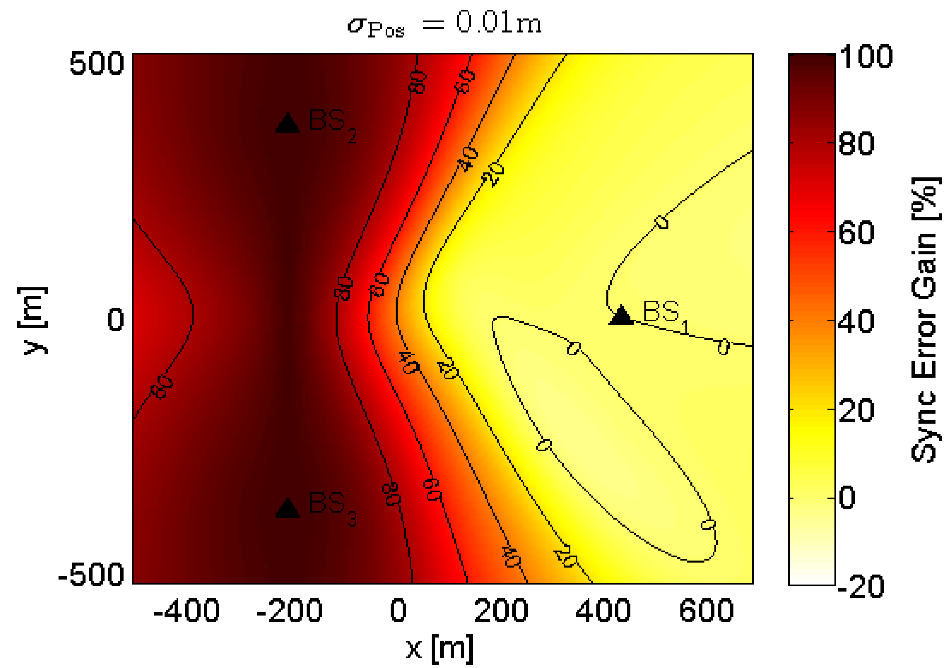
➔ **In general there is loss because of interference which cannot be cancelled!**

T3.1.3 Synchronization in Coordinated Multipoint Transmission (DLR)

Performance with Position Information (2)

This is approximately with perfect position information





T3.1.3 Synchronization in Coordinated Multipoint Transmission (DLR)

Cell Edge Performance

The mobile terminal is located at the cell edge between the 3 BSs

TX Power: 30 dBm

Path loss: A=35.7, B= 42.6, C=23, f_c = 2.6 GHz
Typical Urban Macro Cell
(WINNER C2, NLOS)

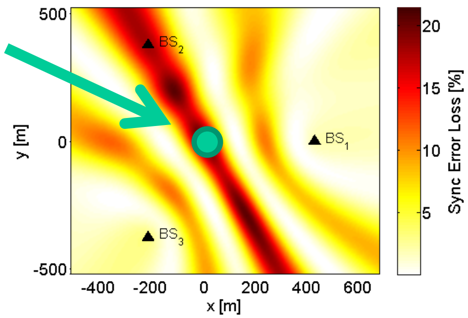
Signals: LTE Secondary Sync Signals
IDs 142, 411, 472

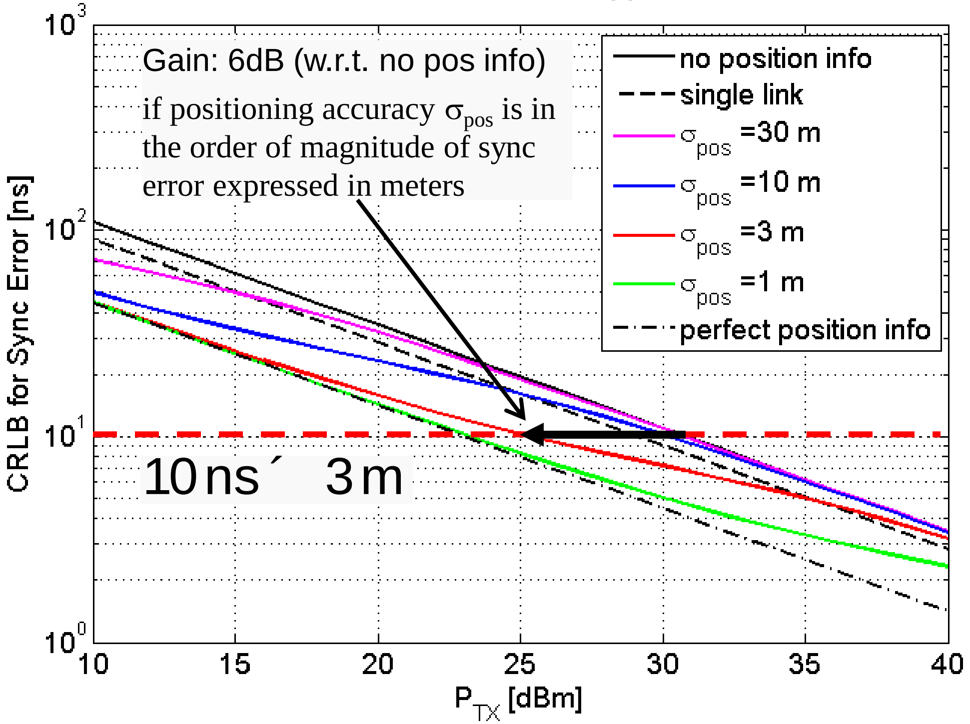
Subcarrier

Spacing: f_{sc} = 15 kHz

➔ **Gain is achievable if positioning accuracy σ_{pos} is in the order of magnitude of sync error expressed in meters.**

MT is here





T3.1.1 – SON System for RAN Optimization **(PTIN)**

- **Context & Problem**:
  - Capacity and Coverage optimization of the network, can produce severe interference problems, once the number of cells starts to increase;
  - Static nature of the network makes it impossible to lead with possible re-arrangements.
- **Principle & Novelty**:
  - Use of position for a scenario computational replication to be fed to a RNP tool;
  - Use of a RNP tool to obtain the best parameters based on the network's knowledge of the vicinity, instead of relying only on sensing solutions.
- **Recent Achievements:**
  - Development of a 3GPP compatible configuration framework, for parameters information exchange;
  - Implementation of a carrier algorithm, responsible to choose the best carrier to be used by the new femtocell considering the lowest SINR at the femtocell installation location;

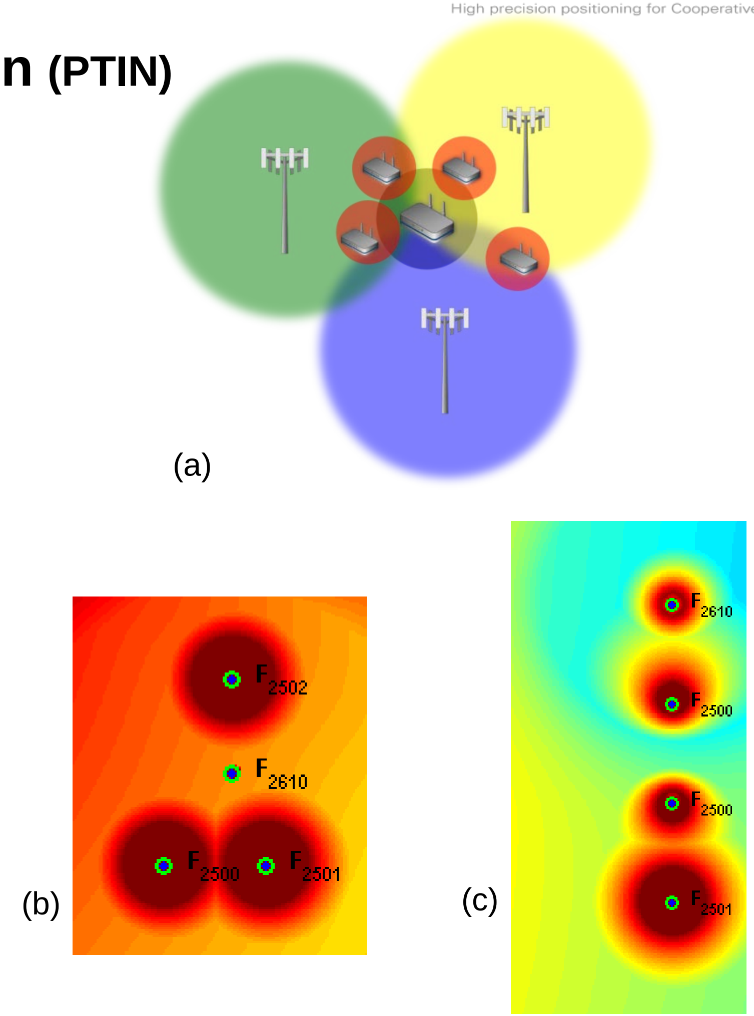


Fig. 1 – (a) Context & Problem Scenario; (b) Interference Between Macro vs Femto (no coverage area); (c) Interference Macro vs Macro (serious coverage deformation)

T3.1.1 – SON System for RAN Optimization (PTIN)

- **Recent Achievements:**
  - Implementation of the power control adjustment to reduce the interference between cells in the same carrier. A minimum value for signal quality is set for both:
    - Existent femtocells – to ensure the QoS already provided;
    - New femtocells – to ensure add value to the new service.

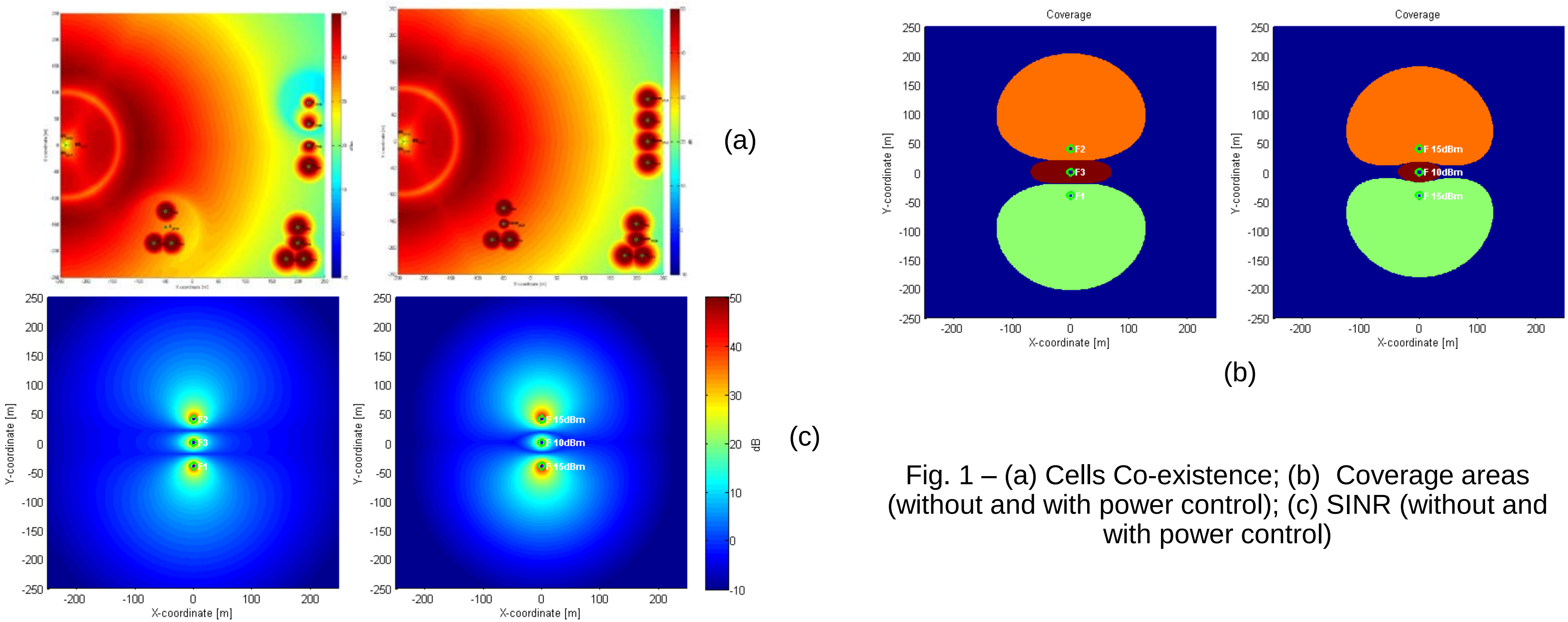
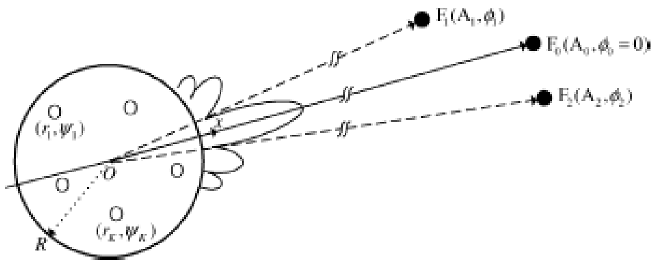
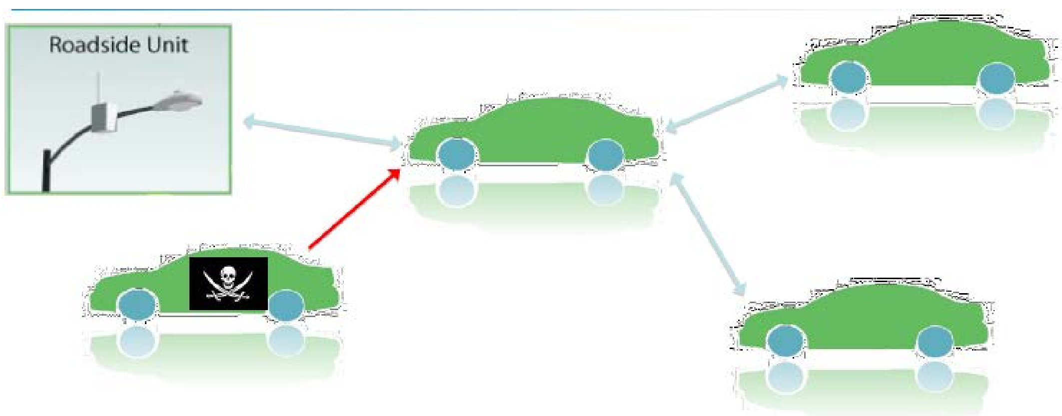


Fig. 1 – (a) Cells Co-existence; (b) Coverage areas (without and with power control); (c) SINR (without and with power control)

Upgrading Wireless Communications to Location Aided Systems (2/3)

- **T3.2 - Cooperation among mobile terminals**
- Partners
  - **AAU, IT, UPM**
- Subtasks
  - T3.2.1: Realization of geo-location based clustering
    - node selection mechanisms for cluster establishment in a mobile environment
    - in a reliable, secure and trustworthy manner
  - T3.2.2: Usage of geo-location based clustering
    - Enhancement of distributed STBC
    - Improved vertical handover
    - Location-aided attack detection and counter-measures



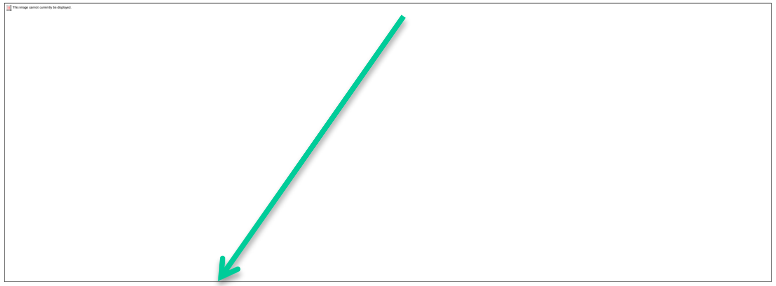


- Focus topic: secure cluster management
  - Reliable relay selection mechanisms
  - Methods for malicious attack detection

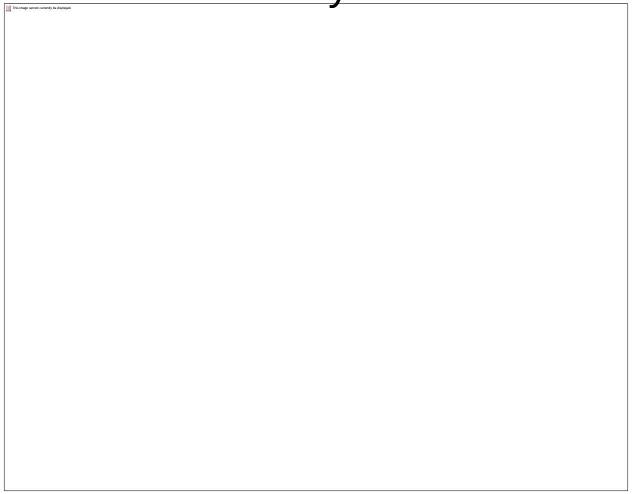
T3.2.1 – Cluster Formation (AAU)

- **Context & Problem**:
  - Clustering in MANETs allows to achieve scalability, power saving, efficient routing and channel allocation through cooperation.
  - Which cluster should a “free” node join?
    - Should use cluster with highest future connectivity time.
- **Principle & Novelty**:
  - Proposed a cluster-assignment scheme that uses movement prediction to estimate the expected time-in-cluster → best cluster to join
- **Recent Achievements:**
  - Study of impact of inaccurate location information and inaccurate mobility prediction

A “free” node should be join one of the existing clusters.



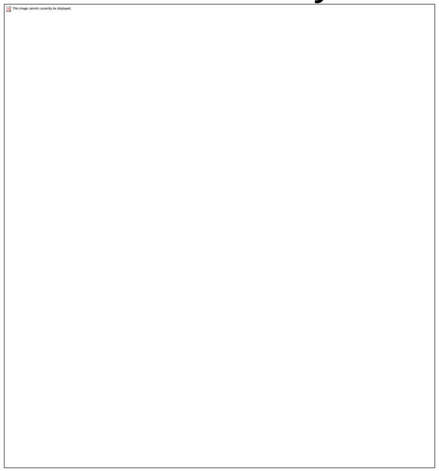
Impact of varying location error on connectivity time



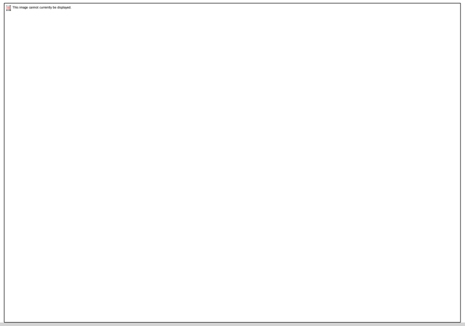
T3.2.1 – Location Based Relay Selection (AAU)

- **Context & Problem**:
  - Relay selection in mobile networks
  - Mobility leads to outdated and inaccurate information.
  - Parameter selection (e.g., information update rate) can be helped by model.
- **Principle & Novelty**:
  - Proposed model combines mobility and information collection Markov Chains.
  - Takes into account
    - measurement update rate (controllable)
    - measurement update delay
    - mobility speed
    - location accuracy
- **Recent Achievements:**
  - Proposed and verified Markov Chain based model using simulations.
  - Case study using T2.3 ray-tracing database of SIRADEL premises
  - Currently studying efficient methods for relay policy optimization

Transmit data packets directly or via mobile relay

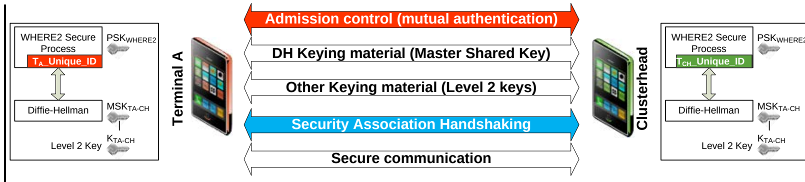


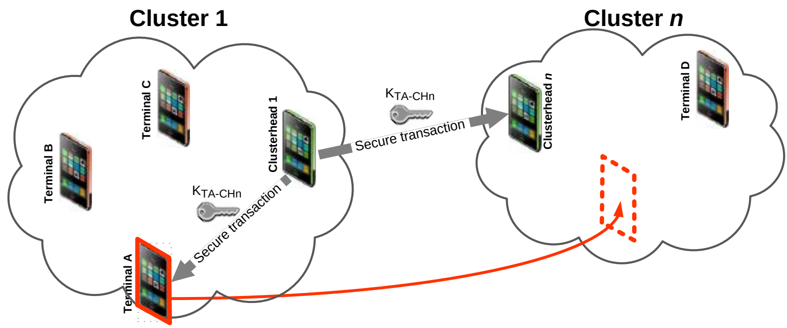
Throughput of relay transmissions for different relay positions for case study

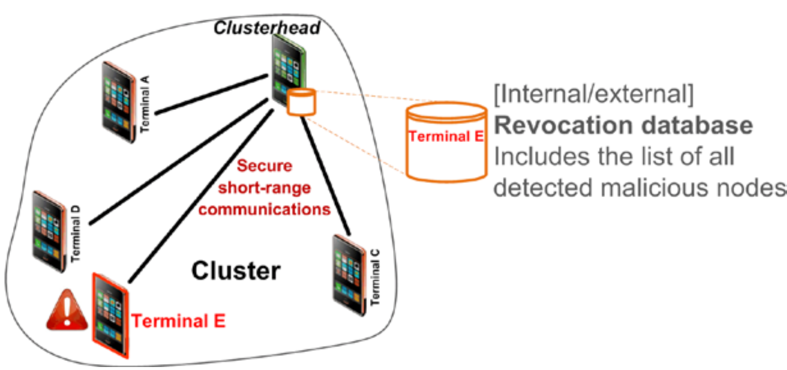


T3.2.1 – Reliable, secure and trustworthy methods for cluster establishment and maintenance (IT)

- **Context & Problem:**
  - Clustering in MANETs allows to achieve scalability, power saving, efficient routing and channel allocation, however not always it operates in benign environments, being vulnerable to attacks from malicious nodes
  - Exchange of data (location) information amongst cluster members is also vulnerable to multiple attacks
- **Principle & Novelty:**
  - **Principle**: Provide security to both cluster formation and maintenance and also on data exchange
  - **Novelty**: Use *clusterheads* as Authenticators that exploit authenticated Diffie-Hellman exchanges and secure software development characteristics to perform secure key distribution operations.
  - **Result**: Robust Security Architecture that allows:
    - Reliable, secure and trustworthy cluster establishment, maintenance & handover (fig.1&2)
    - Secure data exchange (fig.1)
    - Location-aided attack detection and counter-measures (fig.3)

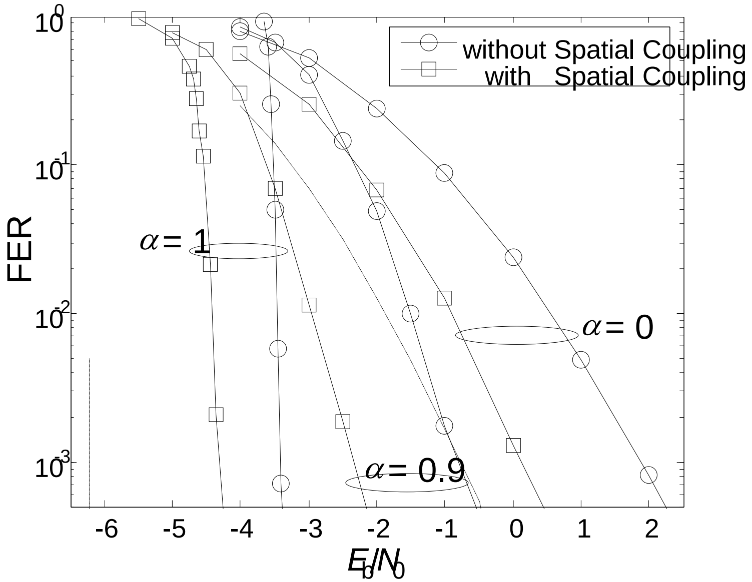






T3.2.2 – Robust Pre-coding for MIMO Systems (HKC)

- **Context & Problem**:
  - Partial CSIT can be in the form of channel gains in different directions. Such partial CSIT can come from positioning information.
  - We develop linear pre-coding schemes with partial channel state information at transmitter (CSIT).
- **Principle & Novelty**:
  - We studied optimization techniques for the pre-coder matrix and applied the spatial-coupling technique to encoder design.
- **Recent Achievements:**
  - We developed a spatially coupled LDPC coding and linear pre-coding scheme for MIMO systems.

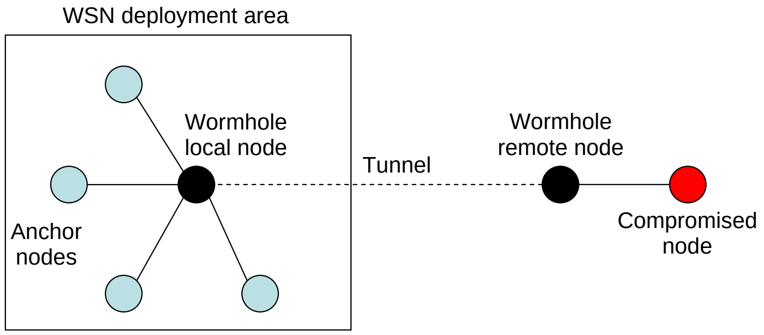


The proposed scheme can efficiently utilize the partial CSIT and achieves very good performance.

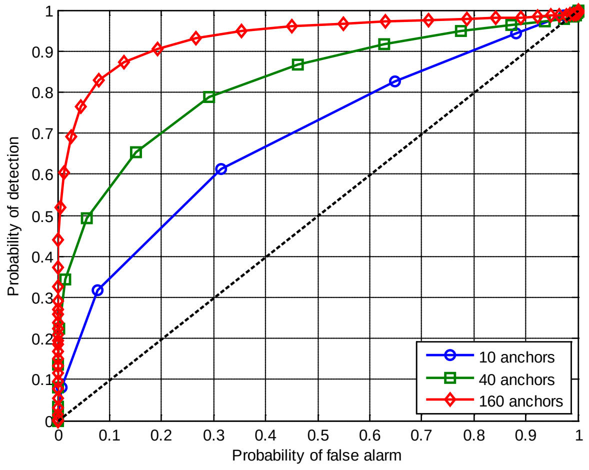
T3.2.2 – Secure neighbor discovery protocols (UPM)

- **Context & Problem**:
  - Objective: A network node wants to identify other nodes directly reachable so as to establish single-hop links with them.
  - Attack model: Relay (aka "wormhole") attack. Two nodes collude and try to trick a remote node into believing that is a neighbor of a set of anchor nodes.
  - Countermeasure: Wormhole detection using localization techniques.
- **Principle & Novelty**:
  - We use as a test statistic a measure of the quality of the localization achieved by a "range-free" localization technique.
  - This test uses only received signal strength (RSS) measurements, but is not tied to any particular path-loss model; therefore, it is fairly robust to changes in the environment.
- **Recent Achievements:**
  - Simulations were conducted to show the ability of the proposed test to detect the presence of wormholes.
  - Good detection performance was achieved.

Wormhole attack to a Wireless Sensor Network (WSN)



Receiver Operating Characteristic (ROC) under shadowing conditions (σ = 3 dB)



T3.2.2 – WHERE2 Secure Architecture Implementation (IT)

- **Work plan for the implementation of the Secure Architecture was defined and already initiated**:
  - Android has recently added support for P2P and ad hoc networks (supported only on Android 4.0 (API level 14) and higher versions of the platform)
  - **Wi-Fi Direct** API allows Android devices to connect directly to each other via Wi-Fi without an intermediate access point
  - All apps are written in Java and executed within a custom Java virtual machine
  - There are also some aftermarket firmware based on Android, such as *CyanogenMod* that offer some very powerful tweaks
- **Integration plan of Secure Architecture within WP4 (task T4.4)**
  - Step 1: Implementation of the WHERE2 process
  - Step 2: Implementation of security functionalities
  - Step 3: Implementation of advanced functionalities

Software packages

- **android.net.wifi.p2p**
  provides classes to create peer-to-peer (P2P) connections with Wi-Fi Direct
- **android.location**
  provides classes that define Android location-based and related services
- **javax.crypto.spec**
  provides the classes and interfaces needed to specify keys and parameter for encryption
- **javax.crypto.interfaces**
  provides the interfaces needed to implement the *Diffie-Hellman* (DH) key agreement algorithm
- **javax.crypto**
  provides the classes and interfaces for cryptographic applications implementing algorithms for key generation, encryption, decryption, or key agreement

Distributed Links Selection & Data Fusion for Cooperative Positioning in GPS-aided IEEE 802.11p VANETs

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WPNC 2015, March 11th 2015, Dresden

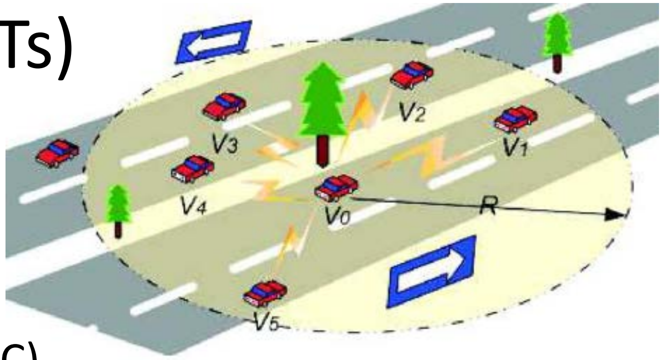
Work currently being pursued in HIGHTS project.

Outline

- Introduction
- Overall Problem Statement
- Data Re-Synchronization
- Measurements & Links Selection
- Simulation Results
- Conclusions & Perspectives

Introduction (1) - Context

- Vehicular Ad hoc NETworks (VANETs)
  - Vehicle to Vehicle (V2V) communications
  - Infrastructure-less
  - IEEE 802.11p (~ WiFi @ 5.9GHz)
    - Dedicated Short Range Communication (DSRC)
    - Safety-related data (GPS position, speed…) encapsulated in broadcasted Cooperative Awareness Messages (CAMs)



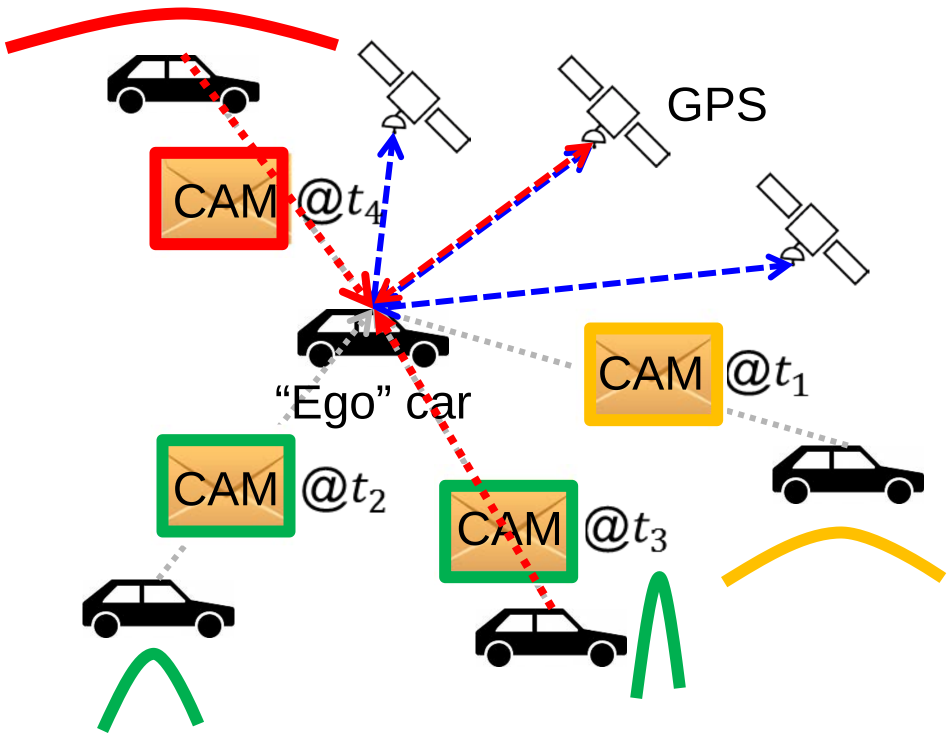
- New needs for precise location in the vehicular context
  - High-precision "ego" vehicle localization (~ 1m)
  - Local Dynamic Maps (e.g., relative "constellation" of surrounding vehicles)
  - Advanced safety systems (anti-collision anticipating on lane changes…), autonomous and/or assisted driving, geographic information routing…

Introduction (2) - Motivations

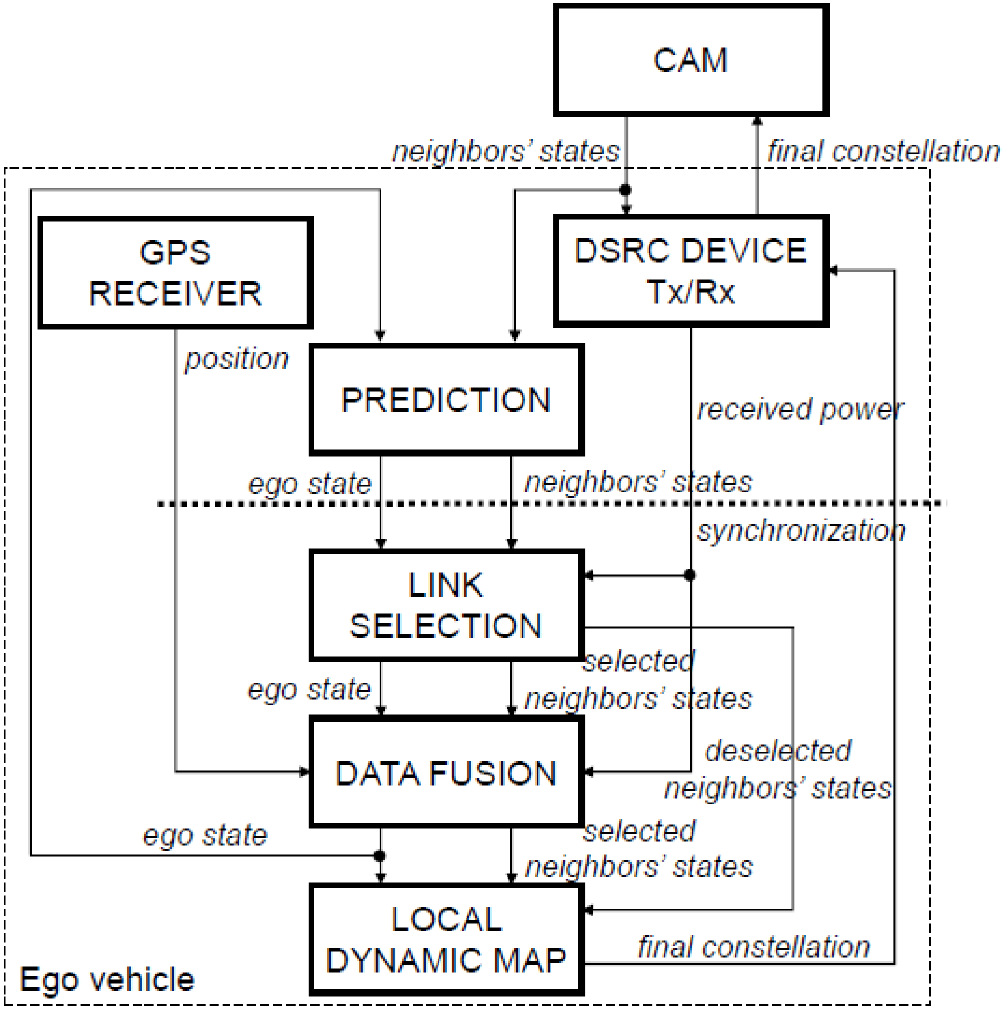
- Cooperative Positioning (CP) in VANETs
  - Non-Coop. Positioning (Non-CP) w.r.t. static known anchors only
  - Cooperative Positioning (CP) w.r.t. both static known anchors and other unknown mobile agents/nodes
  - Pure VANET context → No real known anchors but positioned vehicles as virtual anchors
  - CAM traffic enabling
    - Distributed positioning
    - V2V range-dependent measurements (e.g., Received Signal Strength Indicator)
- Expected benefits from CP in GPS-enabled VANETs
  - Better precision & robustness vs. standalone solutions (e.g., lost GPS)
    - Information redundancy, spatial diversity and Euclidean rigidity…

Overall Problem Statement (1)

- Open issues & stakes
  - Poor/lost GPS → Ensure “Ego” navigation continuity through filtering & cooperative data fusion
  - Asynchronous/missing CAMs → Re-align data in time
  - Poor CAM-based RSSI measurements → Reject outliers
  - Coarsely positioned neighbors → Select the most informative and reliable links
- Underlying question
  - Is V2V cooperation always & truly beneficial ? (under realistic propagation conditions & with basic estimation tools)

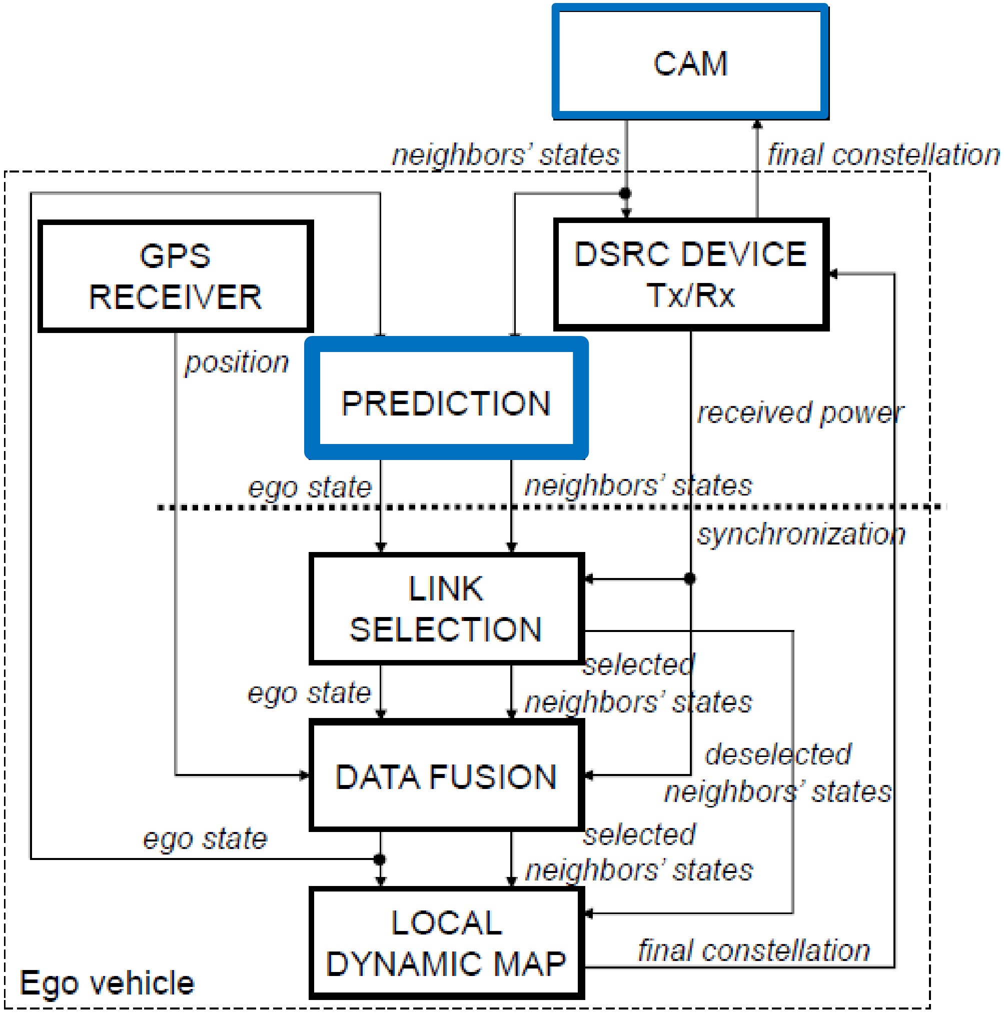


Overall Problem Statement (2)



Overall fusion synopsis and data flow

Data Re-Synchronization (1)

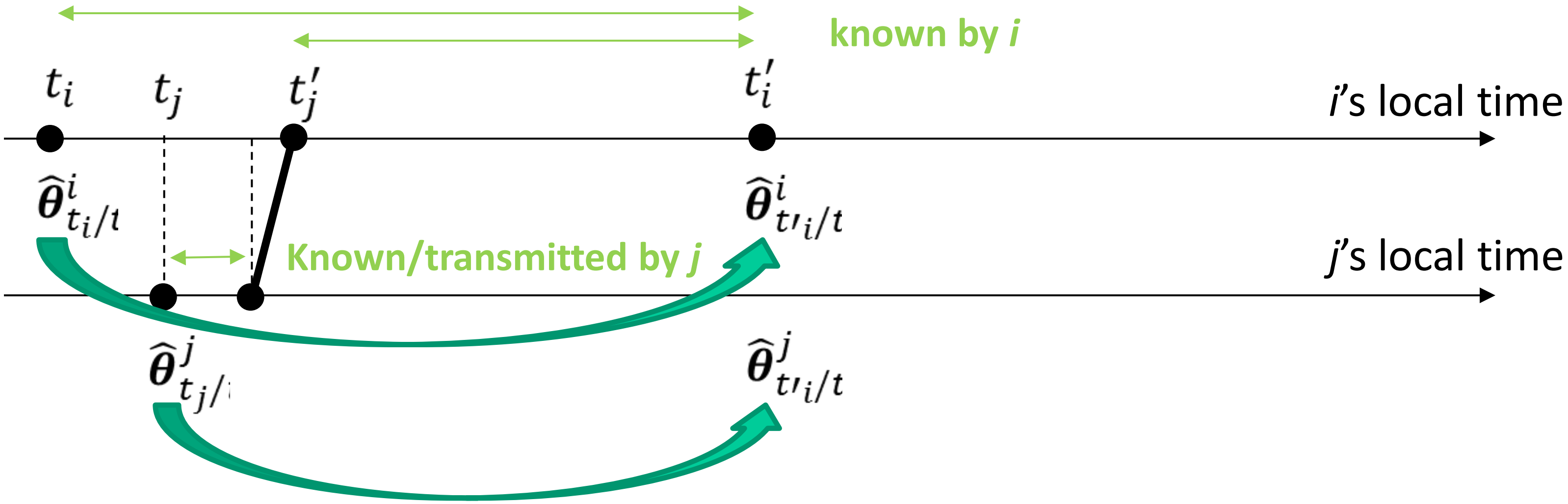


Data Re-Synchronization (2a)

- State of vehicle i at time t

$$\boldsymbol{\theta}_t^i = \left[(x \quad y \quad \dot{x} \quad \dot{y})_t^i\right]^T$$

- To fuse self & coop. information, "ego" vehicle i must predict its own state and that of its neighbors at any arbitrary t_i' given
  - Its latest state estimate calculated for $t_i \leq t_i'$
  - The state of any neighboring car $j, j \neq i$ estimated at t_j (by j) but received (by i in j'm CAM) at t_j', $t_j \leq t_j' \leq t_i'$



Data Re-Synchronization (2b)

HIGHTS
High precision positioning for Cooperative-ITS

- State of vehicle i at time t

$$\boldsymbol{\theta}_t^i = \left[\begin{pmatrix} x & y & \dot{x} & \dot{y} \end{pmatrix}_t^i\right]^T$$

- To fuse self & coop. information, "ego" vehicle i must predict its own state and that of its neighbors at any arbitrary t_i' given
  - Its latest state estimate calculated for $t_i \leq t_i'$
  - The state of any neighboring car $j, j \neq i$ estimated at t_j (by j) but received (by i in j'm CAM) at t_j', $t_j \leq t_j' \leq t_i'$
- Mobility model applicable to vehicle j (Gauss-Markov)

$$\underbrace{\begin{pmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{pmatrix}_{t_i'}^j}_{\boldsymbol{\theta}_{t_i'}^j} = \underbrace{\begin{pmatrix} 1 & 0 & t_i' - t_j & 0 \\ 0 & 1 & 0 & t_i' - t_j \\ 0 & 0 & \tilde{\alpha}^j & 0 \\ 0 & 0 & 0 & \tilde{\alpha}^j \end{pmatrix}}_{\boldsymbol{F}_{t_i'|t_j}^j} \underbrace{\begin{pmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{pmatrix}_{t_j}^j}_{\boldsymbol{\theta}_{t_j}^j} + \underbrace{\begin{pmatrix} 0 \\ 0 \\ (1-\tilde{\alpha}^j)\bar{\dot{x}} \\ (1-\tilde{\alpha}^j)\bar{\dot{y}} \end{pmatrix}_{t_j}^j}_{\boldsymbol{f}_{t_i'|t_j}^j} + \underbrace{\begin{pmatrix} 0 \\ 0 \\ \sqrt{1-\tilde{\alpha}^{j\,2}}\, w_{\dot{x}} \\ \sqrt{1-\tilde{\alpha}^{j\,2}}\, w_{\dot{y}} \end{pmatrix}_{t_j}^j}_{\boldsymbol{w}_{t_i}^j}$$

Data Re-Synchronization (3)

- Stochastic linear (Kalman-like) prediction performed at *i*

$$\hat{\boldsymbol{\theta}}^{j}_{t'_i|t_j} = \boldsymbol{F}^{j}_{t'_i|t_j}\hat{\boldsymbol{\theta}}^{j}_{t_j|t_j} + \boldsymbol{f}^{j}_{t'_i|t_j}$$

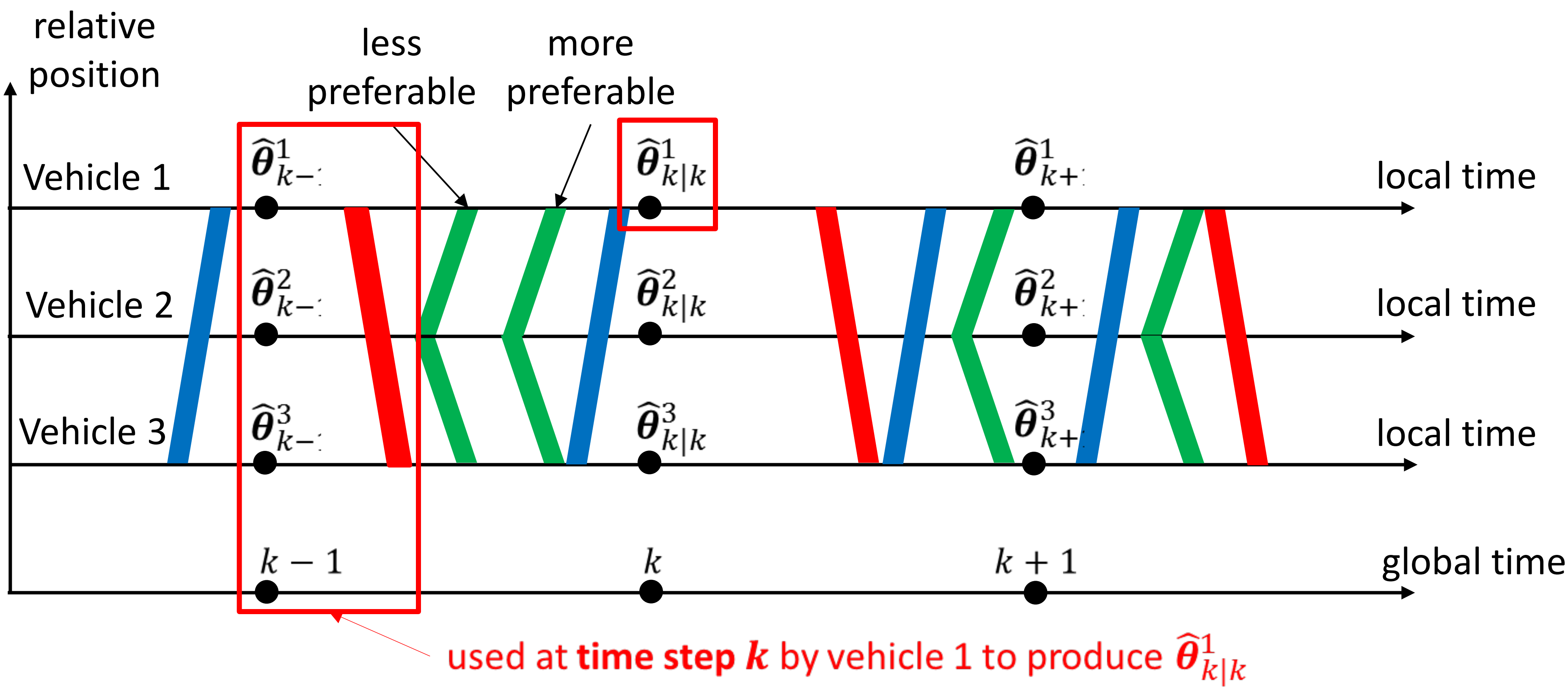
$$\boldsymbol{P}^{j}_{t'_i|t_j}(\hat{\boldsymbol{\theta}}) = \boldsymbol{F}^{j}_{t'_i|t_j}\boldsymbol{P}^{j}_{t_j|t_j}(\hat{\boldsymbol{\theta}})\left[\boldsymbol{F}^{j}_{t'_i|t_j}\right]^{T} + \boldsymbol{Q}^{j}_{t_j}$$

  - Impact of modelling error lowered by fine-tuning the process noise covariance matrix $\boldsymbol{Q}^{j}_{t_j} = \mathbb{E}\left\{\boldsymbol{w}^{j}_{t_j}\left[\boldsymbol{w}^{j}_{t_j}\right]^{T}\right\}$ through e.g.,
    - Innovation magnitude bound test
    - Normalised innovations squared χ^2 test
    - Innovation whiteness (autocorrelation) test

  - System matrices $\boldsymbol{F}^{j}_{t'_i|t_j}$, $\boldsymbol{f}^{j}_{t'_i|t_j}$ can be known *a priori*, determined empirically (i.e., learnt) and optionally included in the CAMs (model

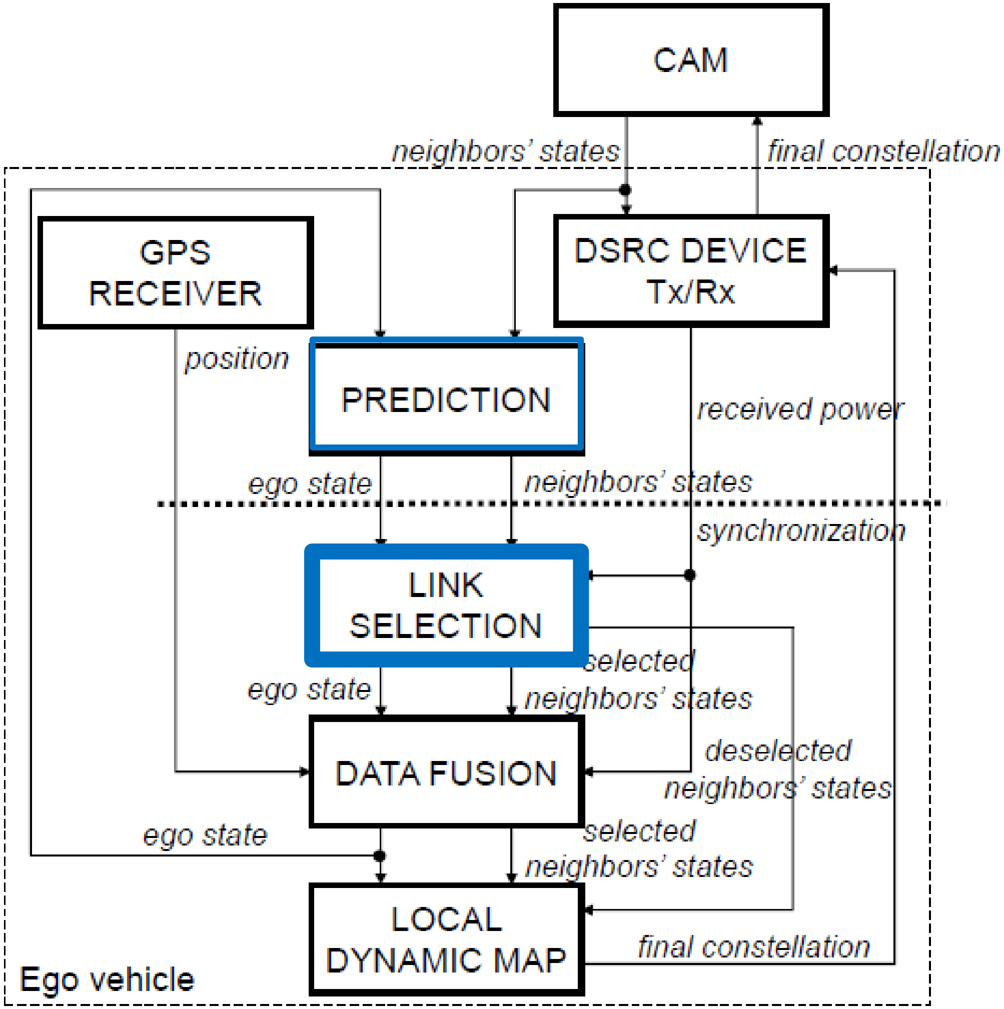
Data Re-Synchronization (4)

- To properly incorporate cooperative information incoming from neighboring vehicles (through CAMs)



Space-time schematic with approximately synchronous location estimates and asynchronous CAMs

Measurements & Links Selection (1)



Measurements & Links Selection (1)

HIGHTS
High precision positioning for Cooperative-ITS

- Assumed measurement model
  - 2D coordinates estimated by vehicle i's GPS receiver affected by Gaussian centred measurement noises (i.i.d) $v^i_{x,k}, v^i_{y,k}$

$$z^i_{x,k} = x^i_k + v^i_{x,k}$$
$$z^i_{y,k} = y^i_k + v^i_{y,k}$$

  - V2V RSSI measurement w.r.t. neighbor j affected by Gaussian shadowing $v^i_{j,k}$

$$z^i_{j,k} = P^j_0 - 10 n_p \log_{10}\left(\frac{\sqrt{\left(x^i_k - x^j_k\right)^2 + \left(y^i_k - y^j_k\right)^2}}{d_0}\right) + v^i_{j,k}$$

where P^j_0 (dBm) is the received power at $d_0 = 1$ m, n_p is path loss exponent

  - Overall observation vector

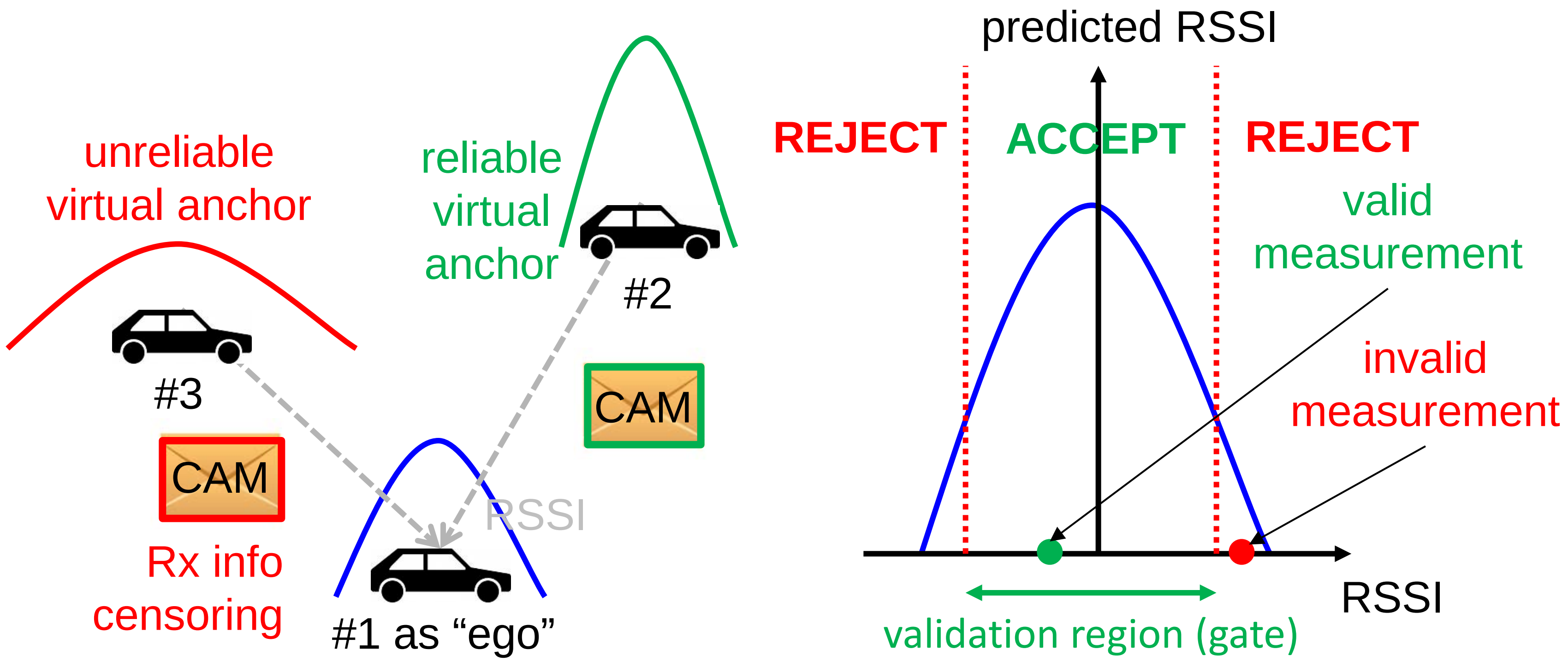
$$\boldsymbol{z}^i_k = \left(z^i_{x,k}, z^i_{y,k}, \dots, z^i_{j\neq i,k}, \dots\right)^T = \boldsymbol{h}\left(\boldsymbol{\theta}^i_k, \dots, \boldsymbol{\theta}^{j\neq i}_k, \dots\right)$$

↔ Non-cooperative

↔ Cooperative

Measurements & Links Selection (2)

- Pre-validation step: Assessing the quality of both transmitted neighbors' information & V2V measurements
  - Large dispersion of neighbors' position estimates → Monitoring the covariance matrices of location estimates transmitted by neighbors (in their CAMs)
  - Unexpected V2V RSSI measurement (outdated, noisy outlier…) vs prediction (still too high estimation covariance) → Monitoring normalized innovation terms



Measurements and Links Selection (3)

HIGHTS
High precision positioning for Cooperative-ITS

Neighbors pre-validation
(*Covariance matrices of location estimates*)

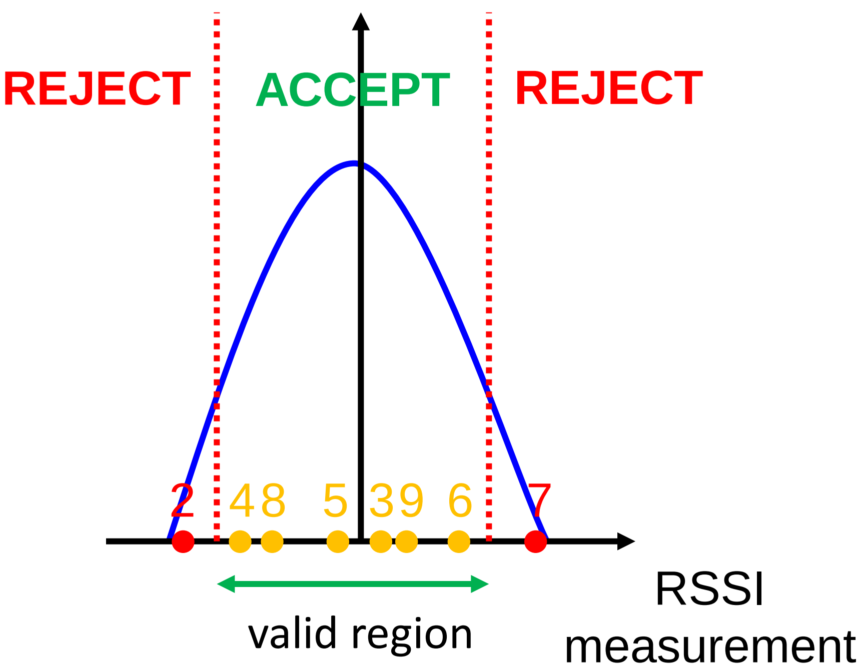
RSSIs pre-validation
(*Normalized innovation terms*)

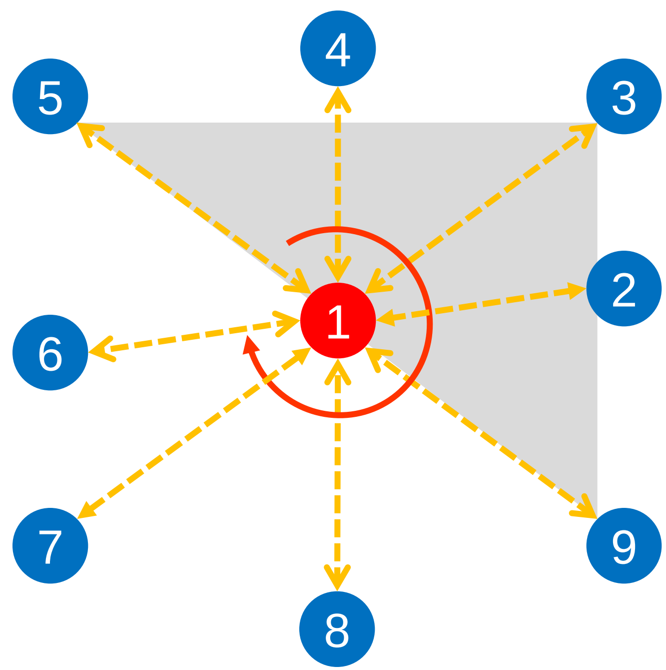
Algorithm 1 Validation gate for link quality (iteration k, "ego" vehicle i, neighboring vehicle j)

```
procedure VALIDATIONGATE(k, i, j, x^i_{k|k-1}, P^i_{k|k-1}(x̂), x^j_{k|k-1}, P^j_{k|k-1}(x̂), P_k^{j→i}, R_k^{j→i}, β_th, γ_th)
    if trace(P^j_{k|k-1}(x̂)) > β_th trace(P^i_{k|k-1}(x̂)) then    ▷ received information censoring
        return remove non-reliable link j
    else
        P^{j→i}_{k|k-1} = h(x^{(i,j)}_{k|k-1})    ▷ predicted RSSI measurement
        ν_k^{j→i} = P_k^{j→i} − P^{j→i}_{k|k-1}    ▷ innovation
        S_k^{j→i} = H_k P^{(i,j)}_{k|k-1} H^T + R_k^{j→i}    ▷ innovation covariance matrix
        q_k^{j→i} = [ν_k^{j→i}]^T S_k^{j→i} ν_k^{j→i}    ▷ normalized innovation error
        if q_k^{j→i} < γ_th then    ▷ validation gate
            return select link j ∈ V_k^{→i}, store q_k^{j→i}
        else
            return remove non-reliable link j
        end if
    end if
end procedure
```

Measurements and Links Selection (4)

- Links selection step: Choosing an "optimized" shorter list among pre-validated links
  - Required low computational complexity/latency ("reactive" VANET) → Option 1 / Nearest Neighbor (NN) : Simply select the 3 links (minimum nb in 2D) with the smallest normalized innovation errors (but still depending mostly on RSSI quality!)





Measurements and Links Selection (5)

HIGHTS
High precision positioning for Cooperative-ITS

Selection of 3 links
(NN = smallest innovations)

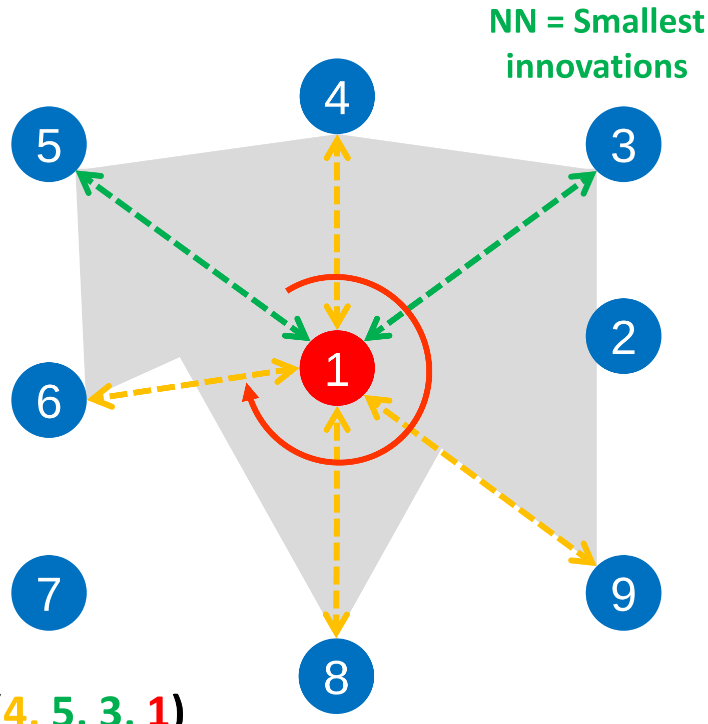
Algorithm 2 NN-based link selection of 3 most informative links (iteration k, "ego" vehicle i, neighboring vehicles $V_k^{\to i}$)

---

procedure NNLinkSelection($V_k^{\to i}$)
  if $|V_k^{\to i}| > 3$ **then**
    $s_1 = \arg\min_{s} q_k^{s \to i}$ ▷ first link
    $s_2 = \arg\min_{s \neq s_1} q_k^{s \to i}$ ▷ second link
    $s_3 = \arg\min_{s \neq s_1, s_2} q_k^{s \to i}$ ▷ third link
    return $S_k^{\to i} = \{s_1, s_2, s_3\}$
  else
    return $S_k^{\to i} = V_k^{\to i}$
  end if
end procedure

Measurements and Links Selection (6)

- Option 2 / Modified CRLB (MCRLB)-based scheme
  - 2 first links with NN criterion
  - 1 last link minimizing the conditional Cramer Rao Lower Bound (characterizing unbiased location estimates given a set a neighbors)
    - Approximated CRLB fed by the latest estimated locations (instead of true ones)
    - Capturing Geometric Dilution Of Precision (GDOP)
    - Avoiding combinatory complexity of exhaustive search (l links out of n would require $\mathcal{O}(n^l)$)



$\mathrm{CRLB}_1\,(4, 5, 3, 1)$

$\mathrm{CRLB}_1\,(6, 5, 3, 1) < \mathrm{CRLB}_1\,(4, 5, 3, 1)$

$\mathrm{CRLB}_1\,(8, 5, 3, 1) < \mathrm{CRLB}_1\,(6, 5, 3, 1) < \mathrm{CRLB}_1\,(4, 5, 3, 1)$

$\mathrm{CRLB}_1\,(8, 5, 3, 1) < \mathrm{CRLB}_1\,(9, 5, 3, 1) < \mathrm{CRLB}_1\,(6, 5, 3, 1) < \mathrm{CRLB}_1\,(4, 5, 3, 1)$

Measurements and Links Selection (7)

HIGHTS
High precision positioning for Cooperative-ITS

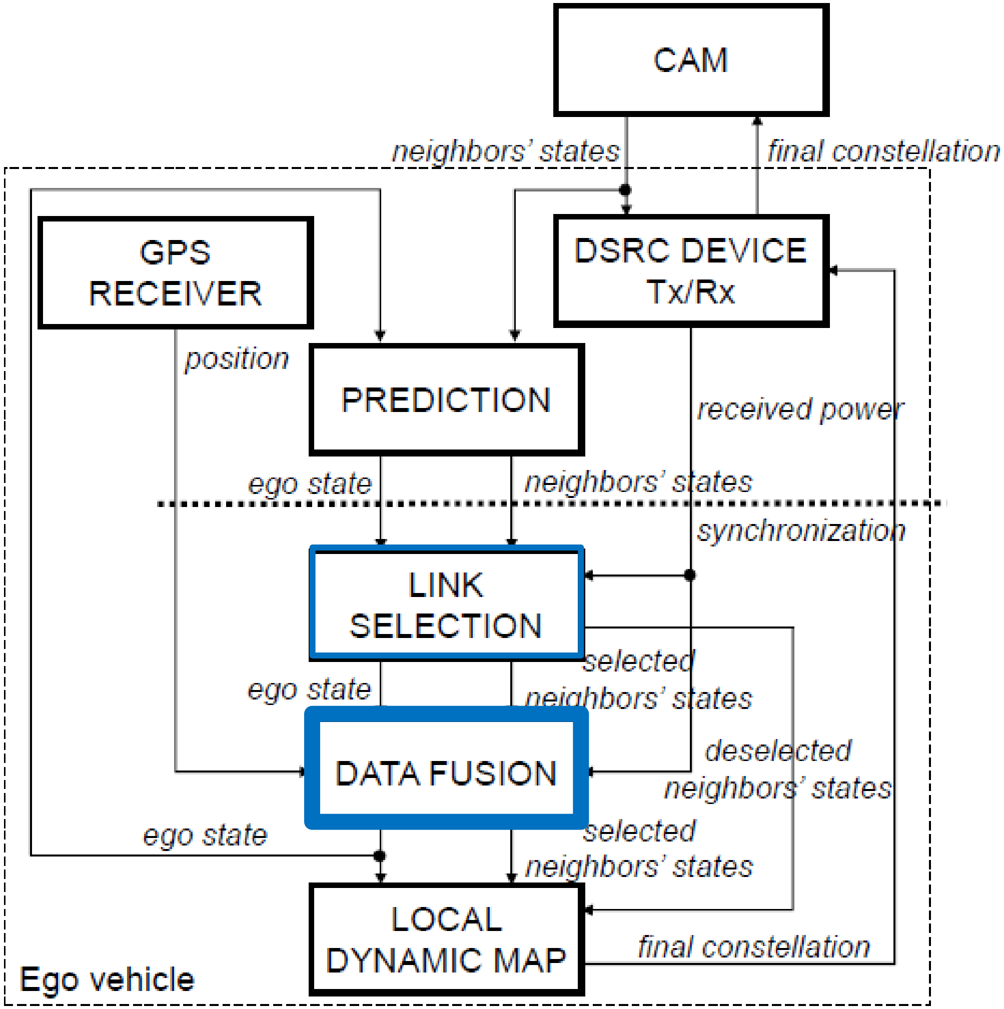
Algorithm 3 Modified CRLB (MCRLB)-based link selection of 3 most informative links (iteration k, "ego" vehicle i, neighboring vehicles $V_k^{\rightarrow i}$)

procedure MCRLBLINKSELECTION($V_k^{\rightarrow i}$)
    if $\left|V_k^{\rightarrow i}\right| > 3$ **then**
        $s_1 = \arg\min_{s} q_k^{s \rightarrow i}$ ▷ first link
        $s_2 = \arg\min_{s \neq s_1} q_k^{s \rightarrow i}$ ▷ second link
        for $s \in V_k^{\rightarrow i} \setminus \{s_1, s_2\}$ **do**
            $s_3 = \arg\min_{s} \mathrm{CRLB}_k^i(s)$ ▷ third link
            return $S_k^{\rightarrow i} = \{s_1, s_2, s_3\}$
        end for
    else
        return $S_k^{\rightarrow i} = V_k^{\rightarrow i}$
    end if
end procedure

Selection of 2 links (*smallest innovations*)

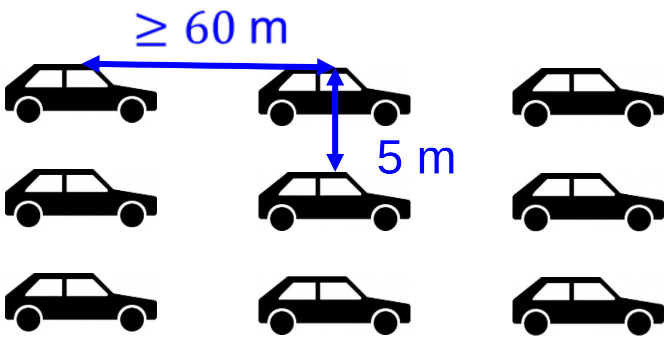
Selection of 3rd link (*CRLB*)

Final Fusion Step through EKF Correction



Simulation Set-Up (1)

- Simulation environment
  - 3-lane highway model
  - 9 vehicles traveling in the same direction



- Gauss-Markov mobility model

$$\boldsymbol{V}_k = \alpha V_{k-1} + (1-\alpha)\boldsymbol{\mu} + \sqrt{1-\alpha^2}\boldsymbol{w}_{k-1}$$

Parameter	Value
Memory level α	0.95
Asymptotic mean velocity $\boldsymbol{\mu}$	28 m/s ~ 100 km/h
Asymptotic velocity standard deviation $\mathbb{E}\{\boldsymbol{w}_k \boldsymbol{w}_k^T\}$	0.1 m/s
Time step	0.1 s ~ Max. CAM rate
Duration	100 s

Simulation Set-Up (2)

- GPS error model → Normally distributed central 2D errors under various conditions

Level of GPS	Max Error Value	Modeled Equivalent std
Favorable	≤ 10 m	3 m
Medium	≤ 15 m	5 m
Harsh	≤ 30 m	10 m
Denied/lost	N/A	N/A

- Log-distance path loss model → IEEE 802.11p
  - Path loss exponent: 1.9
  - Shadowing standard deviation: 2.5 dB
  - Tx power: 33 dBm (max)
  - Operating frequency: 5.9 GHz

Simulation Set-Up (3)

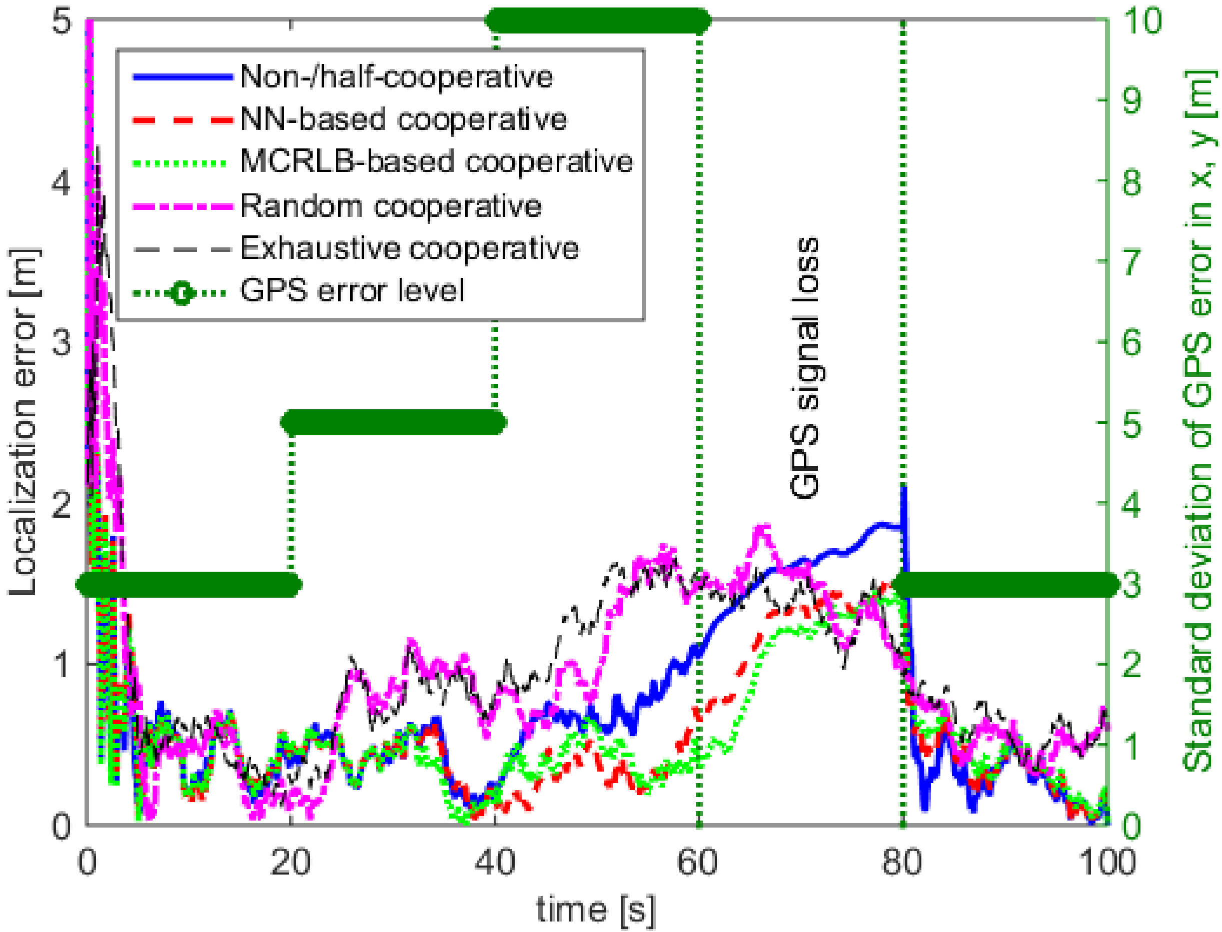
HIGHTS
High precision positioning for Cooperative-ITS

- Evaluation scenario 1 (S1)
  - Central car as “ego” vehicle performing cooperative fusion
  - Other cars just relying on GPS filtering & broadcasting the results in their CAMs
  - GPS error levels randomly assigned to the different vehicles (though constant over time for the whole trajectory)
    - Medium for “ego” vehicle and 20 % of its neighbours
    - Favourable (std of 3 m) for the next 40 %
    - Harsh (std of 10 m) for the last 20 %
  - 1000 independent Monte Carlo simulations

- Evaluation scenario 2 (S2)
  - Idem but time-variant GPS error level (incl. 20 % of loss) for “ego” vehicle

Simulation Results (1)

- Illustration example (varying GPS at the "ego" car only)



Simulation Results (2)

- Worst Case (WC ~ CDF[error]=0.9) & Median ($\mu_{1/2}$ ~ CDF[error]=0.5) localization errors over Monte Carlo simulations

"Ego" localization error statistics (in meter) in both S1 and S2

Algorithm	Whole trajectory				Poor GPS	
	S1		S2		S2	
	$\mu_{1/2}$	WC	$\mu_{1/2}$	WC	$\mu_{1/2}$	WC
Raw GPS	5.90	12.24	N/A	N/A	N/A	N/A
Non-/half-CP	0.53	1.11	0.57	1.78	1.10	1.85
NN-CP	0.49	1.02	0.46	1.43	0.67	1.47
MCRLB-CP	0.48	1.01	0.46	1.37	0.53	1.39
Ran. Sel. CP	0.50	1.18	0.82	1.74	1.41	1.72
Exhaust. CP	0.51	1.28	0.87	1.61	1.39	1.60

Poorest performance & navigation discontinuity

Already significant gains through classical filtering

Degraded performance through exhaustive coop. or wrong selection

More significant gains of 25%−50% in harsh/denied GPS conditions

Modest gains of 10%

Conclusions & Perspectives

- Conclusions
  - CP & V2V RSSI in the GPS-aided IEEE 802.11p context → Evaluation with basic tools/algorithms
  - Practical low-complexity solutions for data synchronization and links/measurements selection before fusion
  - Exhaustive cooperation may not be systematically helpful
  - Better resilience through selective cooperation, mostly in harsh/lost GPS conditions → Context-aware (selective) cooperation
- Perspectives
  - Revised links selection strategy (>3 links) and core estimation engine (e.g., NBP and its variants, Particle Filtering…)
  - Varying update and CAM rates (incl. real event-driven criteria)
  - Generalized correction step including also neighbours → Assessing LDM accuracy as well, instead of "Ego" localization only
  - RSSI-based CP under power and/or rate control mechanisms

Acknowledgement/Advertisement

HIGHTS
High precision positioning for Cooperative-ITS

- H2020 “HIGHTS” project
  - Flag ship collaborative research project in the field of high-precision vehicular localization (through cooperation and hybrid data fusion)
  - Started in May 2015 !
  - Coordinated by Jacobs Univ., Bremen

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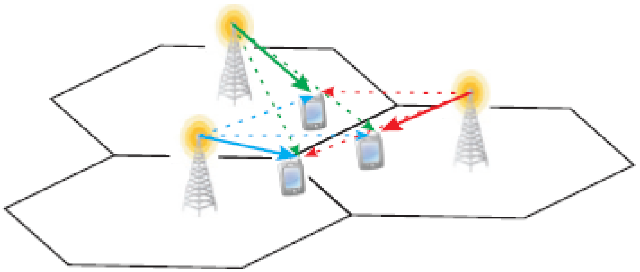
HIGHTS
High precision positioning for Cooperative-ITS

Upgrading Wireless Communications to Location Aided Systems (3/3)

- **T3.3 - Location Aided Cognitive Radio Networks**
- Partners
  - **EUR, HKC, UNIS, UPM**
- Subtasks
  - Cooperative spectrum sensing
  - Location aided channel estimation
  - Advanced cognitive radio techniques such as MIMO cognitive radio, underlay , overlay and interweave DSA, cognitive encoding/decoding and modulation/demodulation schemes
  - Location information is utilized to establish local coordination for allocation of user (time – frequency – space) signatures and transmit power.



- Focus topics:
  - Location aided spectrum sensing
  - Location aided power control (underlay)
  - Location aided beamforming

T3.3 - Location Aided Cognitive Radio Networks (EUR)

- Single antenna case (primaries)
  - In this case we can only play with the Tx powers.
  - There is an obvious use of location information to determine the secondary2primary attenuation.
  - We elaborate in [pimrc11] on the design of underlay secondary MISO interference channels (interfering secondary MISO links with interference power constraints at single antenna primary receivers).

- Multi-antenna case:
  - We propose a new terminology for spatial underlay/overlay/interweave [CogART11panel]
  - Remark on ASA (Qualcomm-NokiaSiemens): moves strongly to overlay
  - [CogART11] spatial interweave MIMO IFC.
  - EUR demo: TDD spatial interweave with RF calibration

T3.3 - Multiple Antennas in CR: a terminology proposal (EUR)

- **P = primary, S = secondary**
- **spatial overlay: MIMO Interference Channel (T3.1.2/T3.1.3 also)**
  - overlay: P and S collaborate
  - exploit multiple antennas and coordinate beamforming to achieve parallel interference-free channels
- **spatial underlay**
  - P Rxs with multiple antennas (P Rx active to suppress interference from S)
  - allows interference subspace of max dimension =

    excess of # P Rx antennas - # P streams
  - consider interference to P Rxs OK as long as interference subspace dimension does not exceed a max; requires active interference ZF by P
- **spatial interweave**
  - # S streams $\leq N_{Tx}^{S} - N_{Rx}^{P}$
  - possible if have excess of S Tx antennas over P Rx antennas
  - S BF nulls to P Rx antennas w/o P cooperation:

    location based (if LOS), reciprocity based in TDD

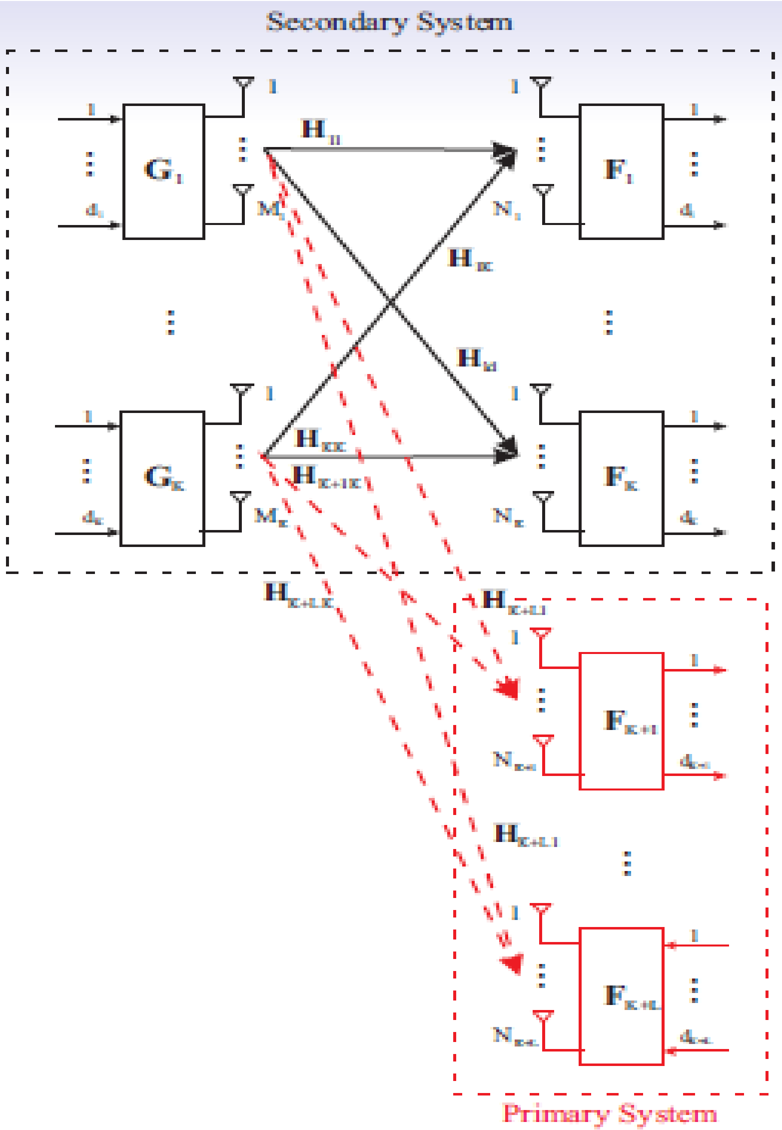
T3.3 - Spatial Interweave Cognitive Radio MIMO IFC (EUR)

- **Context & Problem**:

  Allow a secondary MIMO network to operate in the presence of a primary system with multiple antennas also

- **Principle & Novelty**:
  - Extension of a popular cognitive radio design problem to the multi-antenna case (allows ZF)
  - If secondary2primary link in LOS, number of primary antennas irrelevant, location aided spatial signature

- **Recent Achievements**:
  - Interference Alignment feasibility investigation: # S antennas required as fn of # of S, # of P antennas
  - Solved max sum rate under secondary Tx power constraints and primary ZF constraints [CogART11]
  - Addressed secondary RF calibration in a TDD based CSIT approach [JSAC12subm]



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T3.3 – Spectrum Sensing (UNIS)

- **Context & Problem:**
  - Existing spectrum scheme can hardly meet the requirements of a fast and accurate spectrum sensing particularly in very low SNR range, (the target SNR is about -20 dB) without introducing high complexity to the system
- **Principle & Novelty:**
  - Key contribution is a novel spectrum sensing scheme namely, cluster-based differential energy detection. It has several distinctive features including low latency, high accuracy, reasonable computational complexity, as well as robustness to very low SNR.
  - Key idea of the proposed scheme is to exploit the channel frequency diversity inherent in high date-rate communications using the cluster differential ordered energy spectral density.
  - Location information helps the awareness of sir-interface parameters, which can reduce significantly the signal processing complexity and improving sensing performance. The proposed scheme is not sensitive to positioning accuracy
- **Recent Achievements :**
  - One IEEE Trans. Signal Processing paper and three IEEE conference paper have been published on this topic

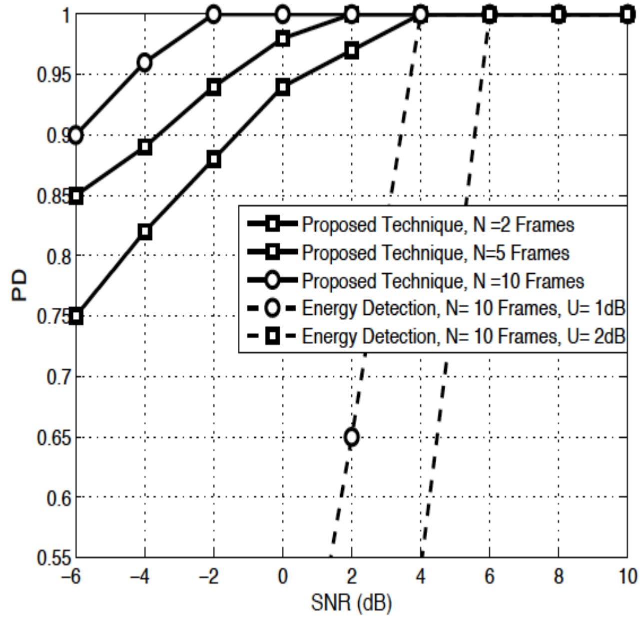


Fig.1 Performance of proposed spectrum sensing vs. SNR at spectrum sensing device of OFDM based systems

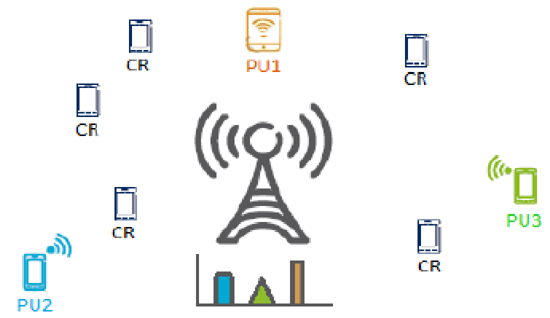
<u>WIFi environment</u>
2,048 subcarrier (FFT size)
Subcarrier spacing: 15 kHz
CP Length: 160 samples
Sensing device speed: 3km/h
WINNER B2 outdoor channel

T3.3 – Location Aided Spectrum Sensing (EUR)

- **Context & Problem**:

  Analyze and combine two of the main enabling features of cognitive radio: location awareness and spectrum sensing taking into account one of the challenging hardware limitations: signal acquisition at Nyquist rate.

- **Principle & Novelty**:
  - Formulate spectrum sensing into compressed sensing framework.
  - Adopting the path-loss model linking path-loss to distance (position) and frequency.
- **Recent Achievements**:
  - A common framework for spectrum sensing and PU position estimation using compressed sampling
  - [CAMAD2012] paper
- **Perspectives**:
  - Needs more realistic channel models to be investigated than AWGN.



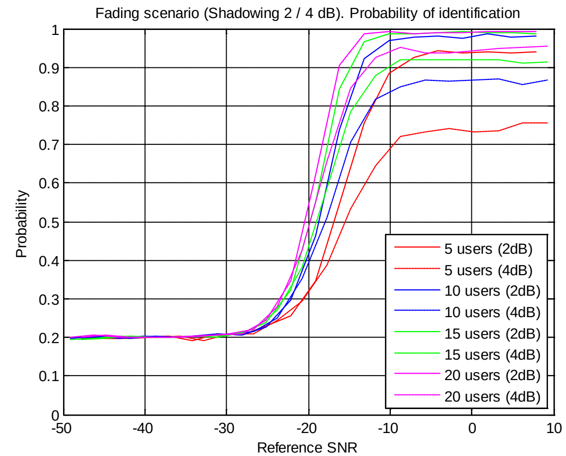
$$\vec{y} = \Phi \vec{f} + \vec{w}$$

$$L(f,d) = P_0 + 20\lg(f) + 10n\lg(d) \qquad [dB]$$

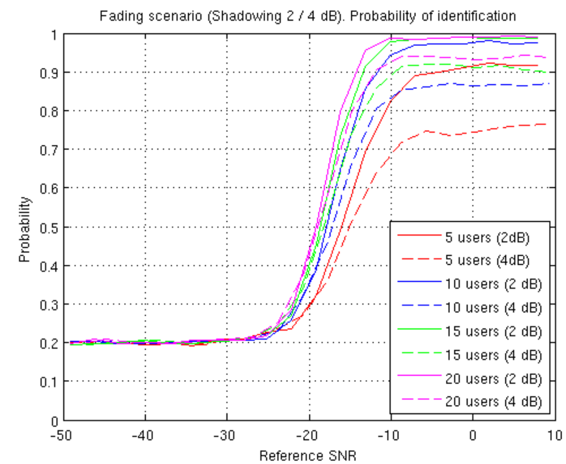
T3.3 – Primary user detection and identification in cognitive radio (UPM)

- **Context & Problem**:
  - Network model: P primary transmitters, S secondary receivers.
  - At most one of the primaries is active at a given time.
  - The positions of the primary transmitters are known.
  - Secondary users try to cooperatively detect the presence of a primary transmission and then identify the active primary.
- **Principle & Novelty**:
  - Only local power estimations are used as test statistics.
  - Power estimations obtained by the secondary receivers are spatially dependent due to correlated shadowing effects. Shadow fading losses are obtained using a random field model for the spatial loss.
  - Two approaches for detection/identification are used: centralized and distributed.
- **Recent Achievements:**
  - Simulations were conducted to compare the centralized and distributed schemes.
  - Both appear to behave similarly.

Centralized approach

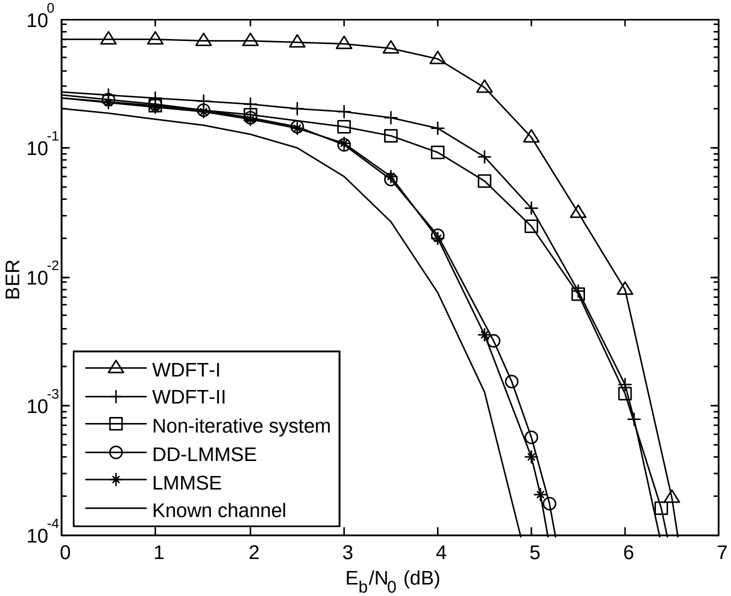


Distributed approach



T3.3 – Channel Estimation Based on A Priori PDP (HKC)

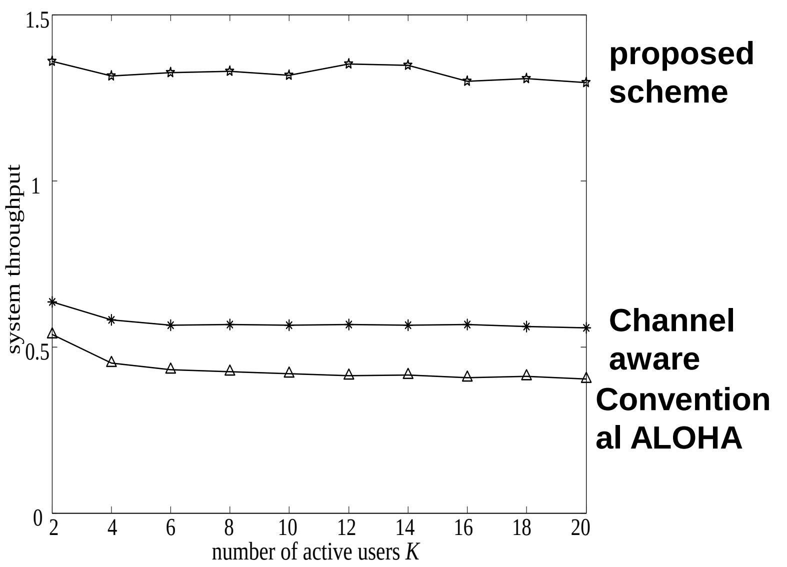
- **Context & Problem**:
  - A priori power delay profile (PDP) can be used to enhance channel estimation performance, e.g., LMMSE channel estimation.
  - PDP may be obtained from positioning information.
  - LMMSE involves matrix inversion, thus has high computational complexity.
- **Principle & Novelty**:
  - The proposed channel estimation algorithm performs close to LMMSE, but with significant lower complexity.
- **Recent Achievements:**
  - IEEE Trans. Signal Process. Paper: Dual-Diagonal LMMSE channel estimation for OFDM.



The proposed DD-LMMSE scheme can efficiently utilize PDP information and performs close to LMMSE, but with significantly lower complexity.

T3.3 – Decentralized Power Control for Random Access with Iterative Multiuser Detection (HKC)

- **Context & Problem:**
  - In a cognitive radio with ALOHA type random access system, packets collision is inevitable due to decentralized control.
  - The system throughout is limited by collision probability.
- **Principle & Novelty:**
  - We assume that multi-user detection can be applied to resolve some collisions, which leads to multiple packet reception (MPR). We developed a decentralized power control mechanism that maximizes the success probability for MPR.
  - Require own instantaneous CSIT, own & other channel probability distribution, to decide whether to Tx or not.
- **Recent Achievements:**
  - ISTC conference paper: decentralized power control for random access with iterative multi-user detection.



With CSIT, the proposed scheme can provide significant gain in multi-user fading channels. The proposed scheme achieves a system throughput >1.

Advanced Dynamic spectrum 5G mobile networks Employing Licensed shared access

ADEL

FP7 ADEL project intermediate results and standardization strategy

Coordinator Contact:
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Institute for Digital Communications,
University of Edinburgh, UK

http://www.fp7-adel.eu/

Key Idea

To explore the potential of LSA as a key enabler of 5G mobile broadband networks.

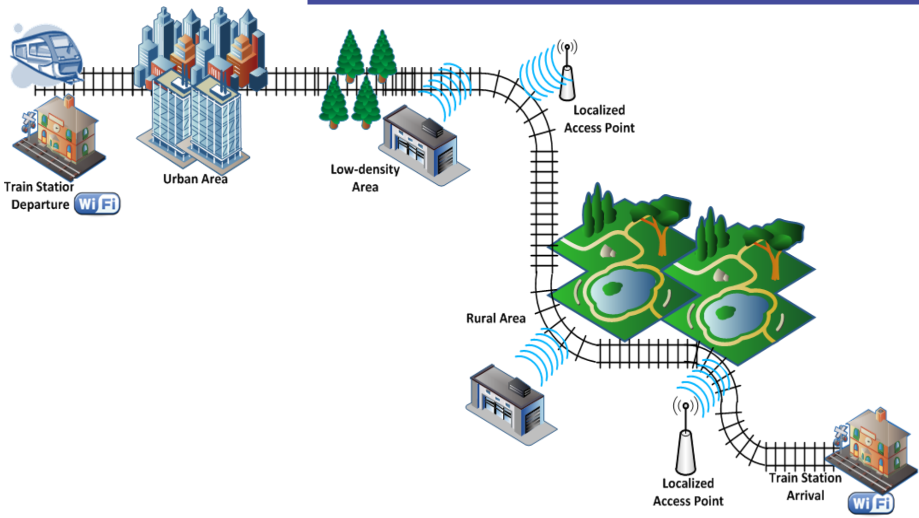
➢ **By developing:**

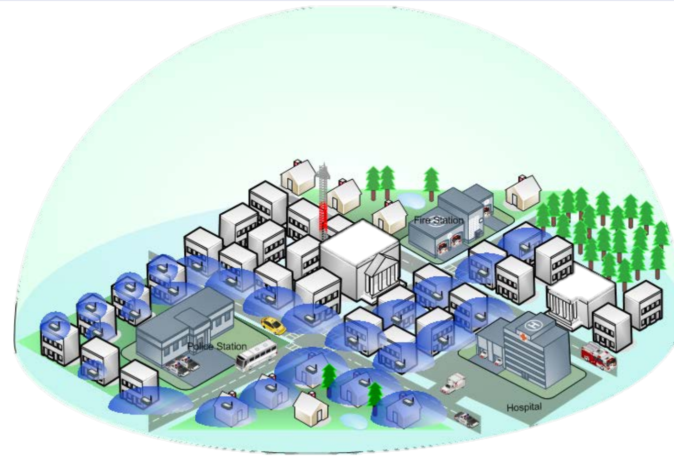
1) ***Collaborative and database assisted sensing techniques***
   - achieving sensitivity requirements set by regulatory authorities at a minimum communication overhead between collaborating nodes;
2) ***Dynamic, radio-aware resource allocation***
   - distributed and centralized processes offering desired network features such as scalability, trust-control, efficiency, etc.;
3) ***Cooperative communication***
   - dense LSA, small-cell based and hierarchical networks.

➢ **With the final goal of providing:**

An order of magnitude improvement in spectral efficiency, more energy and cost efficient mobile broadband networks.

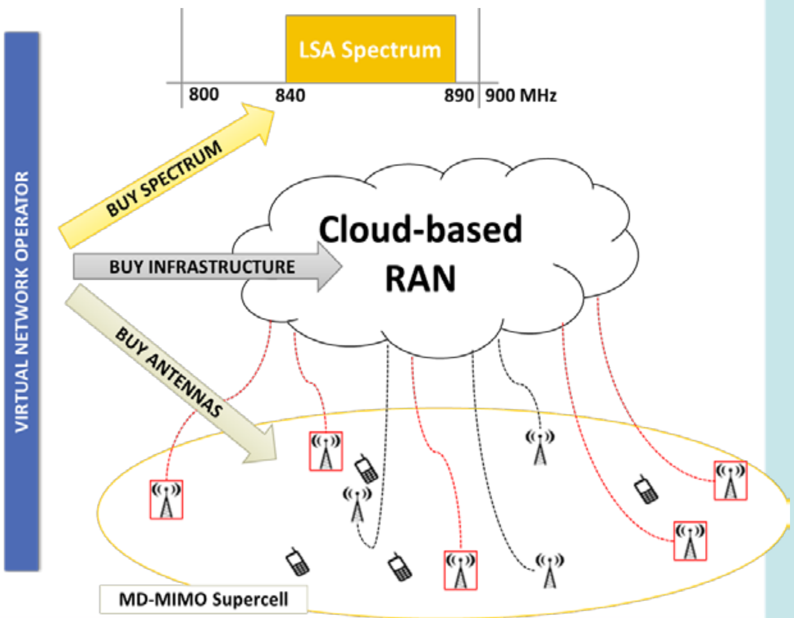
ADEL Reference Scenarios





A number of scenarios covering the full range of:

- Low → High Mobility
- Low → High LSA Dynamics
- Macro cell and small cell deployments
- Reconfiguration capability
- Shared Infrastructure: pool of virtual resources, service-driven networks, MVNOs as LSA licensees, trading between resources.
- Incumbents, existing operator licensees and new entrant operators
- 2.3 GHz band, 700MHz, 1452-1492 MHz, 1.5 GHz, 1980-2010/2170-2200 MHz, 3.8-4.2MHz, 5GHz



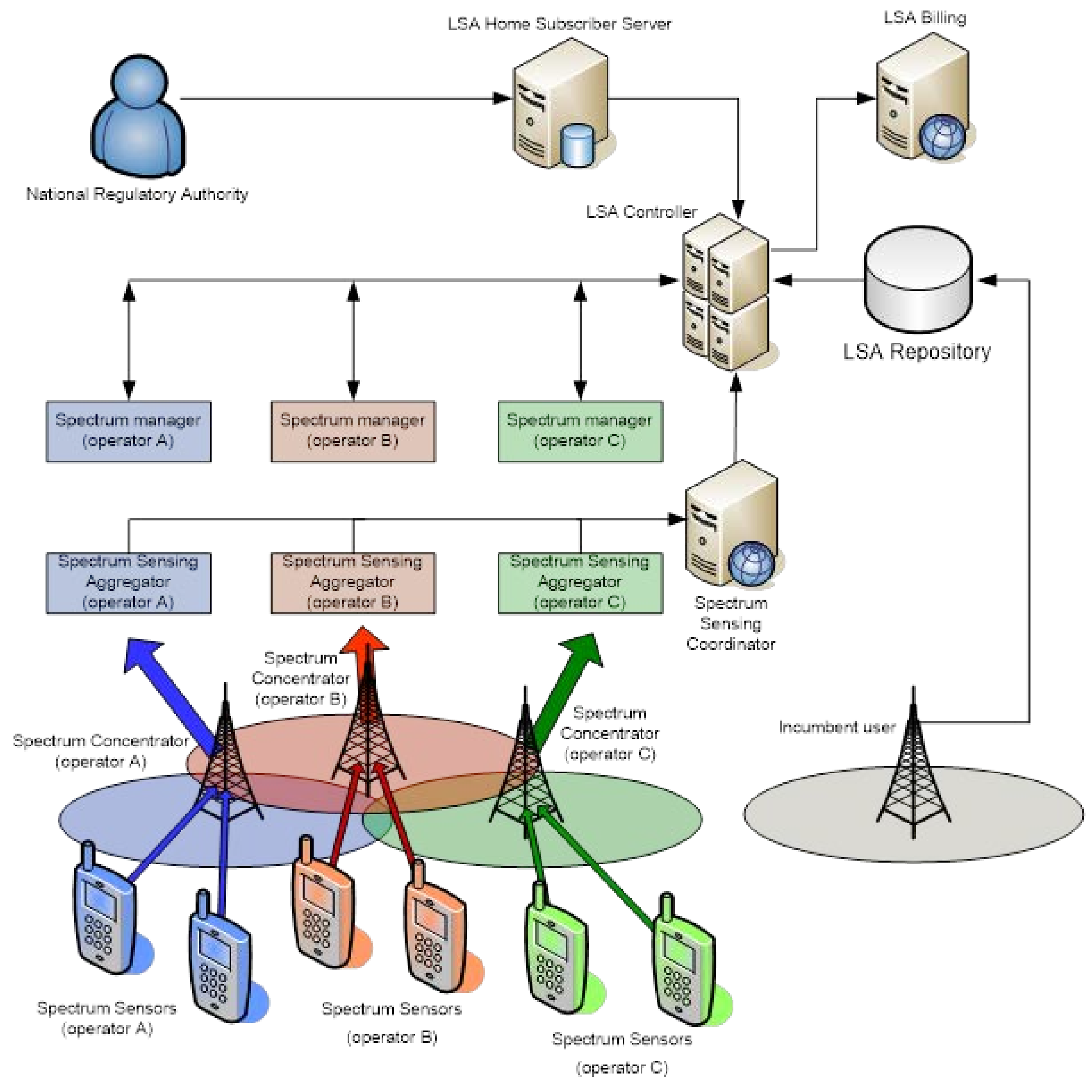
Proposed LSA network

Functional LSA Network proposed:

- LSA Repository
- LSA Controller
- Collaborative spectrum sensing network (sensor, aggregators, coordinator)

Integration with 3GPP

- new functional modules
- 3GPP interfaces
- 3GPP RRC messages



Dissemination & Collaboration

- Papers published – special session organized

I. Y. Lejosne; M. Bashar; D. Slock; Yi Yuan-Wu: **Decoupled, Rank Reduced, Massive and Frequency-Selective Aspects in MIMO Interfering Broadcast Channels**, *6th International Symposium on Communications, Control and Signal Processing*, Athens, May 2014;

II. G. Miguelez; E. Avdic; N. Marchetti; I. Macaluso; L. Doyle: **Cloud-RAN Platform for LSA in 5G Networks - Tradeoff Within the Infrastructure**, *6th International Symposium on Communications, Control and Signal Processing*, Athens, May 2014;

III. N. Taramas; G. C. Alexandropoulos; C. B. Papadias: **Opportunistic Beamforming for Secondary Users in Licensed Shared Access Networks**, *6th International Symposium on Communications, Control and Signal Processing*, Athens, May 2014;

IV. O. D. R. Cantor; J. Belschner; M. Pesavento: **A Cooperative Power Control Scheme For Interference Management in LTE-Advanced Based Cognitive Radio Networks**, *6th International Symposium on Communications, Control and Signal Processing*, Athens, May 2014;

V. M. D. Mueck, V. Frascolla, B. Badic: **Licensed Shared Access – State-of-the-Art and current Challenges**, *2014 1st IEEE International Workshop on Cognitive Cellular Systems (CCS 2014), Bonn September 2014;*

VI. K. Ho-Van, P. C. Sofotasios, G. C. Alexandropoulos, S. Freear, **Bit error rate of underlay decode-and-forward cognitive networks with best relay selection**, *Journal of Communications and Networks*, to appear, 2014

- Meetings with NRA: Ofcom & ANFR

Collaboration with CRS-i: project synergies and standardization strategy

A Trial Within The Ofcom TV White Spaces Pilot

What Is Achievable In TV White Space? How Can Such A White Spaces Framework Be Applied To Military Bands?

Oliver Holland, *King's College London*

On behalf of our trial – see acknowledgement slides at end for range of contributors

Please refer to back-up slides at the end of this presentation for more detailed content—these slides will be made available after the event

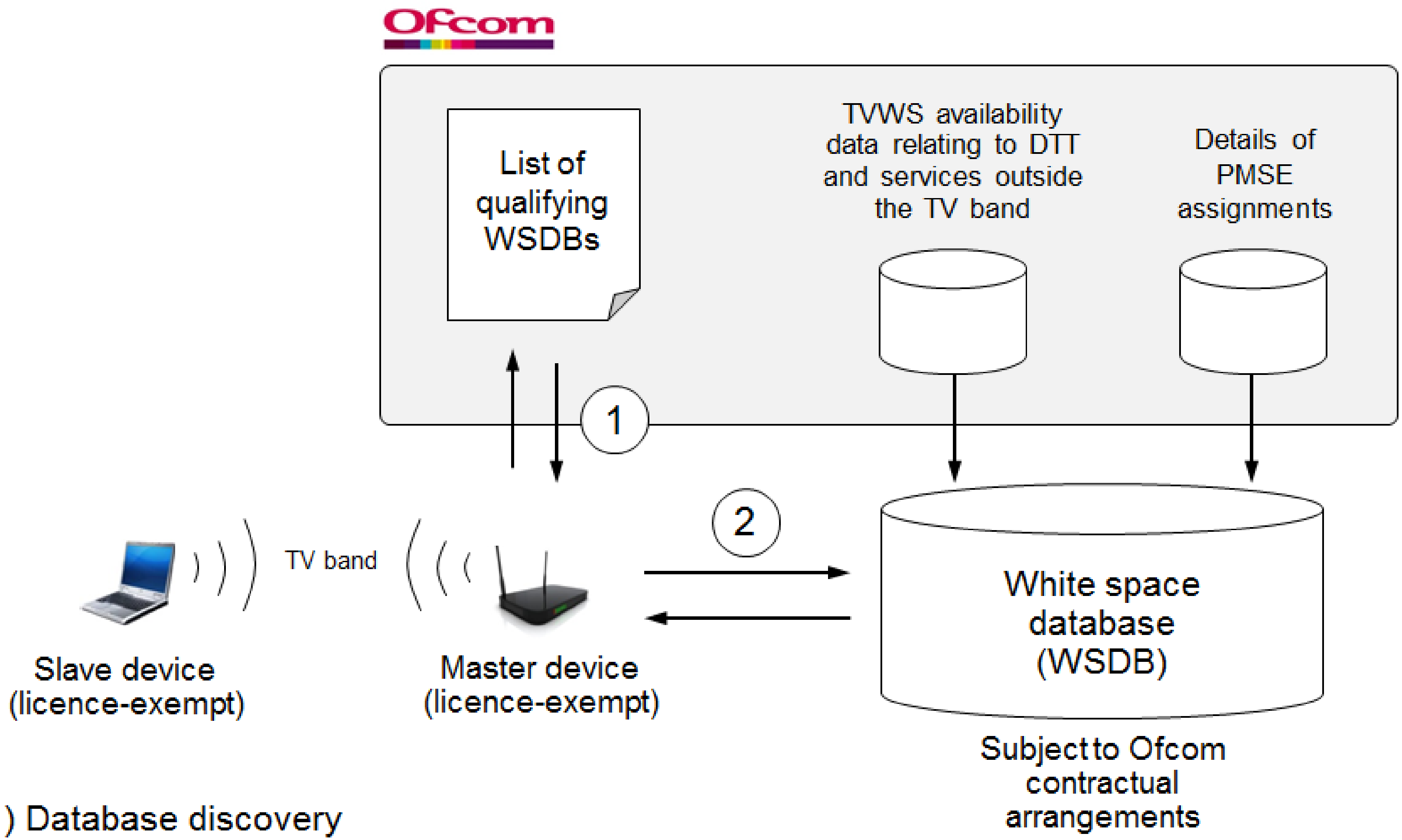
Workshop on Civilian Use of Military Spectrum Bands: Technologies, Impacts and Opportunities

Maynooth, Ireland, 18-19 March 2015

Overview

- Ofcom/ETSI Framework: White Spaces in the UK
- Our Trial
- So, What is Achievable in TV White Space?
  - Of course, considering our trial / UK case
- Relevance to Opportunistic (Civilian) Use of Military Bands
- Conclusion

Database Discovery and Device-Database Communications



1) Database discovery
2) Device-database communications.

Our Utilised Geolocation Databases

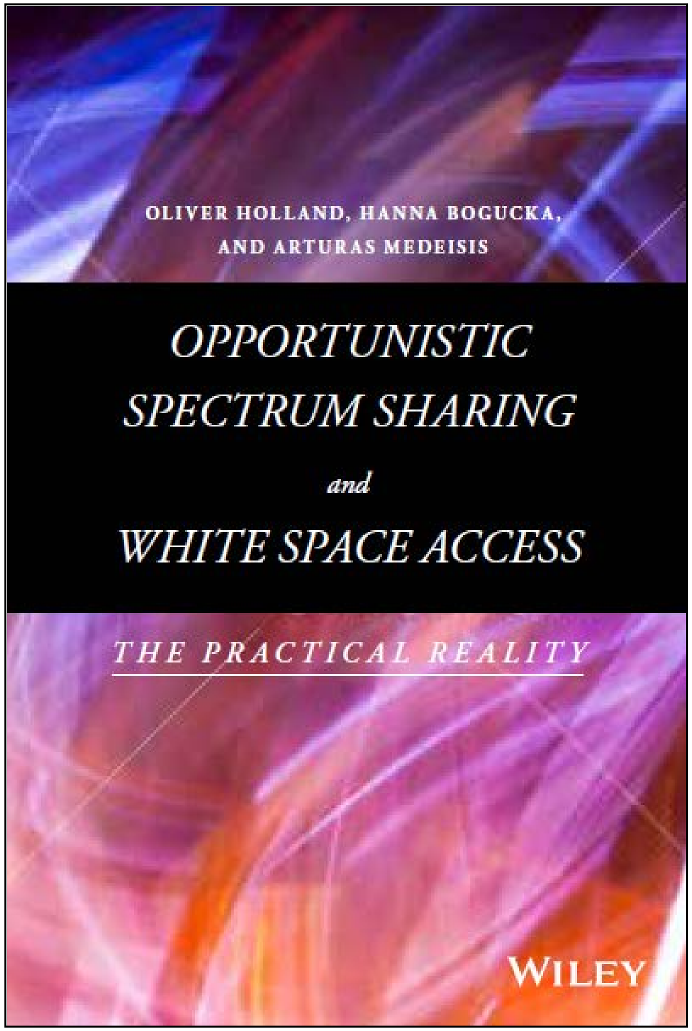
- Noted that the interfaces between TV White Space devices and geolocation databases are not standardised. It is therefore typically the case that particular TV White Space device manufacturers are working with particular databases

- We are using a range of databases in our trials
  - Fairspectrum → Carlson Wireless and Eurecom devices
  - NICT → NICT and Eurecom devices
  - Spectrum Bridge → InterDigital devices, KTS/Sinecom devices
  - Joint Research Centre of the European Commission → for comparison using a range of devices, not deployed in UK

- Also interacting or working to various extents with the following
  - Nominet (although mostly within a dedicated additional trial that Nominet has specifically set up with us)
  - Sony
  - BT (there have been discussions, current status is unknown on whether they will move to qualification for participation in Ofcom Pilot)

Book

- A detailed coverage of aspects of TV white spaces and other solutions for opportunistic spectrum sharing
- O. Holland, H. Bogucka, A. Medeisis (Eds.), *Opportunistic Spectrum Sharing and White Space Access: The Practical Reality*, Wiley
- Available imminently
- Chapters include (among many other high quality contributions)
  - H. R. Karimi, “UK framework for access to TV white spaces”
  - J. Schmidt, P. Stanforth, “Spectrum Sharing using Geo-location Databases”



HIGHTS
High precision positioning for Cooperative-ITS

IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 33, NO. 7, JULY 2015 1331

Deep Sensing for Future Spectrum and Location Awareness 5G Communications

Bin Li, Shenghong Li, Arumugam Nallanathan, *Senior Member, IEEE*, and Chenglin Zhao

Spectrum sensing, taking into account the on/off behavior of transmitters and their mobility (can have moved during silence). Joint sensing and position tracking.

Summary

- Genuine location aided wireless communications
  - The number of example systems resulting from WHERE2 ever increasing
    - Selection of relays: non location aided alternatives represent very high signaling overhead
    - Location aided power control to minimize effect of interference: e.g. ICIC w. very convincing results
    - Location aided underlay cognitive radio
    - Location aided random access schemes
    - Location aided multi-user systems (Broadcast and Interference Channel, Cellular and HetNets): CSIT issue a very hot non-trivial topic (proliferation of schemes: Blind IA, Ergodic IA, Retrospectiive IA, MAT, …), also Tx/Rx design non-trivial. Location aided alternative:
      - + : Replaces most CSIT needs, simplifies (enormously) Tx/Rx design, allows to handle interference strength (mostly ignored so far)
      - - : may not be well applicable to any environment (requires dominant propagation paths)
  - Cooperative positioning and location aided com currently pursued in HIGHTS

References: EU Projects

- WHERE2 : WHERE2 : http://www.kn-s.dlr.de/where2/
- CROWN : http://cordis.europa.eu/fp7/ict/fet-open/portfolio-crown_en.html
- ADEL : http://www.fp7-adel.eu/
- SOLDER : http://ict-solder.eu/
- HIGHTS : http://hights.eu/

HIGHTS
High precision positioning for Cooperative-ITS

Thank you for your attention !