Radio Environmental Maps (REMs): A Cognitive Tool for Environmental Awareness

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Outline

- The concept of REM
- Architectural elements
- Scenarios → operator-centric scenarios
- Example use case: A REM-enabled Soft Frequency Reuse scheme for OFDM networks
- REM Construction: Kriging interpolation
- Faramir FP7 project and ETSI RRS
- Conclusions and further work

The concept of REM

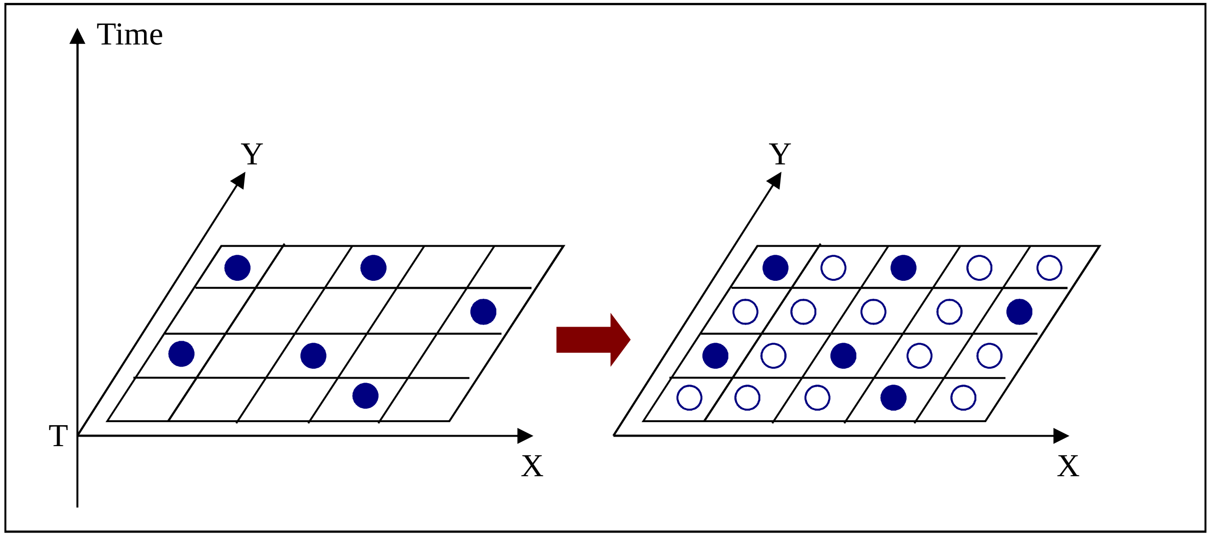
The REM concept - Origins

- REM was introduced by the Virginia Tech team [1]
- It is a centralized or distributed *database* containing information on the radio environment including:
  - Device locations and their activities
  - Policies and regulations
  - Geographical features
  - Services
- Proposed for IEEE 802.22 to exploit TV White Spaces (TV WS)
- The main functionality is *storage*
- REM is a dumb database that is consulted by intelligent entities

[1] Zhao, Youping; Reed, Jeffrey H.; Mao, Shiwen; Bae, Kyung K.; , "Overhead Analysis for Radio Environment Mapenabled Cognitive Radio Networks," *Networking Technologies for Software Defined Radio Networks, 2006.*

The REM concept – ongoing work @ Orange Labs (1/1)

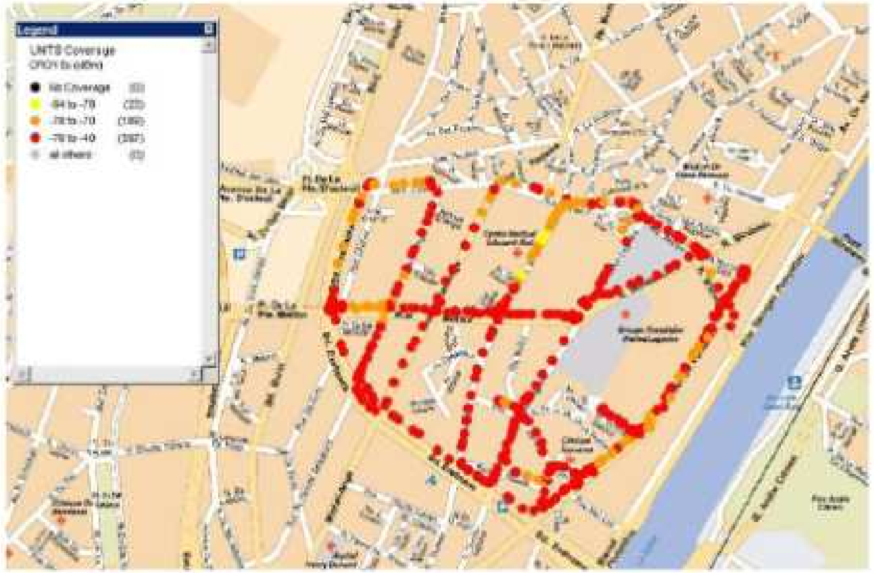
- REM is a concept that is based on *geo-localized measurements*
- Apart from storing, it *processes* data → spatial interpolation

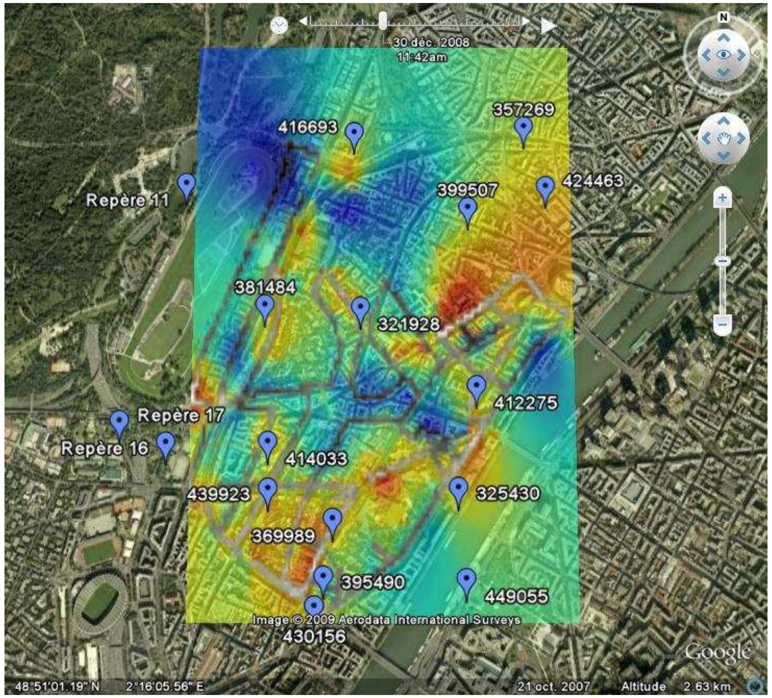


- It can be either static or dynamic
- If dynamic, then *temporal* interpolation/processing is also necessary

The REM concept – ongoing work @ Orange Labs (1/2)

- Dense urban measurements on UMTS downlink
- Kriging to obtain the REM
- Ongoing work on REM (PhD theses)



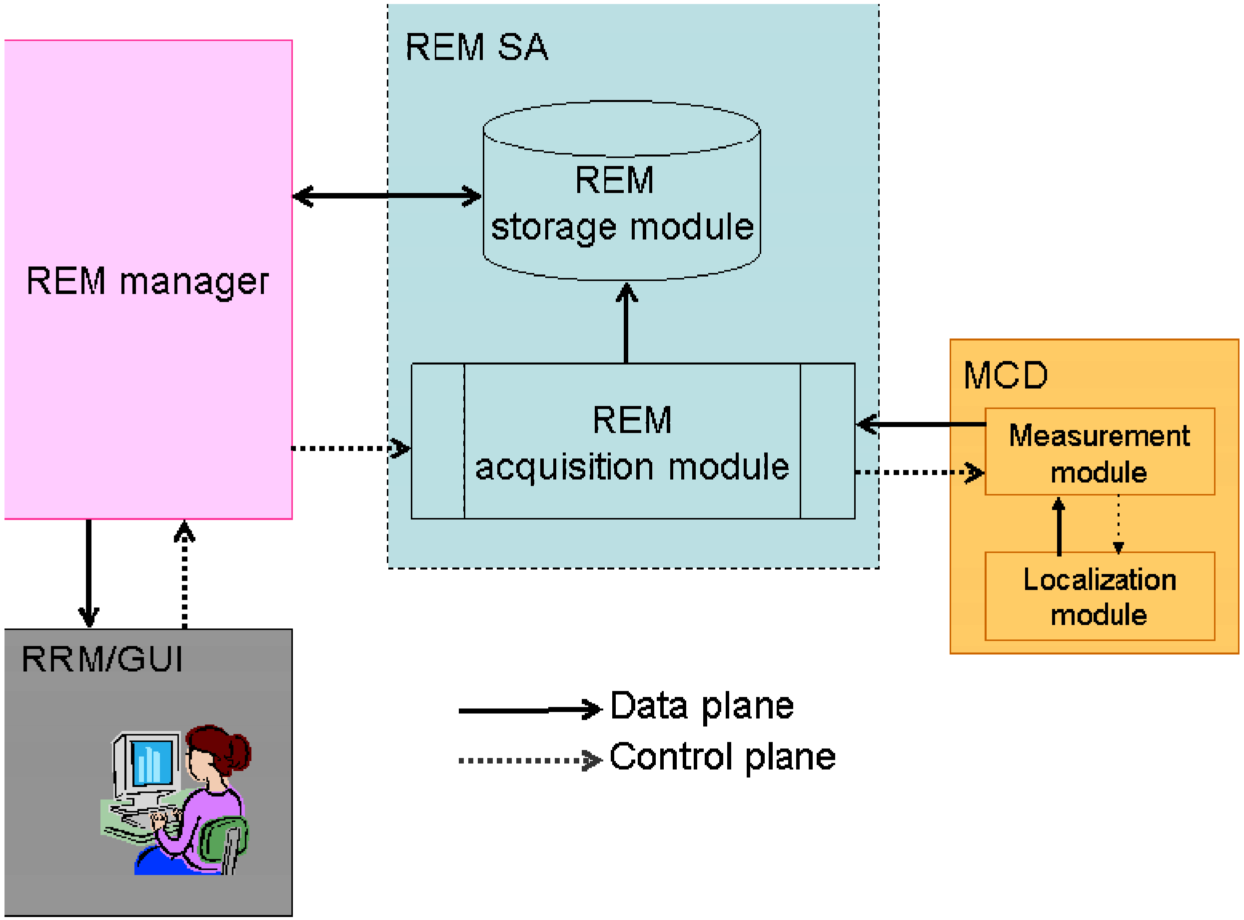


The REM concept – Obtaining Environmental Information

- Network architecture related data (Transmitter locations,…)
  - Small amount of data
  - Easily available
  - Quite static
  - Limited use
- Dedicated measurements
  - High data volume and overheads → measurements are expensive
  - Good knowledge of the radio environment → more efficient optimization possible
- Models
  - Easy to use
  - Requires assumptions → realistic?
- Measurements and statistical modeling
  - Reduces the requirements for measurements
  - Fits the model to the real world data
  - Allows for dynamic updates

REM functional architecture

The REM concept – Functional Architecture



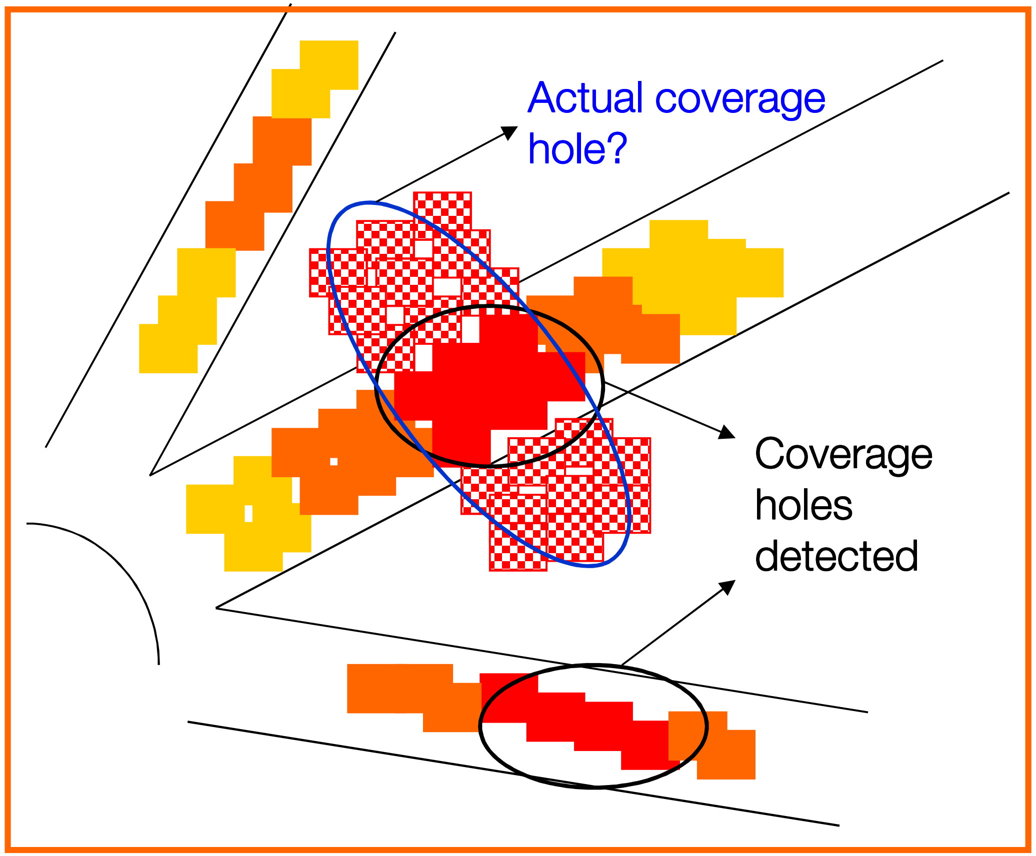
Scenarios

REM is a cognitive enabler in different types of scenarios

- Intra-Operator Radio Resource Management
  - In-band Coverage/Capacity Improvement by Relays
  - Performance Optimization (Interference Mitigation, Handover optimization etc.)
  - Self-Configuration and Self-Optimization of in-band Femto-Cells
  - Introduction of New Technologies through Refarming
- Hierarchical Spectrum Access on Licensed Bands
  - Coordinated and non-coordinated Spectrum Access between PUs and SUs
  - Multiple Secondary Networks: Spectrum Leaser
  - Out-of-band (cognitive) Femto-cells
  - Home Networks (IEEE 802.11af)
  - Smart metering communication in White Space
  - LTE in TV white spaces
- Spectrum Sharing on Unlicensed Bands
  - Coordinated spectrum access: Coordination among ad-hoc networks
  - Non-coordinated Spectrum Access of mobile ad-hoc networks
  - Extension of LDR (Low Data Rate) licensed network to out-of-band HDR (High Data Rate) unlicensed bands
- Dedicated Spectrum Monitoring on Licensed and Unlicensed Bands

Minimization of Drive Tests (MDT)

- 3GPP feature (Rel.11 ongoing)
- RF measurement collection from the mobiles upon the demand of the operator
  - processing at the O&M by the operator for troubleshooting, optimization purposes
- Enhanced diagnosis
  - More accurate detection of the "red zones"
- Enhanced troubleshooting
  - Fine-tuned solution/optimization



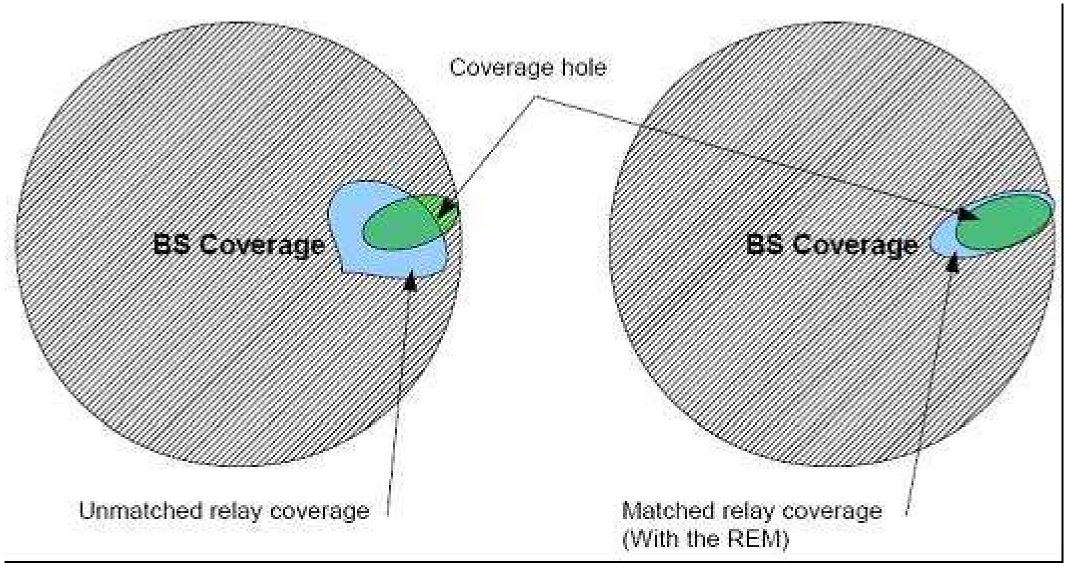
Coverage/Capacity Improvement by Relays

- Relay based solutions

REM helps…

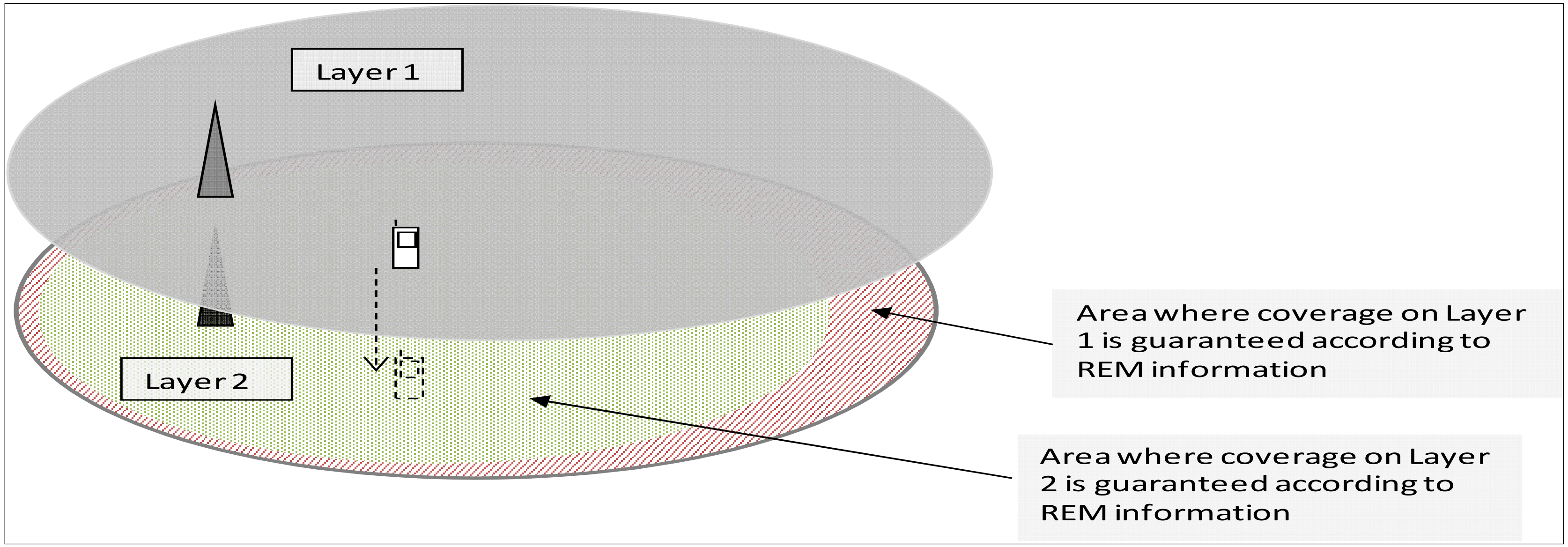
–detecting the coverage holes and traffic hotspots

–fine-tuning the relay parameters to fit the holes/hotspots



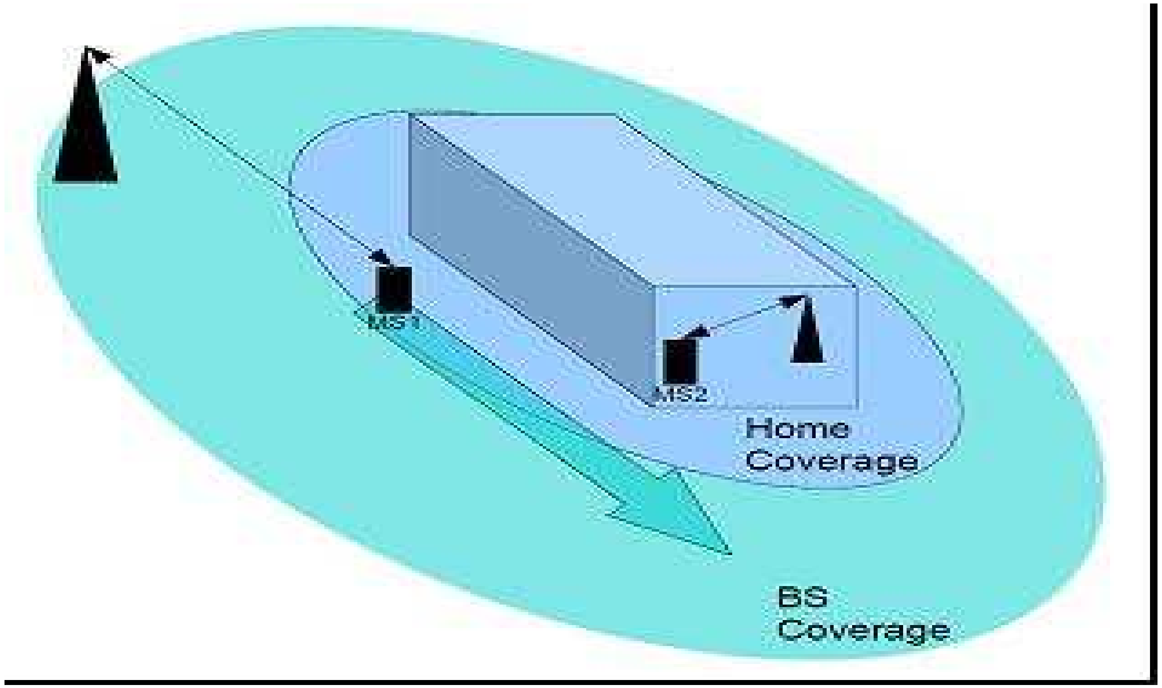
Handover Optimization 1/2

- Vertical HandOvers (VHOs)
  - REM suppresses the need for out of band sensing
  - Enables blind HO to the best inter-system neighboring cell

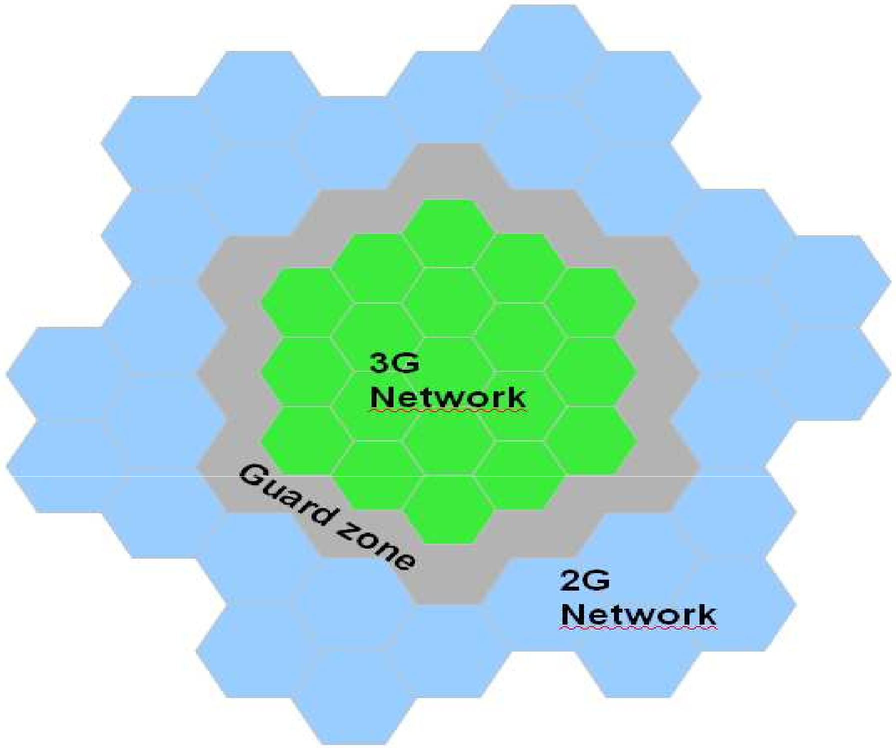


Handover Optimization 2/2

- Handover optimization between macro and femto layers
  - Minimize unnecessary handovers.



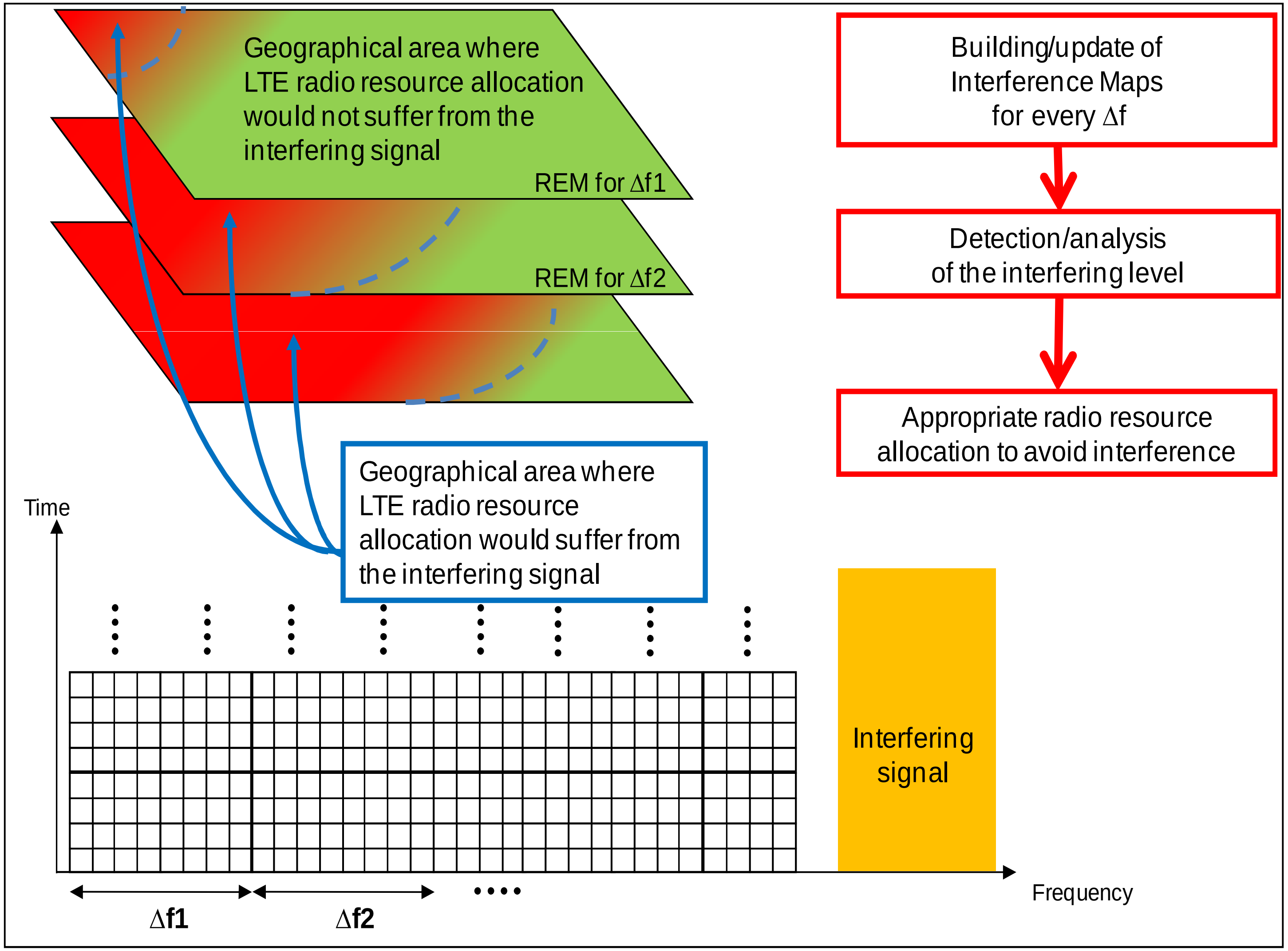
Coexistence of neighboring technologies 1/2



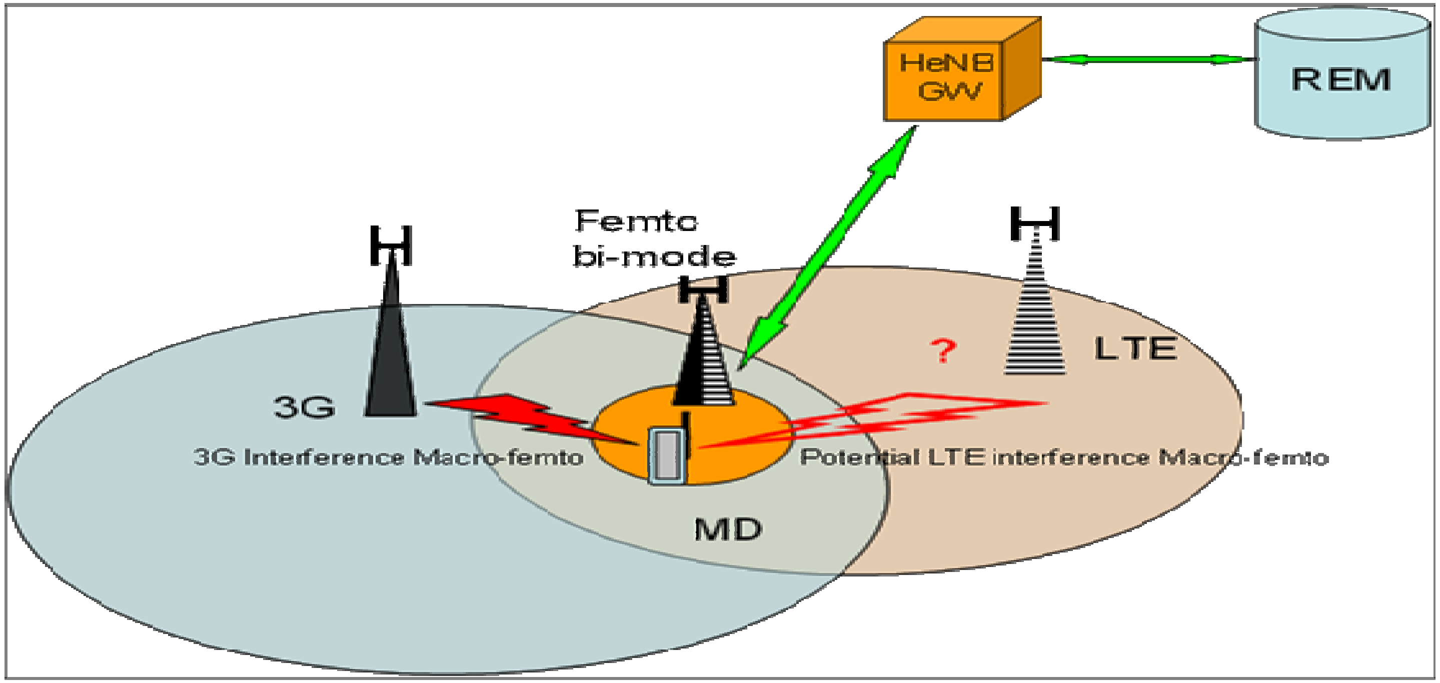
- REM facilitates co-existence planning and significantly reduces the need for margin and guard bands
  - e.g. Introduction of New Technologies through Refarming

Coexistence of neighboring technologies 2/2

- Example: LTE radio resource allocation optimization based on REM information



REM to manage femto/macro interference

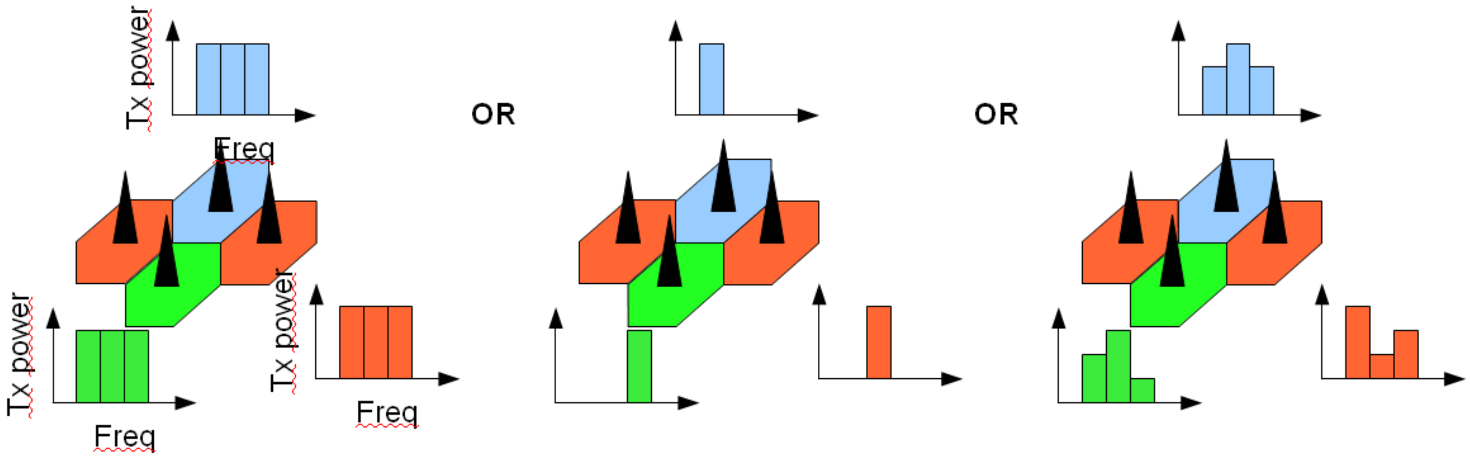


MD connected to femto on 3G mode is interfered by the 3G macro. What if the MD switches to LTE technology (on the femto)?

→REM information guarantees that the switch will not create a worst interference situation with an outdoor LTE eNB

An example use case: Soft Frequency Reuse (SFR) scheme optimization for OFDM based networks

- We consider the downlink of an OFDM based cellular network.
- REM provides the received power and traffic maps available for each BS.
- What would be the most efficient power allocation? Reuse-3, reuse-1 or something else?
- We deal with an optimization zone of 19 BSs each of which has a power mask over 3 sub-bands.



A REM-enabled SFR scheme for OFDM networks

We have developed an algorithm which derives the *expected* throughput:

- for a newly arriving user,
- at any geographical point over the area of interest
- for every power mask configuration of the involved BSs

$$\mathbb{E}(U(T_P)) = \int\int_{m\in\mathcal{T}} \sum_{n\leq n_t} \sum_{b\in\mathcal{T}} \sum_{s\leq S} \mathcal{P}_{n,b,s}^{\mathcal{T},\mathcal{B}_l,n_t}(m) U\left(\frac{t(\mathrm{SINR}(m,b,s))}{n+1}\right)$$

Link-level curve: t; Intereference map: $\mathrm{SINR}(m,b,s)$

$$\mathrm{SINR}(m,b,s) = \frac{P^{bs} L_b(m) A_b(m)}{N_0 + \sum_{b'\neq b} P^{b's} L_{b'}(m) A_{b'}(m)}$$

Power mask: P^{bs}; Pathloss: $L_b(m)$; Shadowing: $A_b(m)$

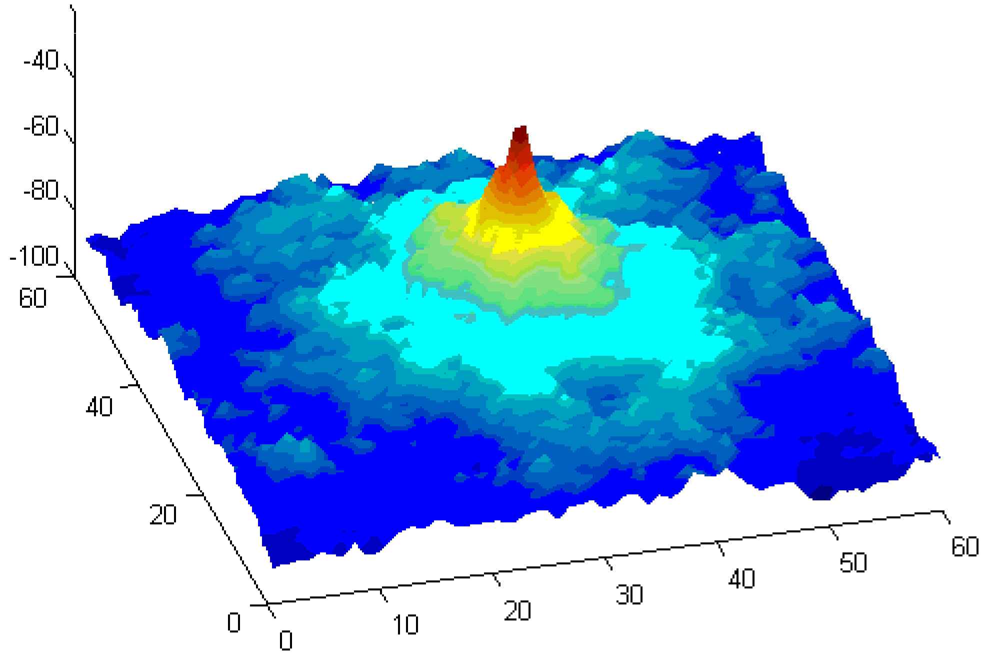
$$\begin{aligned}\mathcal{P}_{n,b,s}^{\mathcal{T},\mathcal{B}_l,n_t}(m) = & \ \mathbb{P}(N_u = n | M_u = m, B_u = b, S_u = s) \\ & \times \mathbb{P}(S_u = s | M_u = m, B_u = b) \\ & \times \mathbb{P}(B_u = b | M_u = m) \\ & \times f_{M_u | M_u\in\mathcal{T}, N_t = n_t}(m)\end{aligned}$$

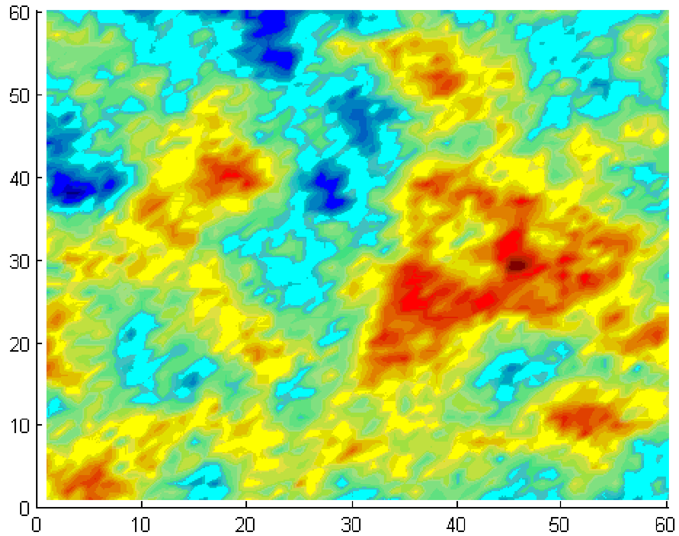
Scheduler: $\mathbb{P}(N_u = n | M_u = m, B_u = b, S_u = s) \times \mathbb{P}(S_u = s | M_u = m, B_u = b)$; Best server: $\mathbb{P}(B_u = b | M_u = m)$; Traffic map: $f_{M_u | M_u\in\mathcal{T}, N_t = n_t}(m)$

- m mobile location
- b serving BS index
- s resource block
- n number of co-channel users scheduled on the same resource block
- U(.) is a utility function (chosen according to operator policies)

A REM-enabled SFR scheme for OFDM networks
What the REM data actually looks like

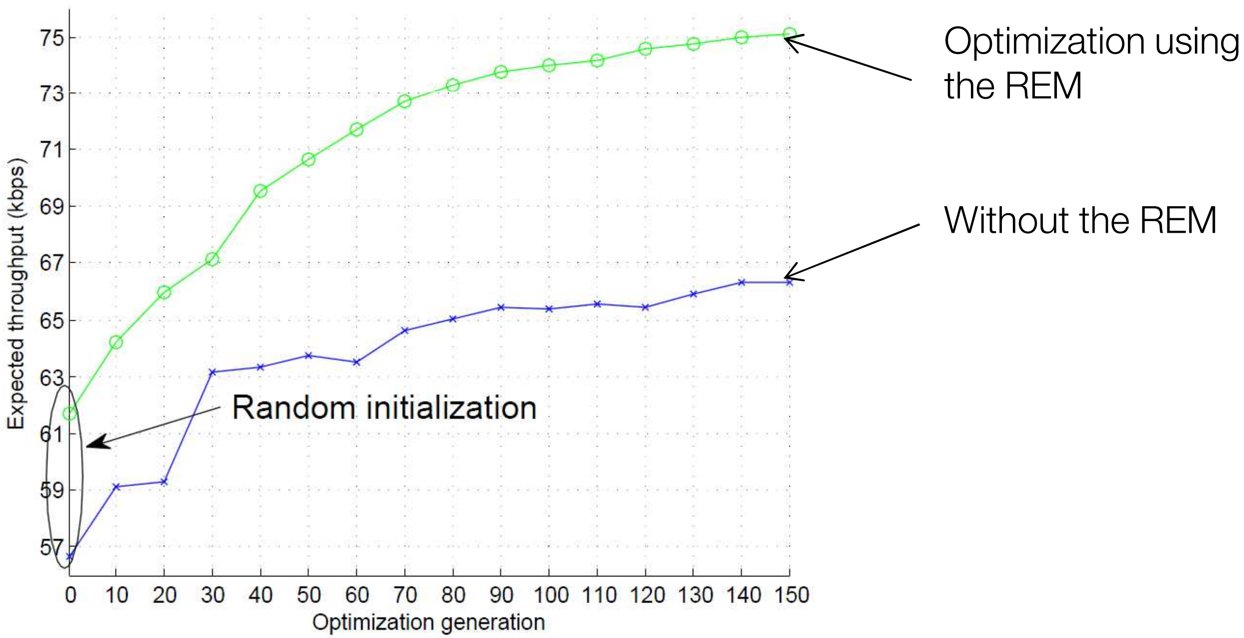
- Traffic maps are used to establish how likely a user repartition is
- Power maps are used to apply link level curves and hence derive the user throughput





A REM-enabled SFR scheme for OFDM networks

- Genetic algorithm for optimization with and without REM
- Results show that neither reuse-1 nor reuse-3 are optimal, and adding the REM gives about 13% of throughput increase



Building the REM

Building the REM – The underlying model

- Trade-off between overhead and accuracy.
- The propagation is modeled as a deterministic loss plus a correlated shadowing term.

$$\vec{\mathbf{P}} = \begin{bmatrix} P_1 \\ \vdots \\ P_N \end{bmatrix} = \mathrm{N}\left(\begin{bmatrix} 1 & -\log_{10}(d_{1,BS}) \\ \vdots & \vdots \\ 1 & -\log_{10}(d_{1,BS}) \end{bmatrix} \begin{bmatrix} P_0 \\ \alpha \end{bmatrix}, \sigma^2 R(\phi) \right)$$

D

- P_m is the received power level at position m
- P_0 is the transmit power of the BS
- α is the path-loss constant
- ϕ is the correlation distance
- σ is the shadowing standard deviation (dBm)
- R positive definite covariance matrix
- $d_{m,BS}$ is the distance between the mobile at position m and its BS

- This stochastic model can be used for capturing the pathloss + shadowing effects and for finding the propagation parameters

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Building the REM – Kriging Interpolation

- Kriging interpolation consists of finding the most likely values of the vector $\vec{\mathbf{P}}$ conditioned on the measurements

Interpolated values → $\vec{P_1}$

Measured values → $\vec{P_2}$

$$\begin{pmatrix} \vec{P_1} \\ \vec{P_2} \end{pmatrix} \equiv \mathcal{N}\left(\begin{pmatrix} D_1 \\ D_2 \end{pmatrix} \begin{pmatrix} p_0 \\ \alpha \end{pmatrix}, \sigma^2 \begin{pmatrix} R_{11}(\phi) & R_{12}(\phi) \\ R_{21}(\phi) & R_{22}(\phi) \end{pmatrix} \right)$$

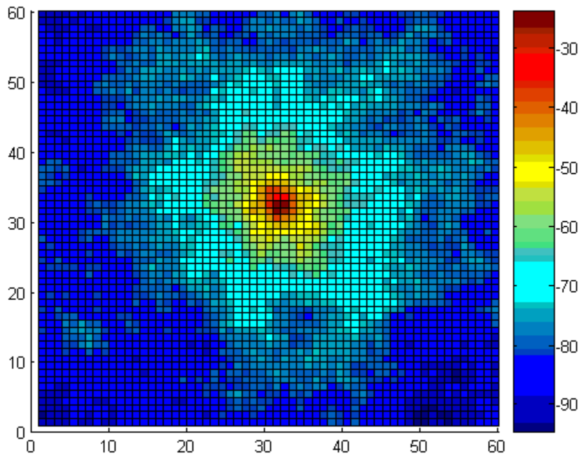
$$\overrightarrow{P_{1|2}} \equiv \mathcal{N}\left(\overrightarrow{\mu_{1|2}}, \Sigma_{1|2}\right)$$

$$\mu_{1|2} = D_1 \begin{pmatrix} p_0 \\ \alpha \end{pmatrix} + R_{12}(\phi) R_{22}(\phi)^{-1} (\vec{P_2} - D_2 \begin{pmatrix} p_0 \\ \alpha \end{pmatrix})$$

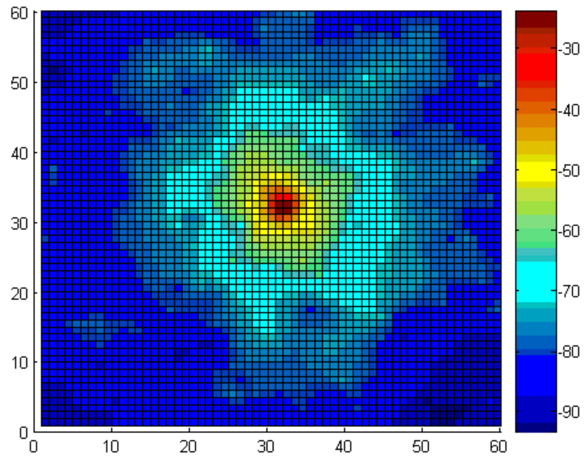
$$\Sigma_{1|2} = R_{11}(\phi) - R_{12}(\phi) R_{22}(\phi)^{-1} R_{21}(\phi)$$

- With a few measurements the Kriging method generates the whole map
- The error variance is minimized subject to unbiasedness condition
- Estimated points are expressed as a linear combination of measurement points
- Kriging computes the best linear unbiased estimator of $\vec{\mathbf{P}}_1$ based on a stochastic model of the spatial dependence quantified by the pathloss model

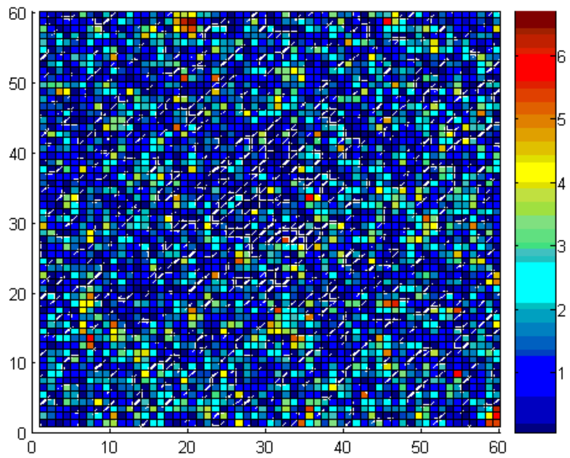
Building the REM – Maps



Simulated map



Interpolated map



Absolute error,
mean=1.29dBm

IST FP7 project Faramir on REMs

- Flexible and spectrum-Aware Radio Access through Measurements and modelling In cognitive Radio systems
- The main goal is to research and develop techniques for increasing the radio environmental and spectral awareness of future wireless systems
  - Spectrum sensing hardware efficiently integrated to handheld devices
  - Measurements performed at multiple nodes in a cooperative fashion on a network level
  - Radio Environmental Map providing basis for system optimization
- FP7 STREP with 10 partners
- FT/Orange contributions on:
  - Scenarios and use cases
  - Measurement campaigns
  - Spectrum usage models
  - Radio Environmental Maps (PhD thesis)

Standardisation on REM in ETSI RRS

- ETSI RRS Scope : Standardization activities related to Reconfigurable Radio Systems encompassing system solutions related to Software Defined Radio (SDR) and Cognitive Radio (CR).
- Active Work Item on REM:
  - TR 102 947 "Use Cases for building and exploitation of Radio Environment Maps for intra-operator scenarios"
  - The working group is led by FT
  - Supporting members: Toshiba, Telefonica, Telecom Italia, DAC-UPC, Huawei.

Conclusion

- REMs are cognitive enablers that enhance environment awareness
- Not only storing, but also processing of geo-localized measurement data
- Background processing at the O&M for troubleshooting & optimization → important tool for the operator
- Further work:
  - Construction with real data → measurement campaigns
  - Steps toward implementation → demonstration platforms
  - Architectural work → interfaces & protocols
  - Standardization → A WI @ ETSI RRS

Thank you…

Questions?