B – MODELLI DI PROPAGAZIONE

- Modelli empirico statistici per la previsione della copertura (intensità di campo) radio
  - Ambienti di propagazione, propagazione laterale e verticale. Classificazione dei modelli.
  - Principali componenti dell’attenuazione e le loro origini. Fast-fading e Shadowing.
  - Modelli generici
  - Modelli per ambiente urbano semplificati e ibridi
- Modelli deterministici per la propagazione multicammino
  - Problematiche di input output.
  - Ray Launching e Ray Tracing
  - Modelli a raggi semplificati
  - Ray tracing in dettaglio - esempi

Deterministic ray models (1/3)

"Numerical simulation of multipath propagation according to GTP"

- Ray models compute (some of the) rays linking the two terminals through free space propagation and multiple interactions with buildings. The geometry and the field of such rays must satisfy GTP rules

- Interactions, i.e. reflections, diffractions, scatterings are also called "***events***". Usually all rays experiencing up to a pre-set number of events, N_{ev} are computed

- N_{ev} also defines the so called ***prediction order***

- Ray models can be fully 3-Dimensional (3D) or can resort to simplified 2-dimensional modelling (2D)

- Ray models's output can be field (before the Rx antenna) or received signal (after the Rx antenna). In the latter case, Rx antenna parameters must be input to the model. Slow fading is predicted. Fast fading *statistics* are also predicted.

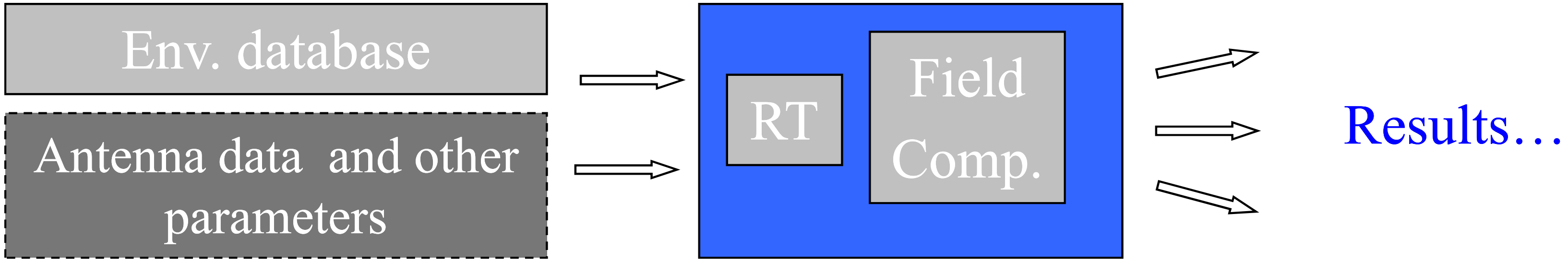
Deterministic ray models (2/3)

- Sometimes beams instead of rays are considered. Rays have a null transverse dimension. Beams (tubes of flux) have a finite transverse dimension because a space discretization is adopted. In the latter case, a limit to space resolution is set.

- Models adopting rays are usually referred to as ***Ray Tracing*** (***RT***) models. Models adopting beams are usually referred to as ***Ray*** (or ***beam***) ***Launching*** (***RL***) models

- Ray models require in input a detailed description of the environment (***environment database***)

- Usually two different computation steps can be identified: **geometrical ray tracing** and **field computation** (***back-tracking***)



Env. database

Antenna data and other parameters

RT

Field Comp.

Results…

Deterministic ray models (3/3)

Advantages over empirical-statistical models:

- ☺ Multipath simulation → multidimensional prediction

$$i^{th}\ ray: (a_i, t_i, \theta_i, \Omega_i) \;\Rightarrow\; power-delay,\ power-angle\ profiles,\ etc$$

- ☺ High accuracy
- ☺ Great versatility

Drawbacks:

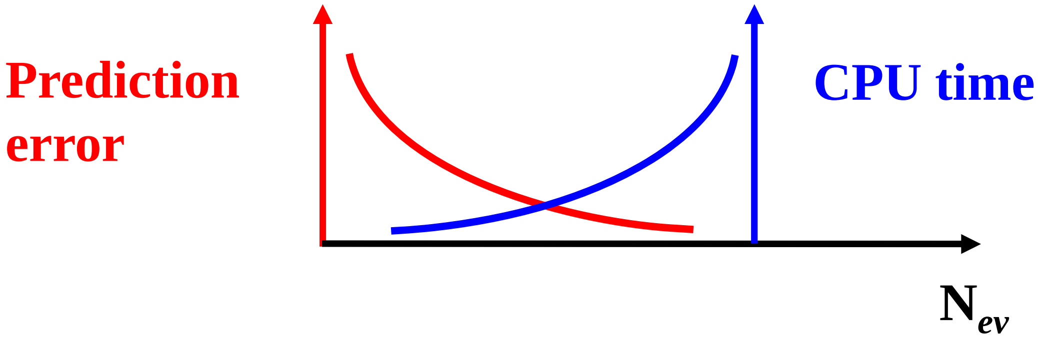
- ☹ Environment database cost (but in the future…)
- ☹ High CPU time
- ☹ Site-specific results

Performance

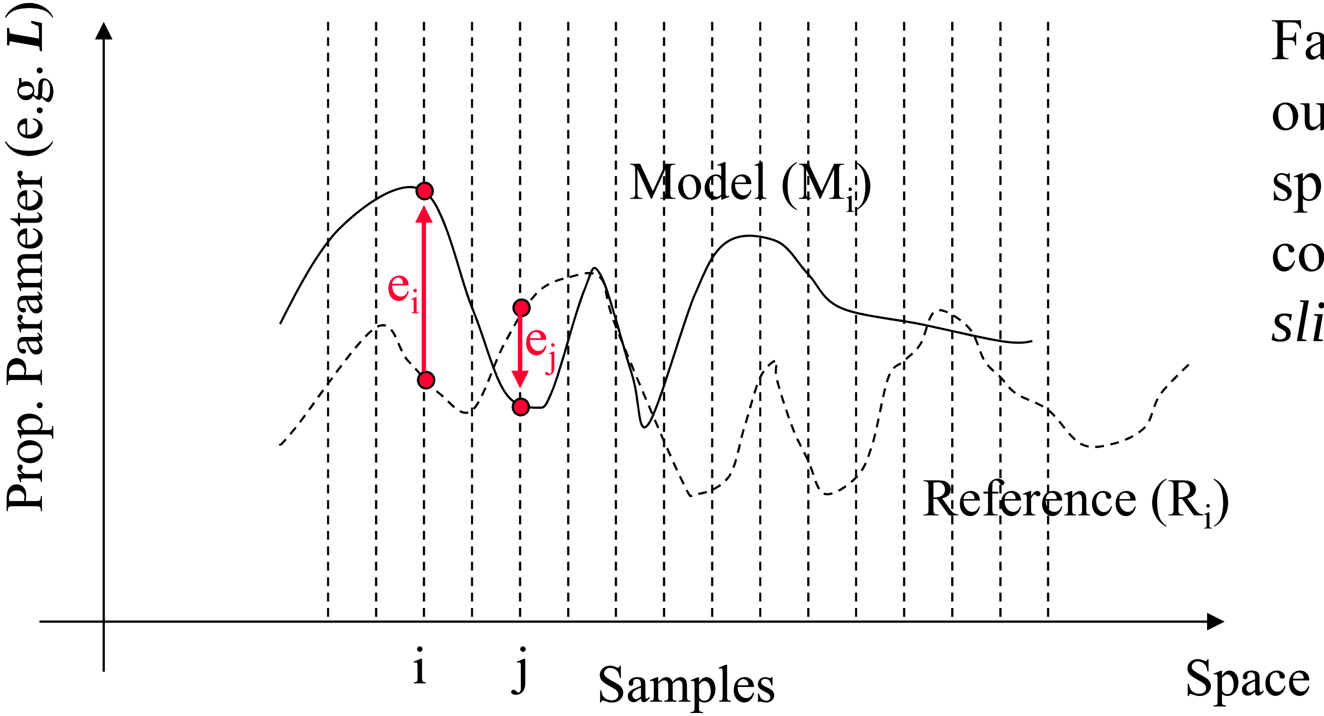
- Prediction accuracy first of all depends on the accuracy of environment database

- Prediction accuracy also depends on N_{ev} : the greater N_{ev} , the better the accuracy. Usually N_{ev} = 3-4 for outdoor, N_{ev} = 2 for indoor prediction.

- Unfortunately, CPU time grows more than linearly with N_{ev}



Performformance metrics



Fast fading must be filtered out with some sort of spatial averaging before comparison (ex. with the *sliding window method*)

Prediction error:

$$e_i = M_i - R_i$$

$$\bar{e} = \frac{1}{N} \sum_{i=1}^{N} e_i \quad \text{mean error}$$

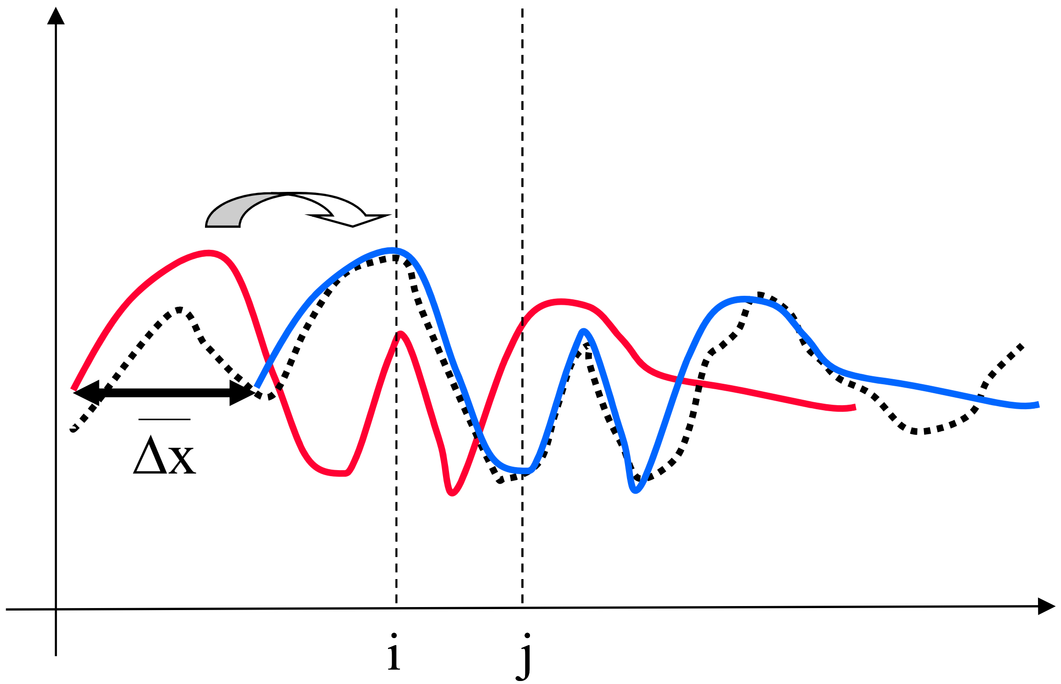
$$std(e) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (e_i - \bar{e})^2} \quad \text{st. dev. of the error}$$

Computation time (CPU time)

Comparison criteria

- If CPU time is high then the model is ***impractical***
- If mean error is high then there is a ***bias*** in the model
- If std(e) is hign, then the model is ***inaccurate***

Sometimes, however the error is high for domain **mis-alignment** between model and reference:



The following alignment should therefore be adopted for comparisons:

$$\overline{\Delta x}\ :\ \mathrm{std}\left(e,\overline{\Delta x}\right)=\underset{\Delta x}{\mathrm{Min}}\left\{\mathrm{std}\left(e,\Delta x\right)\right\}$$

$$\overline{\Delta x}\in\ \text{region of uncertainty}$$

Environment databases

- Deterministic models require detailed environment databases

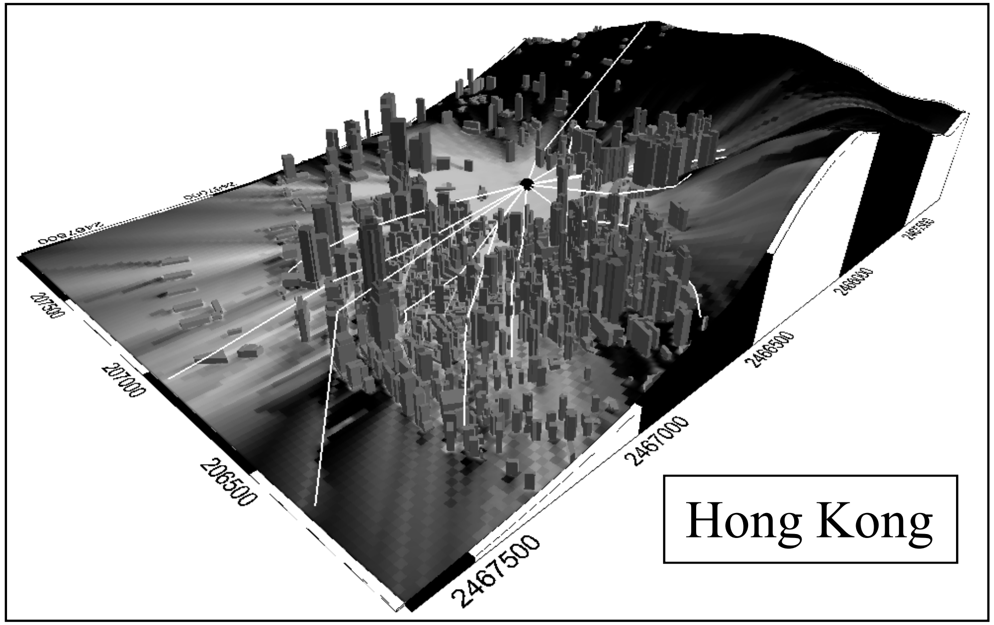
Geometric

Terrain

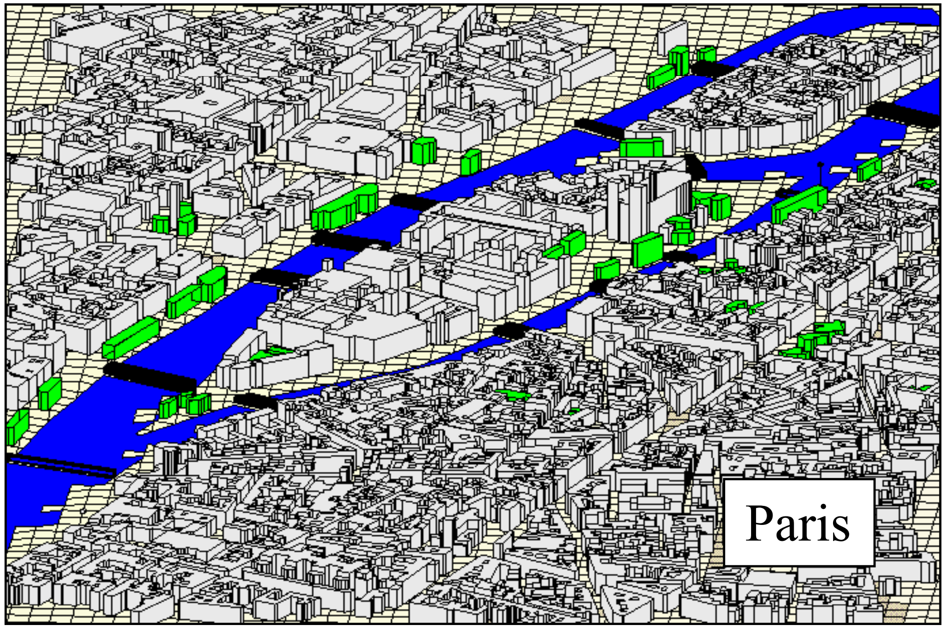
Buildings (vegetation)

Material param’s

Electro magnetic



Hong Kong



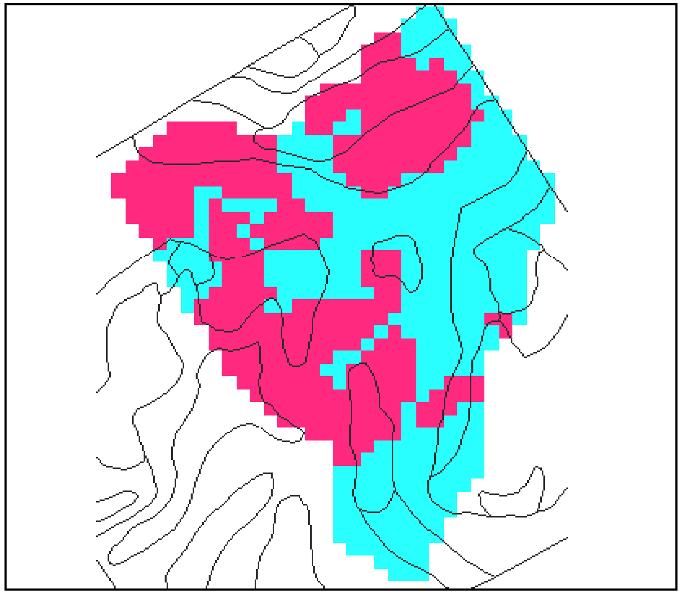
Paris

Geometric env. databases

Raster data

Each pixel associates with a value (ex. terrain height or building height)

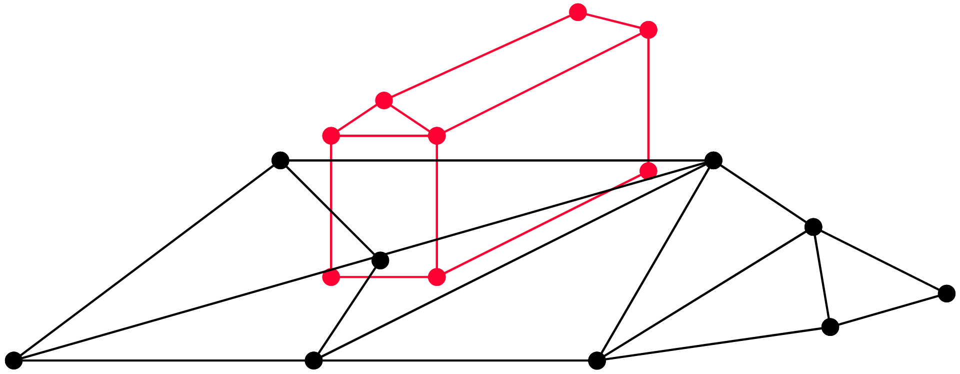
- ☹ Limited definition
- ☹ High memory occupation



Vectorial data

Building-vertexes or terrain-grid nodes are given as coordinates (vectors)

- ☺ Virtually unlimited definition
- ☺ Low memory occupation
- ☹ Requires interpretation (format)



Geometric env. database sources

Aerophotogrammetry:

Geometrical data such as building/terrain height or building shape is determined through µwave/optical sensing from an airborne sensor (camera, laser, interferometer)

Cadastre maps:

Often too detailed

Building height sometimes lacking

City maps:

Low accuracy

Building height lacking

Building/block/sidewalk ambiguity

Electromagnetic env. database

Usually the relative electric permittivity (ε_r) and conductivity (σ [S/m]) or (ε_r', ε_r'') of each env. element (terrain, building, wall, object) are given

- ☹ large variety of materials, literature data are limited [*]
- ☹ parameters often unknown, measurement is difficult and time-consuming
- ☹ how to treat compound materials?

Compound materials can be treated adopting *effective* electromagnetic parameters, i.e. those who yield similar R, T and D

$\varepsilon_r=5$; $\sigma=10^{-2}$ [S/m] often adopted for european building walls at 2 GHz

[*] A.R. von Hippel, Dielectric materials and applications, John Wiley & sons, New York, 1954.

Environment database issues

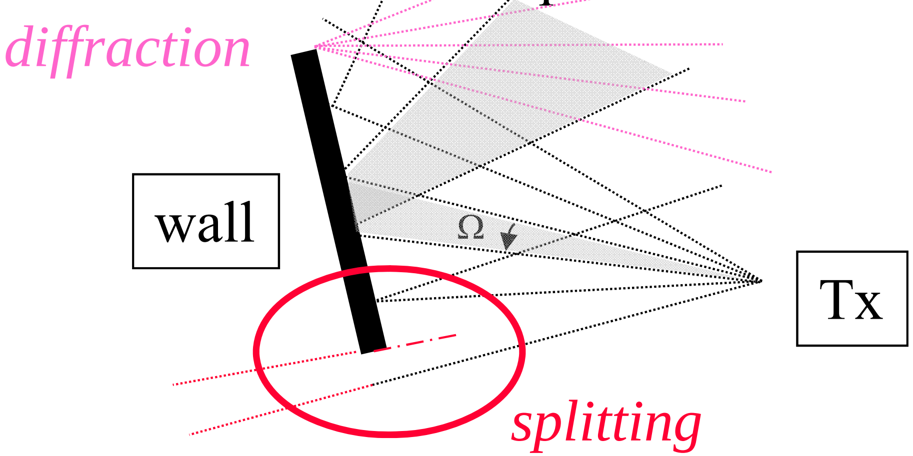
- Environment databases are expensive (hundreds of Euros / km^2)
- Environment databases are difficult to handle by non-expert personnel
- Environment databases are usually not very accurate (precision of 0.5m for horizontal coordinates and 1 to 5 m for vertical coordinates)
- Cluttering – unpredictable/variable/moving objects

⇩

☹ Main limitation to the use of deterministic models

Ray Launching (1/2)

- Given the position of the Tx, **beams** (or **tubes of flux)** are launched with a given angular step in all directions. The field is assumed constant on the cross-section of a beam → low spatial resolution
- If the algorithm is 3D then we have a solid angle.
- When a beam hits an obstacle then it is reflected/diffracted according to GTP rules. A diffracting edge is a secondary source of a new sheaf of beams
- The angular step can be decreased to compensate for low space resolution→ ***beam splitting***:
  - when a beam comes across the border of an obstacle
  - after a given distance to increase spatial resolution

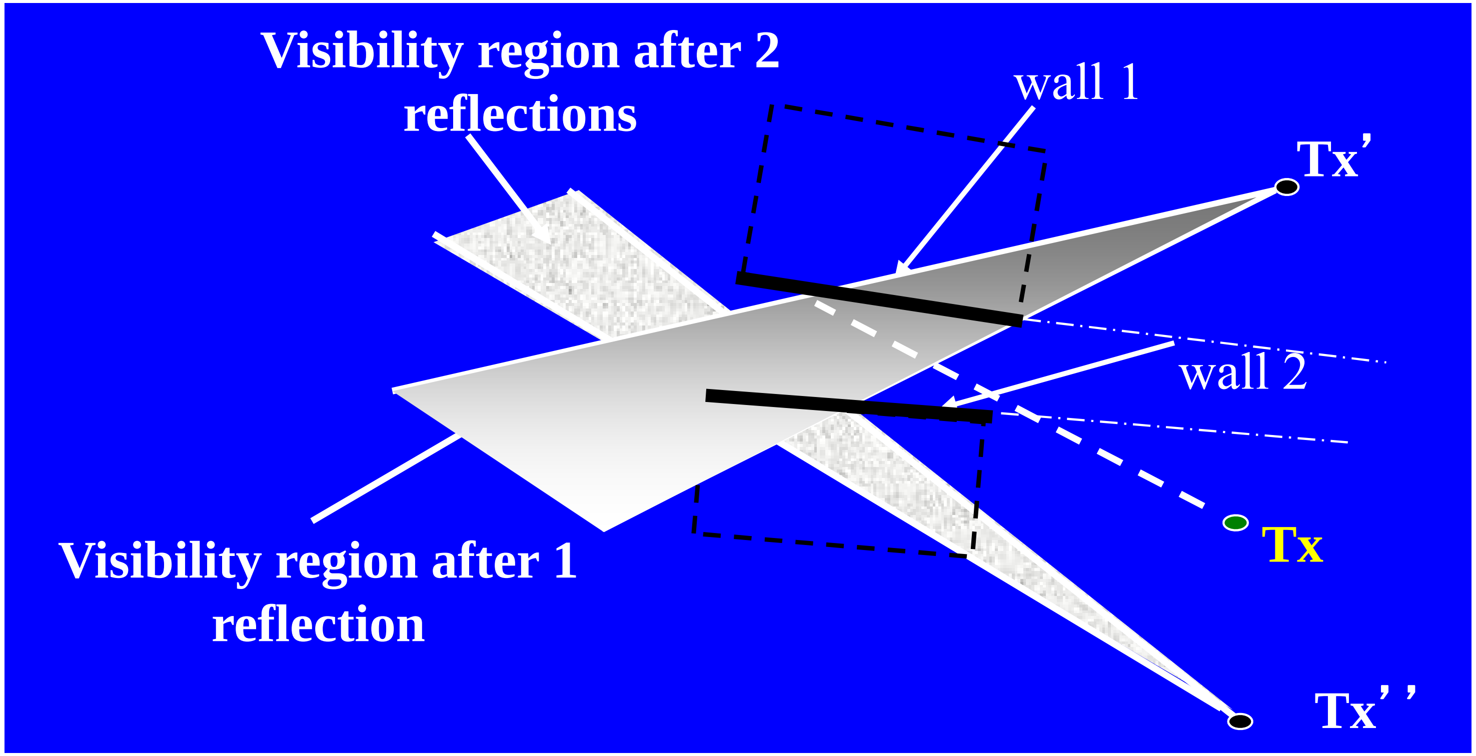


Ray Launching (2/2)

- Ray Launching is basically an area-oriented algorithm and is not suitable for accurate point-to-point propagation prediction
- The computational burden increases nearly linearly with N_{ev} and with database size
- The Ray Launching model is not very appropriate to describe such interactions as diffraction and diffuse scattering due to the complexity in generating the secondary wavefront within a beam

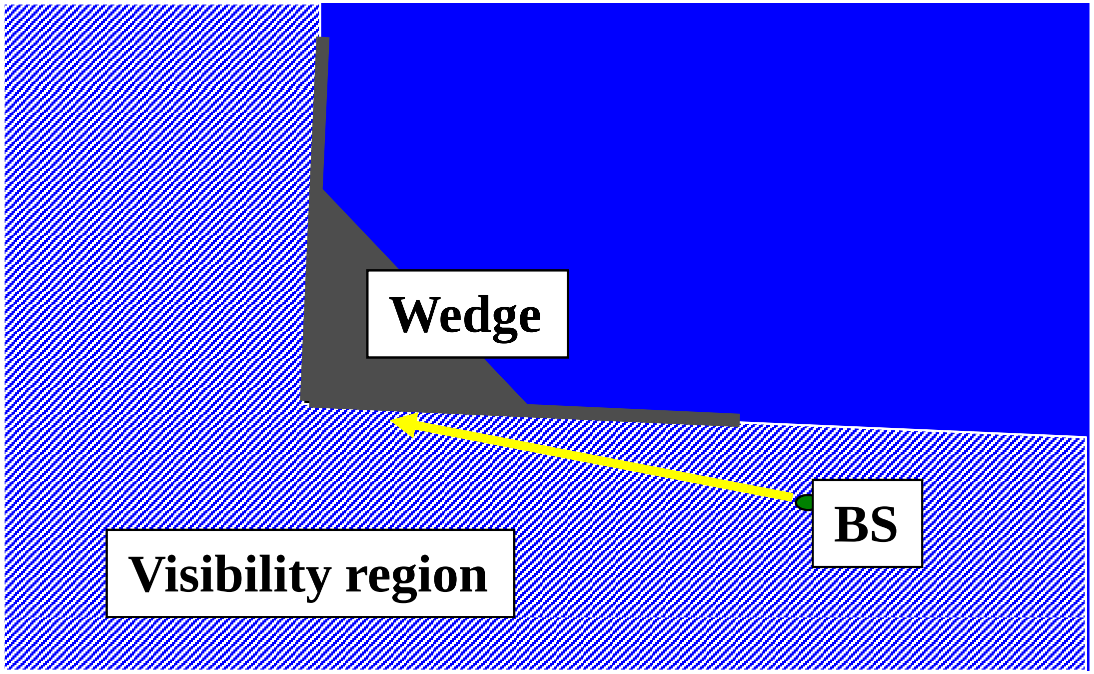
The Ray Tracing Method (1/2)

Ray tracing is based on the concept of **visibility.**
The ***visibility region*** for reflections is determined through an iterative generation of virtual images (***Virtual TX***, VTX)) of one radio terminal (es. the Tx). In the diffraction case the VTX is the edge itself.



The Ray Tracing Method (2/2)

The 2D ***visibility region*** for diffraction is the whole space external to the wedge. In 3D also the Keller's cone must be considered (…)



- The computational burden increases ~ linearly with the database size and ~ exponentially with N_{ev}

The view tree (1/5)

The ***view tree*** contains all relevant visibility information for the actual geometrical tracing of rays in a given environment.

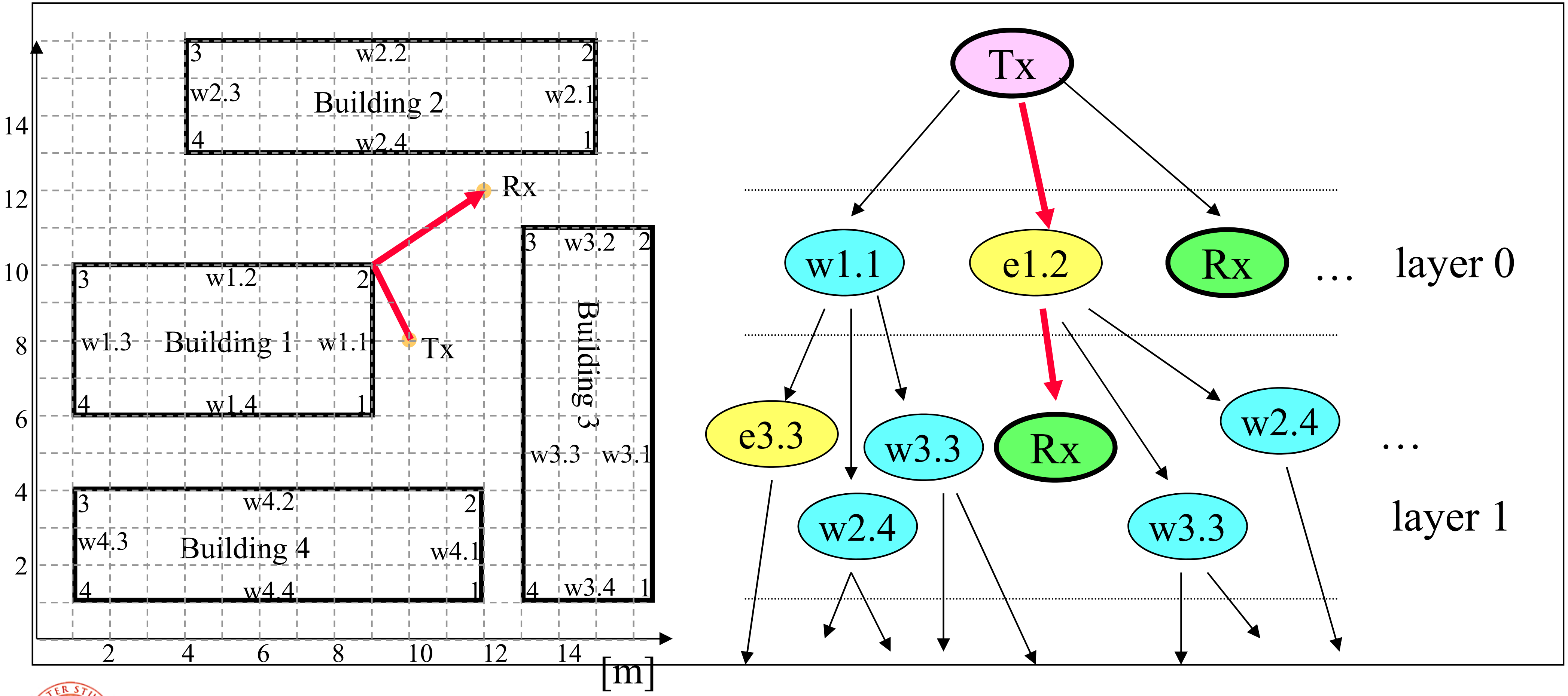
Visibility refer to the existence of a radio propagation path between two objects. Such path may also include multiple interactions. Since visibility is the fundament of ray tracing, also the view tree is so.

Visibility relations do not correspond to exact geometrical information. Therefore, after the view tree is constructed, another step is necessary for the actual computation of the actual ray geometry: **backtracking**

At the end the ray field must be computed according to GTP: **field computation**

The view tree (2/5)

- The environment is decomposed into ***objects*** (walls, edges) + radio teminals
- The view tree is fill-up starting from the Tx on the base of ***visibility relations***
- The tree is layered and the number of layers is equal to Nev+1 (root included)
- The Tx is the root, objects are nodes, interactions are branches, the Rx leaves



The view tree (3/5)

- Nodes correspond to objects or portions of them
- View tree computation is by far the most time-comsuming part of ray tracing

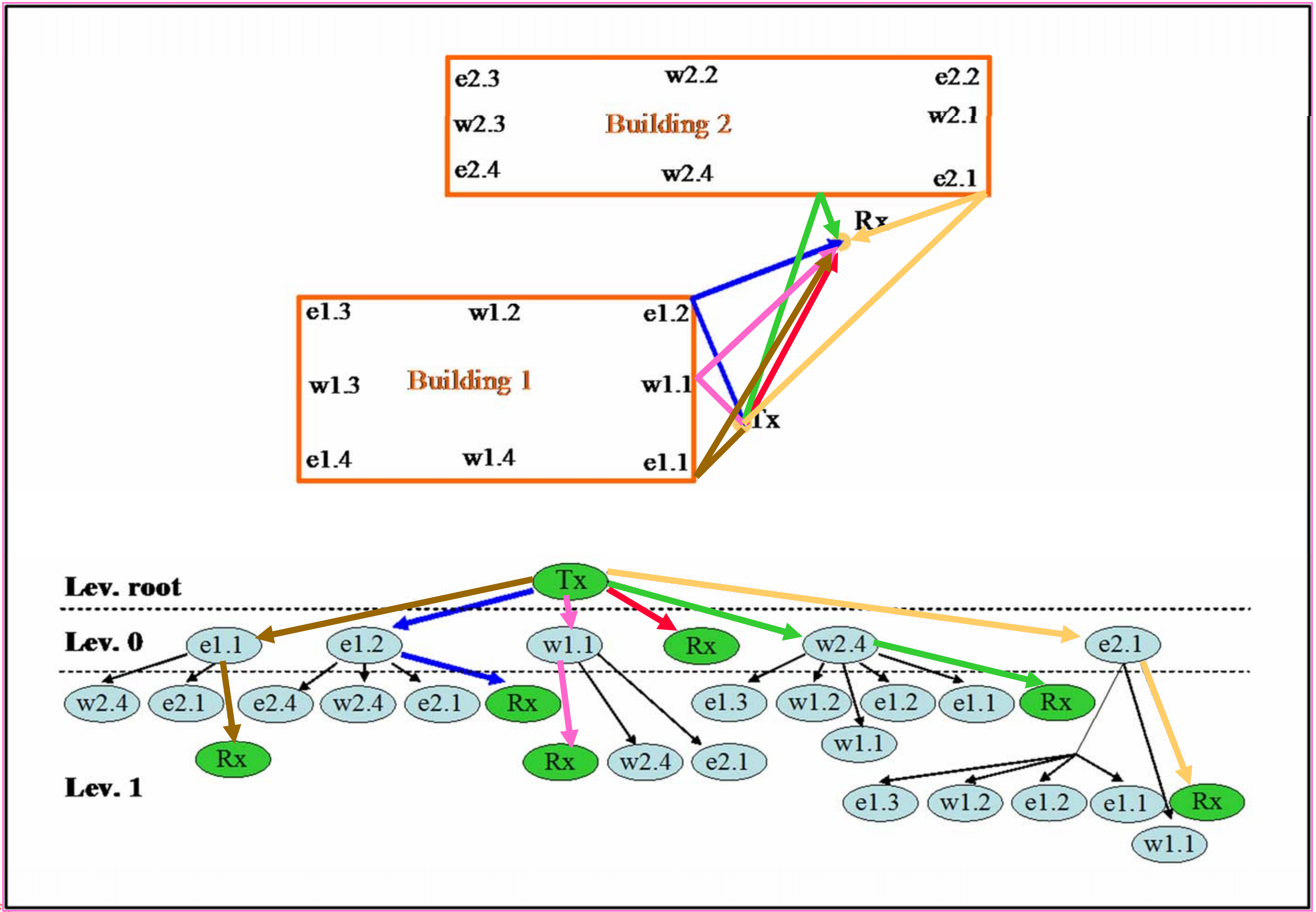
If N_v is the average number of objects viewed from a previous one then it can be shown that the view tree is composed of M objects with

$$\boxed{M \approx N_V^{(N_{ev}+1)}}$$

For example if $N_v=10$ and $N_{ev}=3 \rightarrow M=10^4$ This figure is of course proportional to the computation time involved in creating the view tree.

Each time a new object is added to the tree, then the whole environment must be scanned for visibility. It is therefore important to identify ‘smart’ scanning strategies.

Example: view tree computation



The BackTracking Procedure (1)

☹ diffraction points on edges in 3D can only be exactly determined after visibility is defined (when a Rx is reached)

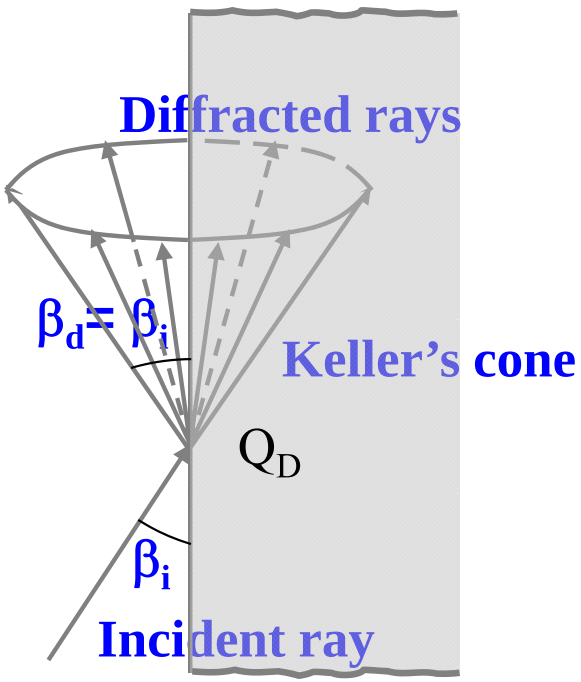
☹ If the considered ray undergoes diffractions, then also reflection points can only be determined after visibility.

↓

If is then necessary to exactly determine the cited interaction points starting from the Rx and backtracking the ray until the Tx is reached. (***backtracking***)

☺ Tx and Rx positions are fixed points

The BackTracking Procedure (2)

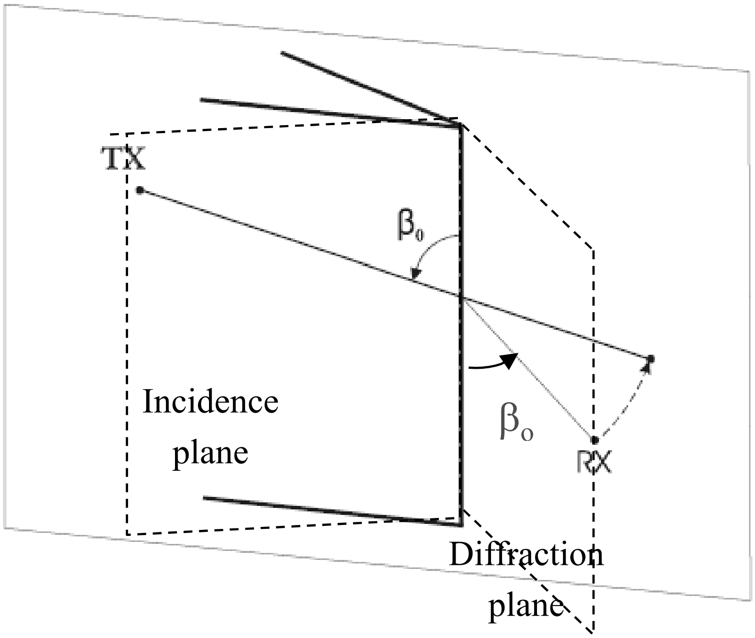


Diffracted rays must satisfy:

$$\boxed{\beta_i = \beta_d} \qquad (1)$$

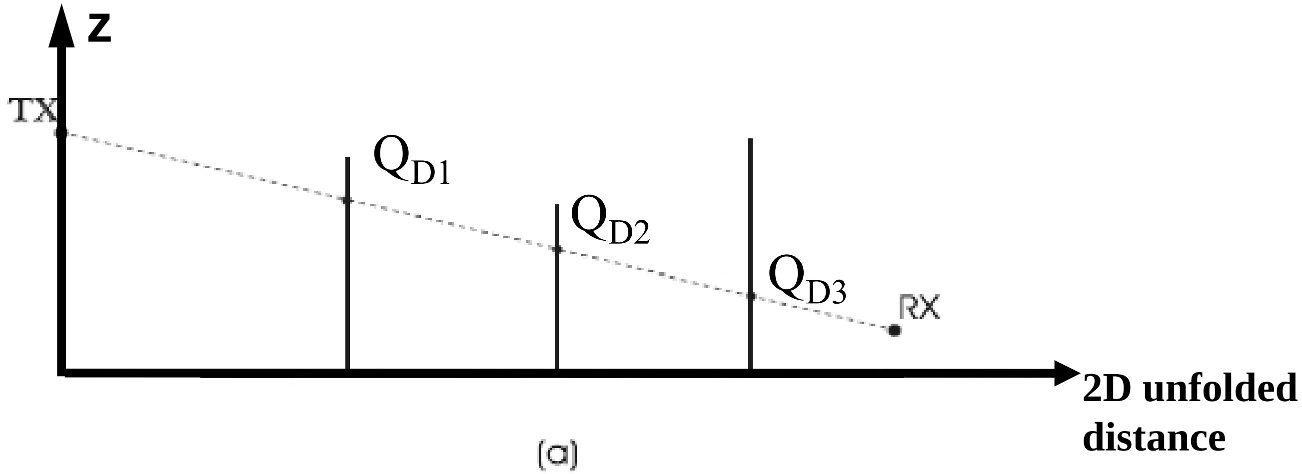
The position of Q_D must be determined in order to satisfy (1)

For vertical edges Q_D can be determined by "unfolding" the ray: the incidence and the diffraction plane are unfolded on one single vertical plane



The BackTracking Procedure (3)

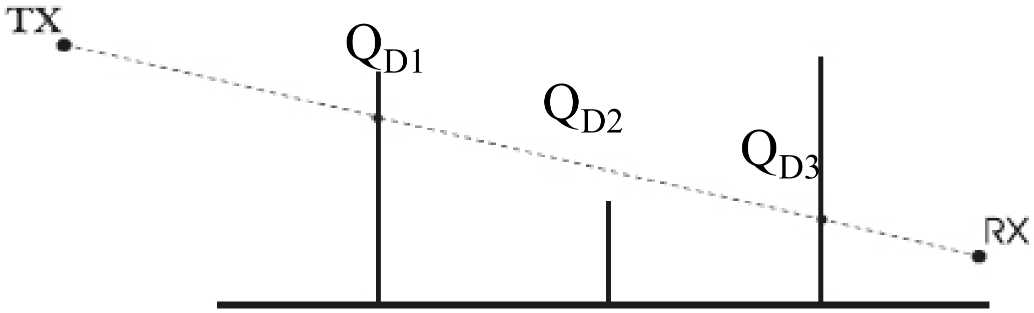
- Once the (multi-)diffracted ray is unfolded then is represented on a graph as a straigh line, also with the diffracting edges and the fixed Tx and Rx



- Then the ray is traced by connecting Tx and Rx and the diffraction points are determined

The BackTracking Procedure (4)

- If during backtracking one diffraction point is found to fall out of the edge then the ray cannot exist, and is therefore discarded



(b)

- Finally, once the diffraction points have been determined also the VTX reflection positions are corrected and thus exact reflection points are determined and non-existent rays dropped as above

The field computation (1)

- Once all interaction points have been determined then ray field can be computed.
- The far field emitted in the generic point P(r,θ,ϕ) by the Tx antenna in free space (no interactions) can be computed through the input signal (not only power) as:

$$\vec{E}_T(r,\theta_T,\phi_T) = I_T \cdot \sqrt{\frac{Z_T \cdot \eta \cdot g_T(\theta_T,\phi_T)}{16\pi}} \cdot \frac{e^{-j\beta r}}{r} \cdot \hat{p}_T(\theta_T,\phi_T) = \vec{E}_{T0}(\theta_T,\phi_T) \cdot \frac{e^{-j\beta r}}{r} \qquad (2)$$

where Z_T is the impedance of the antenna, I_T is the current phasor feeding the antenna, g_T the antenna gain function, η is the intrinsic impedance of the medium, β=2π/λ is the wave number and $\hat{p}_T$ is the antenna polarization vector.

- Formula (2) is valid in case of perfect impedance matching between the antenna and the Tx circuitry and corresponds to the well known expression:

$$\vec{E}_T(r,\theta_T,\phi_T) = \left\| \vec{E}_T(r,\theta_T,\phi_T) \right\| e^{-j\beta r} \hat{p}_T(\theta_T,\phi_T) =$$

$$= \sqrt{\frac{\eta \cdot g_T(\theta_T,\phi_T) P_T}{2\pi}} \cdot \frac{e^{-j\beta r}}{r} \cdot \hat{p}_T(\theta_T,\phi_T) \quad \text{with} \quad P_T = \frac{Z_T I_T^2}{8}$$

The field computation (2)

Considering also interactions, the k-th ray field becomes:

$$\vec{E}_T^k = A_k\left(s_\ell^k, \ell = 0,1,2,\ldots,N_{EV}^k\right)\cdot\left[\prod_{\ell=\min\left\{1,N_{EV}^k\right\}}^{N_{EV}^k}\underline{\underline{C}}_\ell\right]\cdot\vec{E}_{T0}^k\left(\theta_T^k,\phi_T^k\right)e^{-j\beta s^k} \qquad (**)$$

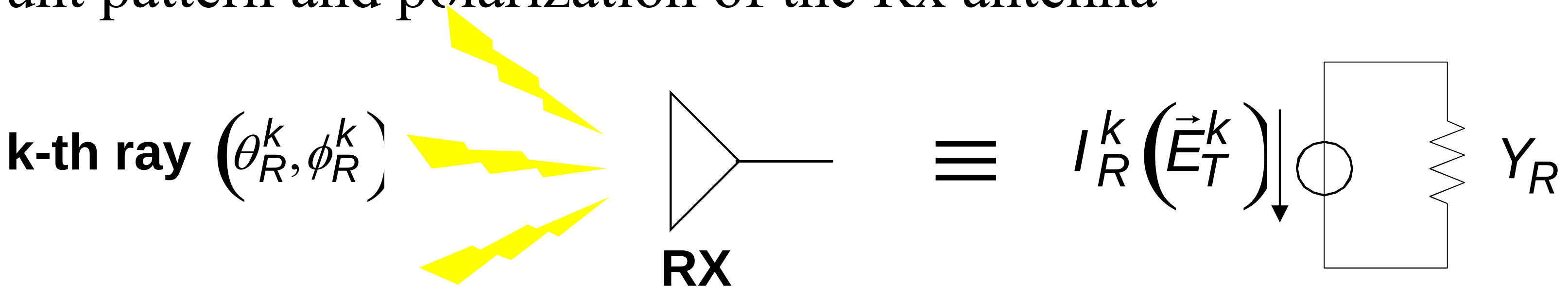
$$\vec{E}_T = \sum_{k=0}^{N_R}\vec{E}_T^k$$

where:

- N_{EV}^k is the number of interactions experienced by the k-th ray
- s_ℓ^k is the length of the ℓ-th segment composing the k-th path
- $s^k = \sum_{\ell=0}^{N_{EV}^k} s_\ell^k$ is the total, unfolded length of the k-th ray
- $\underline{\underline{C}}_\ell$ is an appropriate interaction dyadic to properly decompose the field into orthogonal polarizations at the ℓ-th interaction point, and includes the interaction coefficients
- A_k is the <u>overall</u> *divergence factor*

The Received signal

- Once the field for each ray has been computed it is necessary to take into account pattern and polarization of the Rx antenna



Equivalent circuit of the RX antenna

- The current phasor induced in the RX antenna by the k-th ray can be computed as (Reciprocity Theorem):

$$\boxed{I_R^k = -j\lambda\sqrt{\frac{\Re e\left(Y_R\right) g_R\left(\theta_R^k,\phi_R^k\right)}{\pi\eta}}\left\{\hat{p}_R\left(\theta_R^k,\phi_R^k\right)\cdot\vec{E}_T^k\right\};\quad I_R=\sum_{k=0}^{N_R} I_R^k}$$

where $Y_R = 1/Z_R$ and the subscript "R" refers to the Rx antenna. $\left(\theta_R^k,\phi_R^k\right)$ are the arrival angles of the considered ray in the Rx-based local coordinate system.

The Received power (1)

- If there is perfect impedance matching between the Rx antenna and the Rx circuitry then received power becomes:

$$P_R = \frac{\left|I_R^{TOT}\right|^2}{8 \cdot \Re e\left(Y_R\right)}$$

- Therefore, the <u>total power</u> can be expressed as:

$$\boxed{P_R = \frac{\left|I_R^{tot}\right|^2}{8 \cdot \Re e\left(Y_R\right)} = \frac{\left|\sum_{k=1}^{N_r} I_R^k\right|^2}{8 \cdot \Re e\left(Y_R\right)} = \frac{\left|\sum_{k=1}^{N_r}\left(-j\lambda\sqrt{\frac{\Re e\left(Y_R\right) g_R\left(\theta_R^k,\phi_R^k\right)}{\pi\eta}}\left\{\hat{p}_R\left(\theta_R^k,\phi_R^k\right)\cdot\vec{E}_T^k\right\}\right)\right|^2}{8 \cdot \Re e\left(Y_R\right)}}$$

where g_R and $\hat{p}_R$ are the antenna gain and the polarization vector of the RX antenna evaluated in the arrival direction of each incoming ray.

The Received power (2)

Developing the above expression, and simplifying the RX antenna admittance, we obtain:

$$P_R = \frac{\lambda^2}{8\pi\eta} \cdot \left| \sum_{k=1}^{N_R} \left(\sqrt{g_R\left(\theta_R^k, \phi_R^k\right)} \cdot \left\{ \hat{p}_R\left(\theta_R^k, \phi_R^k\right) \cdot \vec{E}_T^k \right\} \right) \right|^2 \quad (1)$$

assuming <u>perfect polarization matching between the incident field and the RX antenna</u> eq. (1) becomes:

$$P_R = \frac{1}{2\eta} \cdot \left| \sum_{k=1}^{N_R} \left(\sqrt{g_R\left(\theta_R^k, \phi_R^k\right)} \cdot \vec{E}_T^k \right) \right|^2 \cdot \frac{\lambda^2}{4\pi} \quad (2)$$

If only the direct path exists, the eq. 1 reduces to the Friis equation:

$$P_R = \frac{\left|\vec{E}_T\right|^2}{2\eta} \cdot \underbrace{\frac{\lambda^2}{4\pi} g_R\left(\theta_R, \phi_R\right)}_{A_R^{eff}} = P_T g_T\left(\theta_T, \vartheta_T\right) g_R\left(\theta_R, \vartheta_R\right) \left(\frac{\lambda}{4\pi r} \right)^2$$

Multidimensional prediction

Instead of summing up, the different ray contributions can be recorded with their delays and angles of departure/arrival to get a multidimensional prediction.
For the k-th ray we have:

$I_R^k = \rho^k e^{j\vartheta^k}$ signal (current, amplitude and phase)

s^k total unfolded length

$t^k = s^k / c$ propagation delay

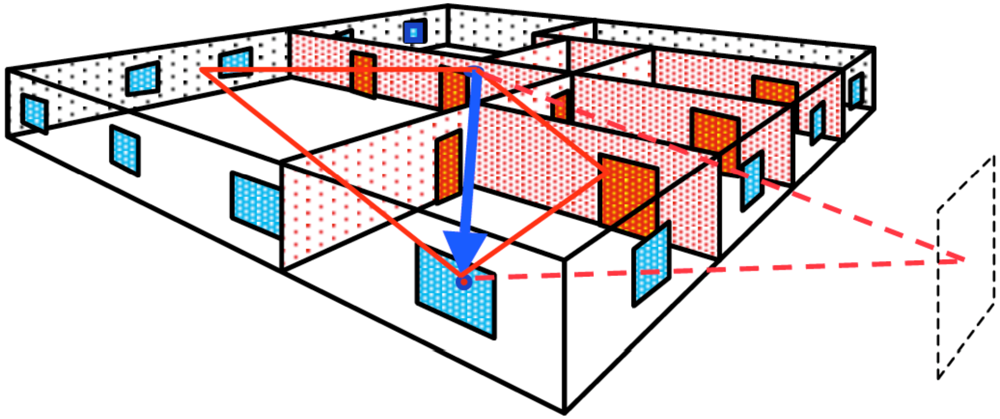
$\chi^k \equiv \left(\theta_T^k, \phi_T^k\right)$ angles of departure

$\psi^k \equiv \left(\theta_R^k, \phi_R^k\right)$ angles of arrival

Therefore, cosidering all rays ($k=1,N_r$) we know that the signal modulated over the carrier will be spread at the receiver in time and space according to the above-mentioned parameters.
Time and space (angle) spreading is a very important characteristic of a given radio channel (see further ahead)

Indoor Ray Tracing (1/2)

- A ***3D approach*** is required
- A multitude of rays is present but the radial, transmitted ray is almost always dominant → it is necessary to consider ***multiple transmission***
- A detailed 3D plan of the building is required. Autocad® DXF is the most used format
- ***Furniture*** can have a great impact on propagation, but it’s not reported in building plans → diffuse scattering is important
- ***Outdoor paths*** can be relevant



Indoor Ray Tracing (2/2)

- Since there is a dominant multi-transmitted ray, if only coverage is required, ray tracing is not worth it in indoors. The MWM model gives similar results with a negligible CPU time [*]

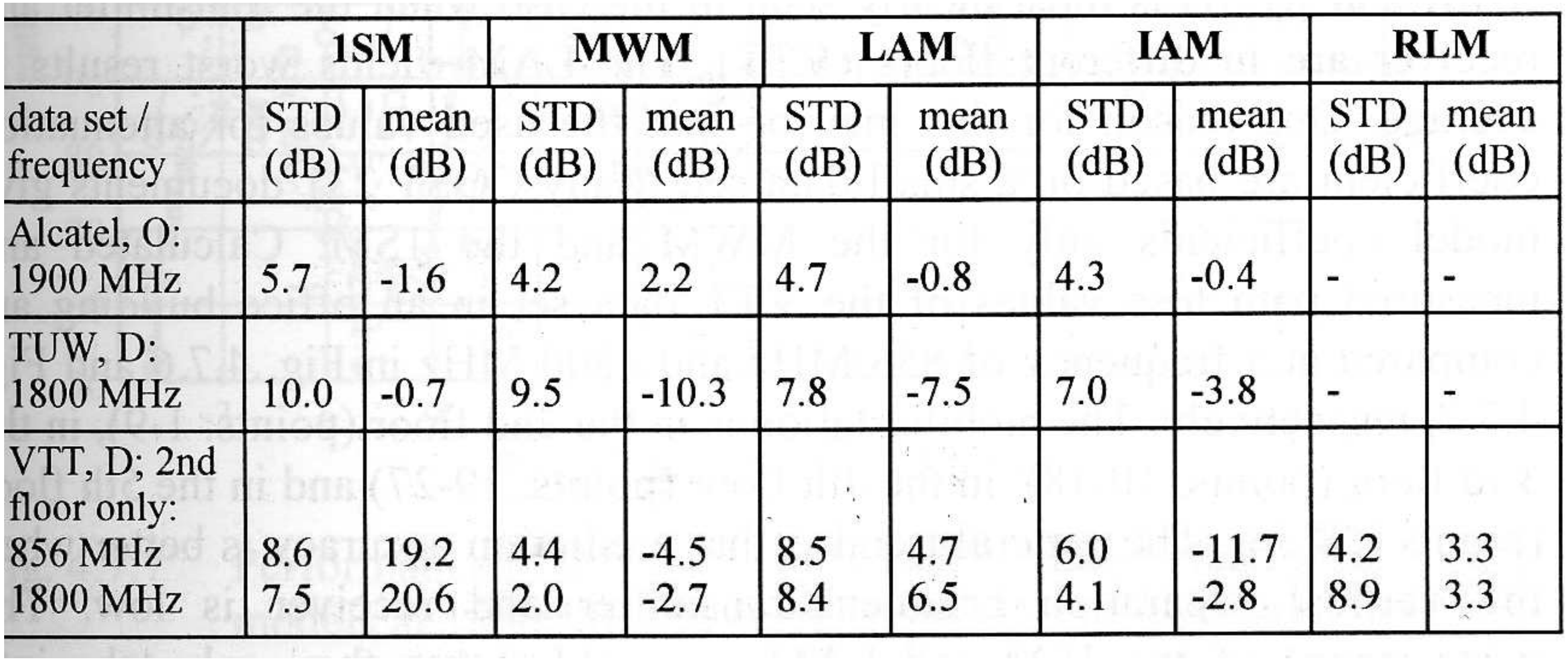
1 Slope Model

Multi Wall Model

Linear Attenuation Model

Ray Tracing Model

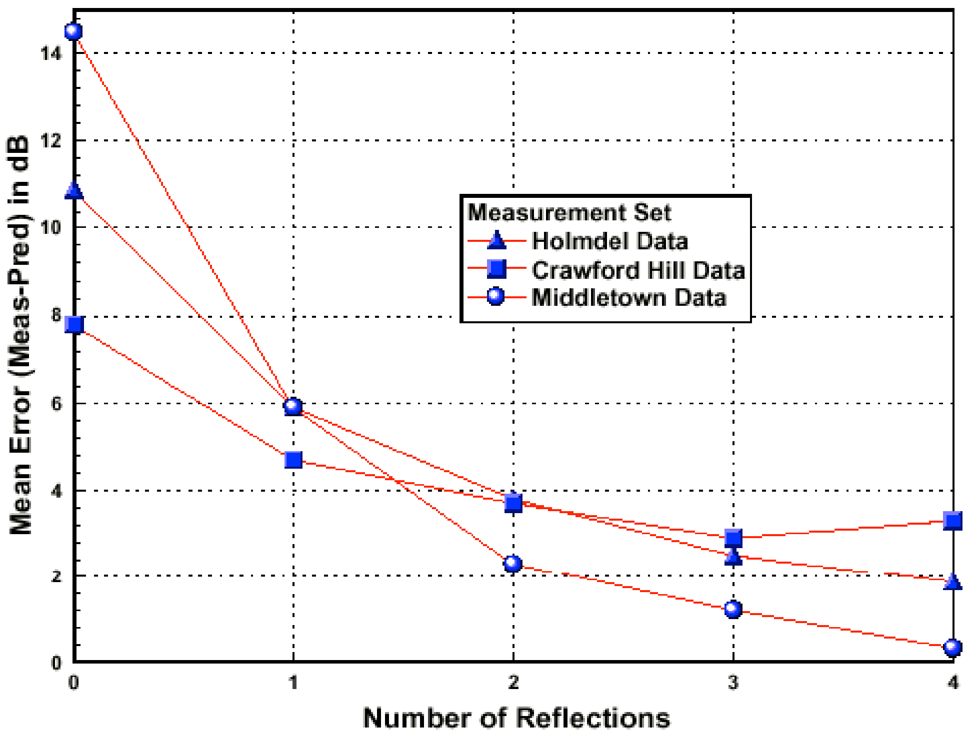
Ray Launching Model

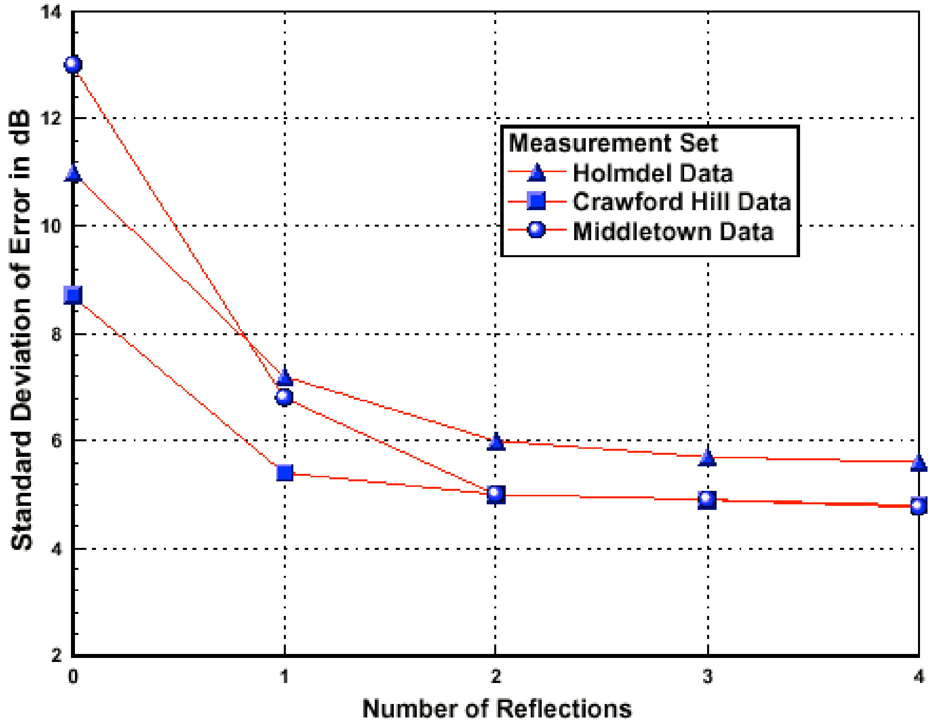


	1SM		MWM		LAM		IAM		RLM	
data set / frequency	STD (dB)	mean (dB)	STD (dB)	mean (dB)	STD (dB)	mean (dB)	STD (dB)	mean (dB)	STD (dB)	mean (dB)
Alcatel, O: 1900 MHz	5.7	-1.6	4.2	2.2	4.7	-0.8	4.3	-0.4	-	-
TUW, D: 1800 MHz	10.0	-0.7	9.5	-10.3	7.8	-7.5	7.0	-3.8	-	-
VTT, D; 2nd floor only: 856 MHz 1800 MHz	8.6 7.5	19.2 20.6	4.4 2.0	-4.5 -2.7	8.5 8.4	4.7 6.5	6.0 4.1	-11.7 -2.8	4.2 8.9	3.3 3.3

[*] COST Action 231 “Digital mobile radio towards future generation systems” Final Report, 1999

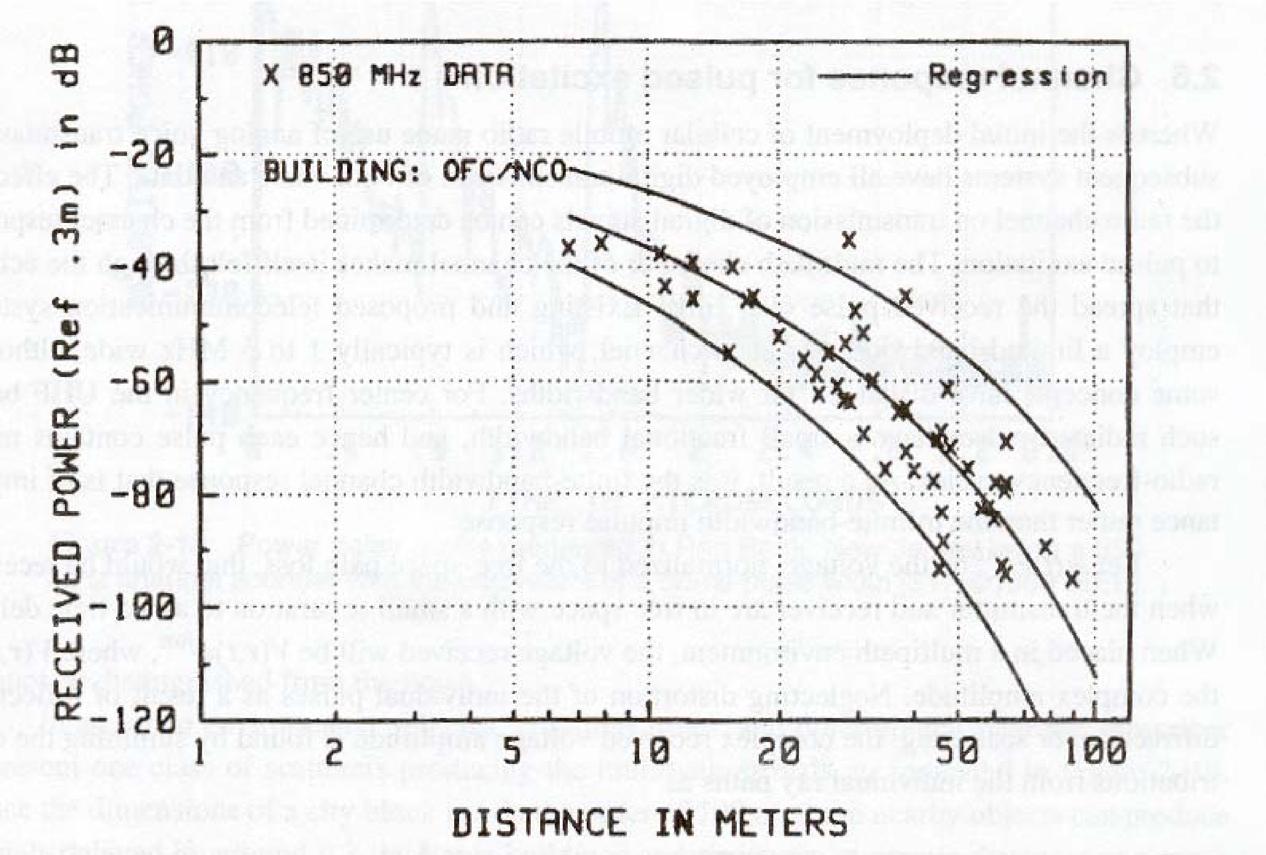
Influence of the Number of Reflections on Prediction Accuracy





(Source: Valenzuela, et al., IEEE VTC'98, p. 539)

Distance Dependence of Received Power (Measured at 850 MHz)



Excess Loss

at 100 w.r.t. 10 m is

~ 50 dB

so that

$$\alpha_S = \frac{50}{90} = 0.55 \text{ dB/m}$$

because:

$$L_{TOT} = 20 Log\left(R / R_o \right) + \alpha_S \left(R - R_o \right)$$

$$= 20 + \alpha_S \cdot 90 = 70 dB$$

$$\Rightarrow \alpha_S = 50/90 = 0.55 \text{ dB/m}$$

(Source: Devasiravatham, et al., Proc. IEEE ICC’90, p. 1334)

Simplified ray models

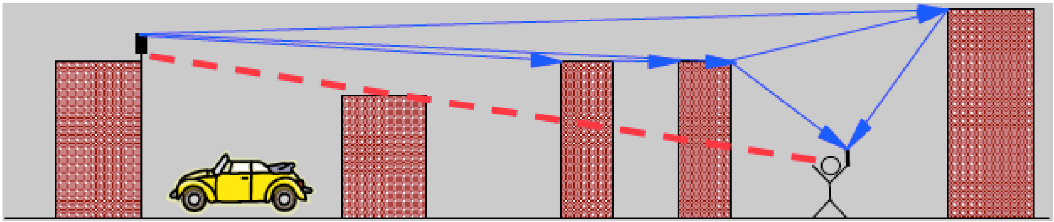
- “Simplified ray models” conceptually derive from deterministic ray models. However, the geometry of the multipath pattern is somehow simplified to ease the computational burden while still taking major rays into account

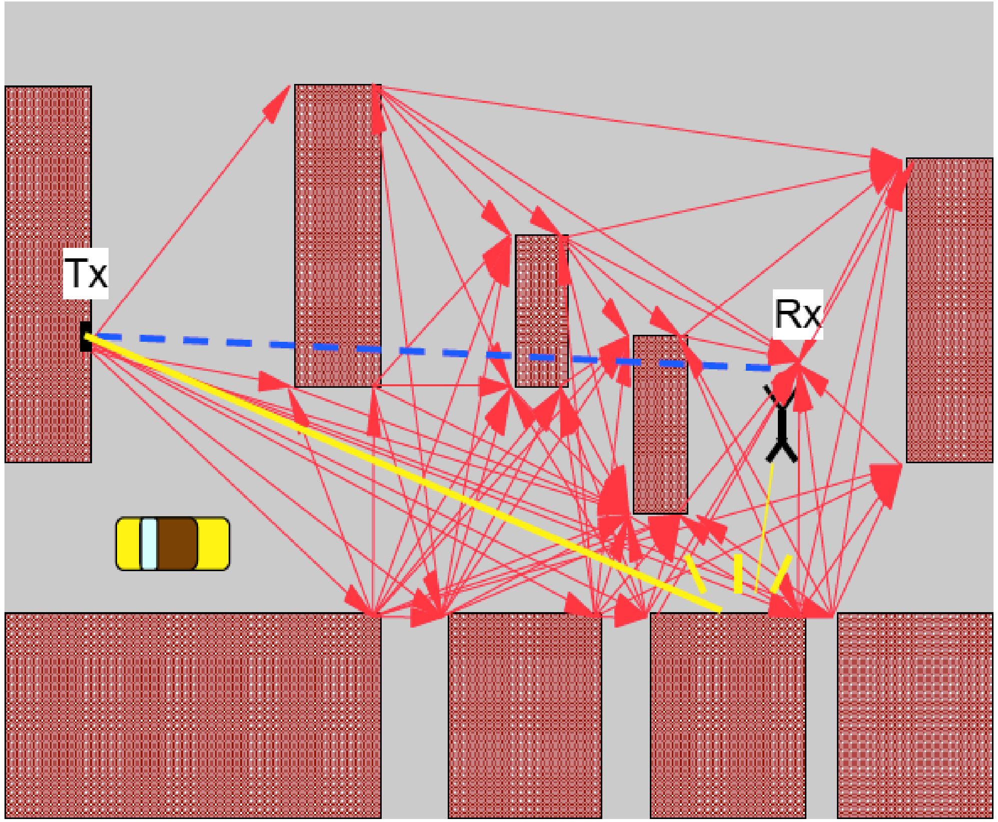
- Usually, the problem is simplified by identifying planes where most rays lie, thus resorting to a 2-dimensional (2D) approach. Such simplifications however are not rigorous since multipath propagation in urban environment is intrinsically 3D

- Of course 2D computation is much simpler and faster than 3D computation

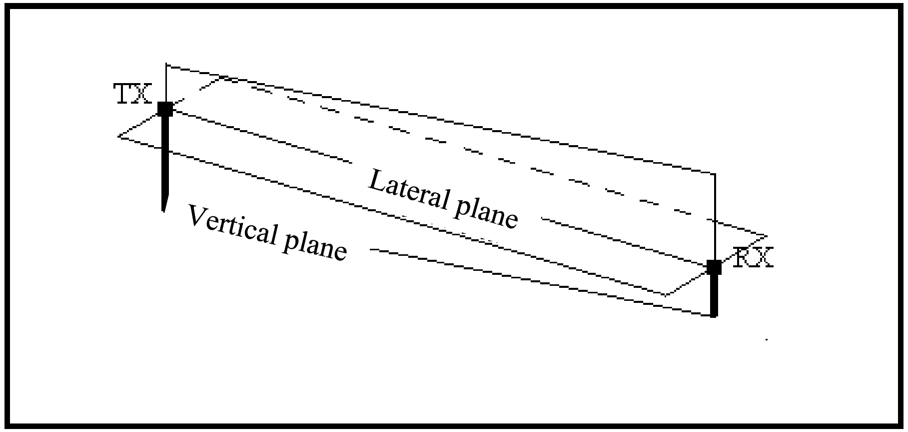
- 2 different approaches can be identified: ***2D+2D*** (lateral plane+vertical plane ray tracing) and ***quasi-3D*** (Vertical Plane Launch, VPL ray tracing)

2D+2D ray models (1/2)



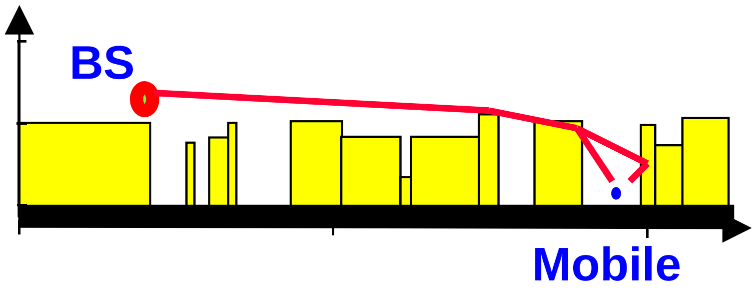


- Two planes are identified where LP and VP are assumed to take place: the ***lateral plane*** and the ***vertical plane***
- In the vertical plane also roof-to-street propagation can be taken into account
- Strictly speaking, LP takes place on the lateral plane only if the terminals have the same height

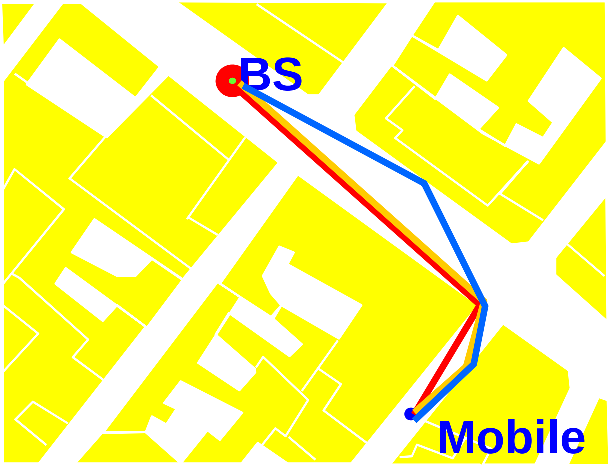


2D+2D ray models (2/2)

- In the vertical plane either a real 2D ray tracing or an ORT model combined with a roof-to street model is applied

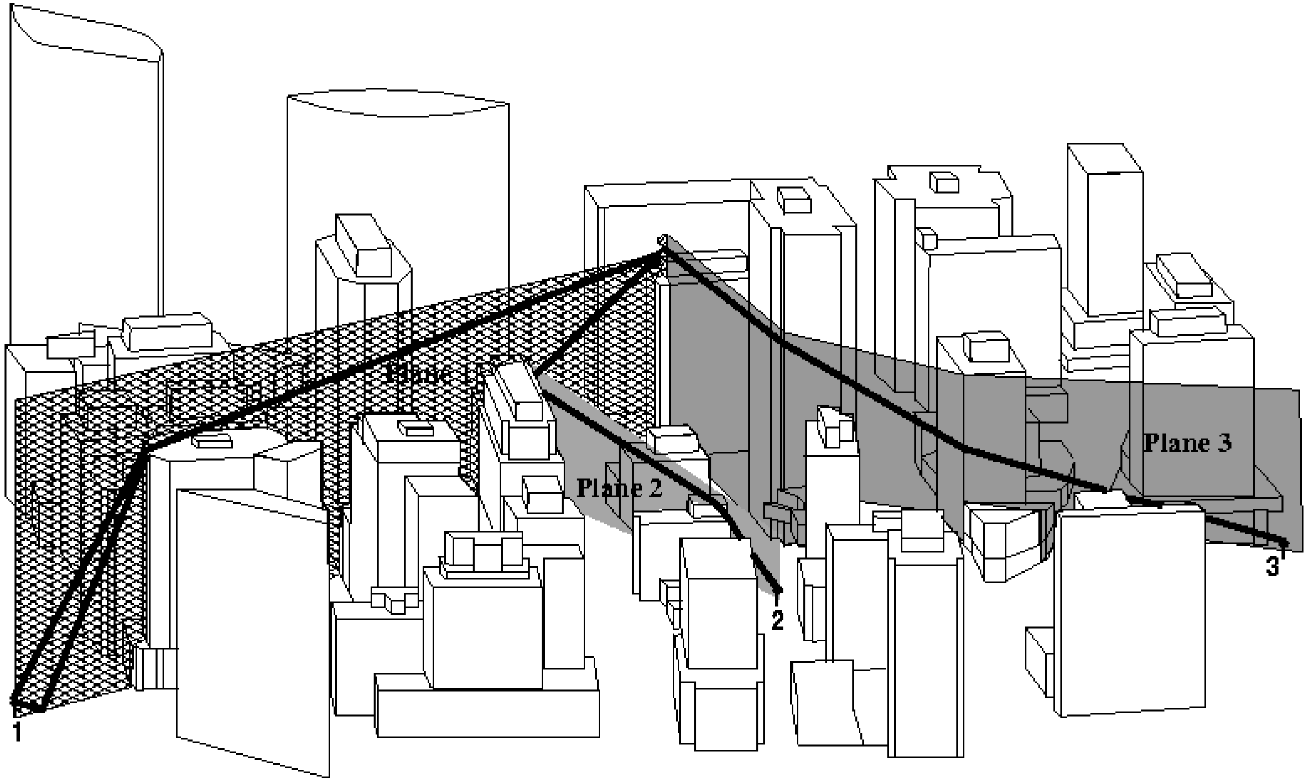


- In the lateral plane a 2D ray tracing is performed



The VPL method [*] (1/2)

Since rays satisfying GTP rules belong to ***folded vertical planes*** (see figure), and the projection of these planes onto the ground plane results in piece-wise lines also satisfying GTP rules as rays in 2D, the basic idea is to perform a 2D ray tracing in a plane parallel to terrain, and then to find the actual 3D paths of the rays in the unfolded vertical planes by analytical treatment.



Since each ray in the horizontal plane represents a vertical plane, then the method is as sort of “vertical plane-tracing”, therefore: ***Vertical Plane Launch (VPL).***

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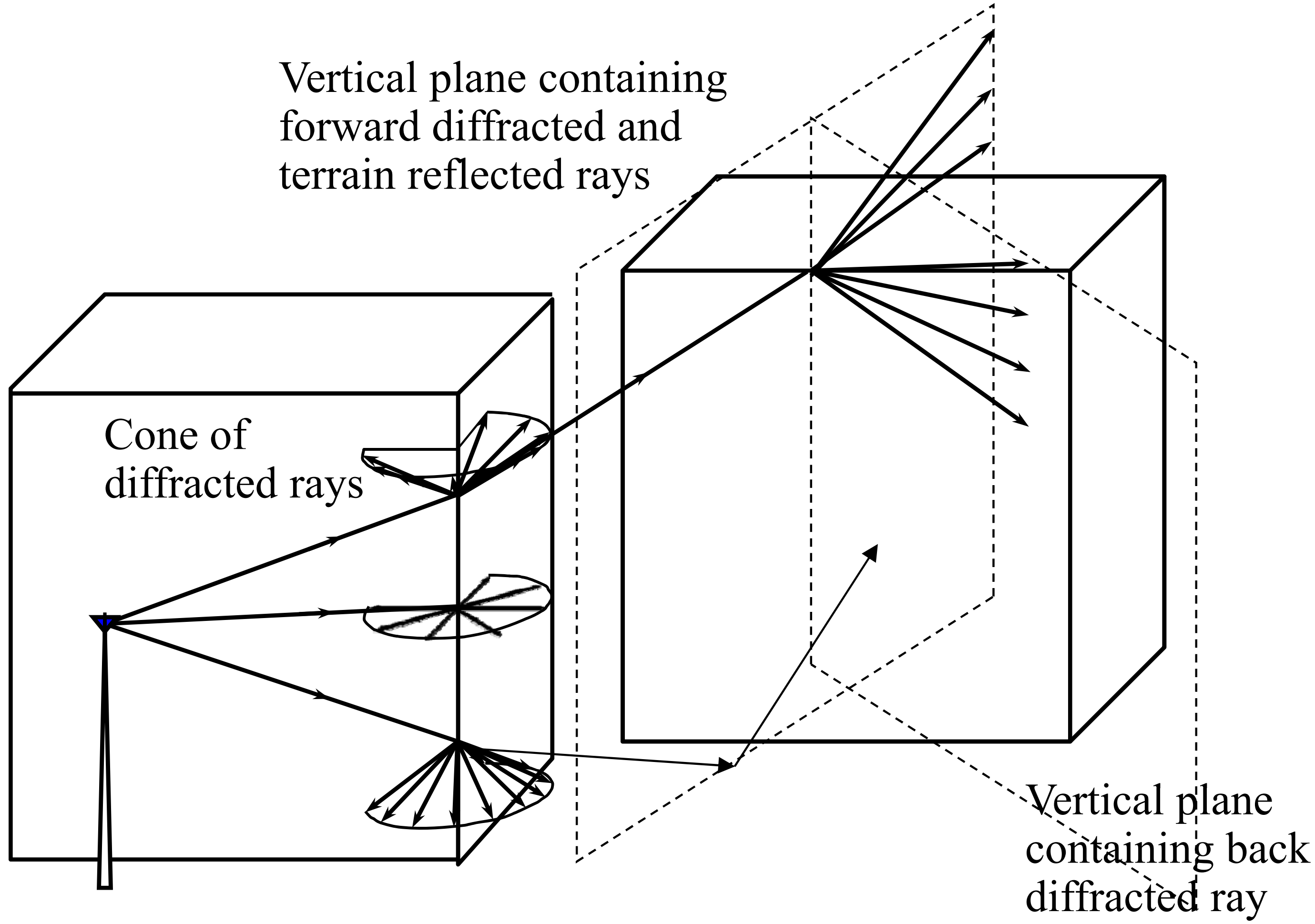
[*] G. Liang and H. L. Bertoni, “*A new approach to 3-D ray tracing for propagation prediction in cities,*” IEEE Trans on Ant. And Propagat., Vol. 46, pp.853-863, 1988.

The VPL method (2/2)

Rays diffracted at horizontal edges belong to the vertical planes defined by the incident or reflected rays (replaces diffraction cone by tangent planes). The same happens for terrain-reflected rays.



Deterministic Ray Tracing: trends

- Speed up techniques to decrease CPU time
- A-priori determination of computation parameters and ray selection
- Integration of deterministic and statistical elements such as diffuse scattering
- Exploitation of the multidimensional prediction potential

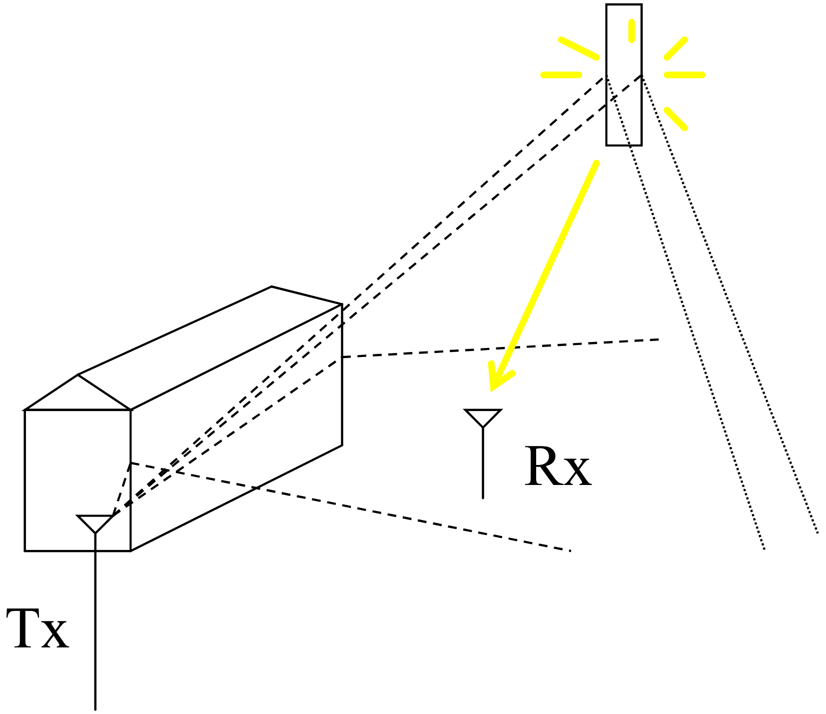
Hybrid ray models and diffuse scattering

- In coherent ray models, if diffuse scattering is to be taken into account then an ***hybrid approach*** is necessary.
- Coherent rays are treated coherently
- Rays which have experienced at least one scattering interaction must be treated incoherently → an *incoherent field background* is superimposed to the coherent component

- In general, all models in which both deterministic and empirical/statistical elements cohexist are called ***Hybrid Models***
- Ex: if a *mean* additional path loss for rays going through vegetated regions is considered (typically 1 dB every 10 m’s) then the ray model is hybrid.

Impact of diffuse scattering

· Diffuse scattering dramatically increases Rx visibility from far walls



· Diffuse scattering is important in roof to street propagation