Multipath Propagation Simulation in Mobile and Wireless Communications

Application of Ray-Tracing for the Propagation Prediction in Microcellular Environments

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Table of Contents

Motivation
Environment under consideration
Ray tracing simulation
  Electromagnetic theory
  Tracing of ray
  Treatment of phase
Validation by field test
Conclusion and future works
Multiple reflected and diffracted paths are arrival.
Impacts of Multipath Propagation

- Large propagation loss compared with line-of-sight (LOS) scenarios
- Fast level fluctuation called fading
- Time dispersion of channel resulting intersymbol interference (ISI)
Purpose of Propagation Simulation

Two different purposes

- Pathloss prediction for cell site design
  — Site-specific information is necessary for smaller cells

- Channel modeling for transmission evaluation
  — Typical and realistic model is eagerly needed
Advanced Transmission Technologies

Dependent on the channel properties

- SIMO (SISO) systems
  - Equalizer: removal of ISI
  - Interleaver: homogenization of fading
  - Diversity antenna: removal of fading
  - Adaptive array antenna: removal of ISI and CCI (co-channel interference)

- MIMO (MISO) systems
  - Multiuser detector: separation of CCI
  - Space division multiplex receiver: parallel spatial channels
  - Transmit diversity by space-time coding: removal of fading
Environment under Consideration

This presentation focuses on
- Outdoor microcellular environment;
Environment under Consideration

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- Outdoor microcellular environment;
- Base station antenna below rooftop;
Environment under Consideration

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- Outdoor microcellular environment;
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- Diameter less than 500 m.
Environment under Consideration

This presentation focuses on
  - Outdoor microcellular environment;
  - Base station antenna below rooftop;
  - Diameter less than 500 m.

Examples: PHS, hot spot wireless access.
Outdoor Microcellular Environment

Main scatterers are *buildings* and ground.

- Building database required
- Otherwise: simulation cost >> measurement cost
- Full utilization of vector database
  - Useless pixel database ⇒ extraction of surfaces
  - ZENRIN Z-map
    - Commercial vector database
    - Polygon plan + numerical height
Propagation Mechanisms in Ray Tracing

Implemented

Specular reflection: Fresnel reflection coefficient

Edge diffraction: UTD + reflection coefficient (empirical UTD)

Under study

- Surface roughness
- Edge roughness

Items to be modeled

- non-specular component — increase of computational cost
- loss and its fluctuation — stochastic model
- de-polarization
Specular Reflection

Fresnel reflection coefficient for infinite thickness is used for simplicity.

Finite thickness model does not result in accuracy improvement due to inhomogenous materials.
Keller cone is considered for direction of diffracted waves.

UTD diffraction coefficient for conductor or its empirical modification for dielectric.
Ray-Tracing Simulation

Ray-Launching Method
- Launching to each direction from Tx
- Capture circle

Image Method
- Image source of Tx
- Huge memory to store various orders of image sources
- Shadow testing
2D-3D Hybrid Ray-Tracing

1. 2D ray-launching and then 3D ray-path formulation
2. Diffraction edges: treated as new point sources
3. Intersection with points: capture circle
4. Ground reflection: image method
1. Semi-infinite ray is drawn as a ray.
Ray Tracing

1. Semi-infinite ray is drawn as a ray.
2. Each wall is checked for crossing.
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Launched ray
Candidate surfaces
1. Semi-infinite ray is drawn as a ray.
2. Each wall is checked for crossing.
3. All the candidate walls are determined.
Ray Acceleration Techniques

1. Back-face culling
2. Volume bounding
3. Partition vector
Back-Face Culling

Only visible faces are tested.
Back-Face Culling

Only visible faces are tested.

Normal vectors of faces
Back-Face Culling

Only visible faces are tested.

Negative inner product with ray = visible face
Volume Bounding

Instead of each of the buildings, bounded volumes are tested for crossing.
Volume Bounding

Instead of each of the buildings, bounded volumes are tested for crossing.
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Launched ray

Candidate boundaries

Bounded volumes
Volume Bounding

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Instead of each of the buildings, bounded volumes are tested for crossing.

1. Semi-infinite ray is drawn as a ray.
Partition Vectors

Instead of searching all the region, only within the region bounded by partition vectors are tested.
Properties of Spatio-Temporal Channel Model

Ray parameters
- Magnitude and *phase*
- Directions of arrival and departure
- Delay time
- Doppler frequency

(spatial / temporal properties)
Model of Single Ray

Dyadic (vector to vector) complex path gain between Tx and Rx origins

\[
\overline{\gamma}_l(t, \tau, \Omega_R, \Omega_T) = \begin{bmatrix}
\hat{\theta}_R(\Omega_{Rl}) & \hat{\varphi}_R(\Omega_{Rl})
\end{bmatrix}
\begin{bmatrix}
\gamma^{\theta\theta}_l & \gamma^{\theta\varphi}_l \\
\gamma^{\varphi\theta}_l & \gamma^{\varphi\varphi}_l
\end{bmatrix}
\begin{bmatrix}
\hat{\theta}_T(\Omega_{Tl}) \\
\hat{\varphi}_T(\Omega_{Tl})
\end{bmatrix}
\]

\[
\cdot \delta(\Omega_R - \Omega_{Rl})\delta(\Omega_T - \Omega_{Tl})\delta(\tau - \tau_l)
\]

\[
\cdot \exp(j\psi_l) \exp(jf_{dl}\tau) \exp(-jk(\Omega_{Rl} \cdot \vec{v}_R t)) \exp(+jk(\Omega_{Tl} \cdot \vec{v}_T t))
\]
Model of Single Ray

Dyadic (vector to vector) complex path gain between Tx and Rx origins

\[
\overline{\gamma}_l(t, \tau, \Omega_R, \Omega_T) = \left[ \hat{\theta}_R(\Omega_{Rl}) \hat{\phi}_R(\Omega_{Rl}) \right] \left[ \begin{array}{cc} \gamma_{l\theta} & \gamma_{l\varphi} \\ \gamma_{l\varphi} & \gamma_{l\varphi} \end{array} \right] \left[ \begin{array}{c} \hat{\theta}_T(\Omega_{Tl}) \\ \hat{\phi}_T(\Omega_{Tl}) \end{array} \right] \\
\cdot \delta(\Omega_R - \Omega_{Rl}) \delta(\Omega_T - \Omega_{Tl}) \delta(\tau - \tau_l) \\
\cdot \exp(j\psi_l) \exp(jf_{dl}t) \exp(-jk(\Omega_{Rl}) \cdot \bar{v}_R t) \exp(+jk(\Omega_{Tl}) \cdot \bar{v}_T t)
\]

R: Receiver
Dyadic (vector to vector) complex path gain between Tx and Rx origins

\[
\overline{\gamma}_l(t, \tau, \Omega_R, \Omega_T) = \begin{bmatrix}
\hat{\theta}_R(\Omega_{Rl}) & \hat{\phi}_R(\Omega_{Rl}) \\
\end{bmatrix}
\begin{bmatrix}
\gamma_{\theta\theta}^l & \gamma_{\theta\phi}^l \\
\gamma_{\phi\theta}^l & \gamma_{\phi\phi}^l \\
\end{bmatrix}
\begin{bmatrix}
\hat{\theta}_T(\Omega_{Tl}) \\
\hat{\phi}_T(\Omega_{Tl}) \\
\end{bmatrix}
\cdot \delta(\Omega_R - \Omega_{Rl}) \delta(\Omega_T - \Omega_{Tl}) \delta(\tau - \tau_l)
\cdot \exp(j\psi_l) \exp(jf_{dl}t) \exp(-jk(\Omega_{Rl}) \cdot \overline{v}_R t) \exp(+jk(\Omega_{Tl}) \cdot \overline{v}_T t)
\]

\^{T}: Transmitter
Model of Single Ray

Dyadic (vector to vector) complex path gain between Tx and Rx origins

\[ \overline{\gamma}_l(t, \tau, \Omega_R, \Omega_T) \]
\[ = \begin{bmatrix} \hat{\theta}_R(\Omega_{RL}) & \hat{\phi}_R(\Omega_{RL}) \end{bmatrix} \begin{bmatrix} \gamma^\theta\theta_l & \gamma^\theta\phi_l \\ \gamma^\phi\theta_l & \gamma^\phi\phi_l \end{bmatrix} \begin{bmatrix} \hat{\theta}_T(\Omega_{TL}) \\ \hat{\phi}_T(\Omega_{TL}) \end{bmatrix} \]
\[ \cdot \delta(\Omega_R - \Omega_{RL}) \delta(\Omega_T - \Omega_{TL}) \delta(\tau - \tau_l) \]
\[ \cdot \exp(j \psi_l) \exp(j f_d t) \exp(-jk(\Omega_{RL}) \cdot \overline{v}_R t) \exp(+jk(\Omega_{TL}) \cdot \overline{v}_T t) \]

\( \psi_l \): Path phase between Tx and Rx origins
Model of Single Ray

Dyadic (vector to vector) complex path gain between Tx and Rx origins

$$\overline{\gamma}_l(t, \tau, \Omega_R, \Omega_T)$$

$$= \left[ \hat{\theta}_R(\Omega_{Rl}) \quad \hat{\varphi}_R(\Omega_{Rl}) \right] \left[ \begin{array}{cc} \gamma_{\theta\theta}^l & \gamma_{\theta\varphi}^l \\ \gamma_{\varphi\theta}^l & \gamma_{\varphi\varphi}^l \end{array} \right] \left[ \begin{array}{c} \hat{\theta}_T(\Omega_{Tl}) \\ \hat{\varphi}_T(\Omega_{Tl}) \end{array} \right]$$

$$\cdot \delta(\Omega_R - \Omega_{Rl}) \delta(\Omega_T - \Omega_{Tl}) \delta(\tau - \tau_l)$$

$$\cdot \exp(j\psi_l) \exp(j f_{dl} t) \exp(-j k(\Omega_{Rl}) \cdot \vec{v}_R t) \exp(+j k(\Omega_{Tl}) \cdot \vec{v}_T t)$$

$f_{dl}$: Doppler frequency due to motion of scatterer
Model of Single Ray

Dyadic (vector to vector) complex path gain between Tx and Rx origins

\[
\overline{\gamma}_l(t, \tau, \Omega_R, \Omega_T) = \left[ \hat{\theta}_R(\Omega_{Rl}) \quad \hat{\varphi}_R(\Omega_{Rl}) \right] \begin{bmatrix} \gamma_{l\theta} & \gamma_{l\varphi} \\ \gamma_{l\varphi} & \gamma_{l\varphi} \end{bmatrix} \left[ \hat{\theta}_T(\Omega_{Tl}) \quad \hat{\varphi}_T(\Omega_{Tl}) \right] \\
\cdot \delta(\Omega_R - \Omega_{Rl}) \delta(\Omega_T - \Omega_{Tl}) \delta(\tau - \tau_l) \\
\cdot \exp(j\psi_l) \exp(j \int \omega \, dt) \exp(-j \overline{k}(\Omega_{Rl}) \cdot \overline{v}_R t) \exp(+j \overline{k}(\Omega_{Tl}) \cdot \overline{v}_T t)
\]

\( \overline{k}(\Omega_R) \): Propagation vector toward \( \Omega_R \)
Model of Single Ray

Dyadic (vector to vector) complex path gain between Tx and Rx origins

\[
\overline{\gamma}_l(t, \tau, \Omega_R, \Omega_T) = \begin{bmatrix}
\hat{\theta}_R(\Omega_R) & \hat{\varphi}_R(\Omega_R)
\end{bmatrix} \begin{bmatrix}
\gamma_{l\theta} & \gamma_{l\varphi} \\
\gamma_{l\varphi} & \gamma_{l\varphi}
\end{bmatrix} \begin{bmatrix}
\hat{\theta}_T(\Omega_T) \\
\hat{\varphi}_T(\Omega_T)
\end{bmatrix}
\]

\[
= \delta(\Omega_R - \Omega_R) \delta(\Omega_T - \Omega_T) \delta(\tau - \tau_l)
\]

\[
\cdot \exp(j\psi_l) \exp(jf_dlt) \exp(-jk(\Omega_R) \cdot \overline{v}_R t) \exp(+jk(\Omega_T) \cdot \overline{v}_T t)
\]

\(\overline{v}_R\): Velocity vector of receiver antenna
Model of Single Ray

Dyadic (vector to vector) complex path gain between Tx and Rx origins

$$\bar{\gamma}_l(t, \tau, \Omega_R, \Omega_T)$$

$$= \left[ \hat{\theta}_R(\Omega_Rl) \; \hat{\varphi}_R(\Omega_Rl) \right] \left[ \begin{array}{cc} \gamma_{l\theta} & \gamma_{l\varphi} \\ \gamma_{l\varphi} & \gamma_{l\varphi} \end{array} \right] \left[ \hat{\theta}_T(\Omega_Tl) \; \hat{\varphi}_T(\Omega_Tl) \right]$$

$$\cdot \delta(\Omega_R - \Omega_Rl) \delta(\Omega_T - \Omega_Tl) \delta(\tau - \tau_l)$$

$$\cdot \exp(j\psi_l) \exp(jf_d t) \exp(-jk(\Omega_Rl) \cdot \vec{v}_R t) \exp(+jk(\Omega_Tl) \cdot \vec{v}_T t)$$

Result of ray tracing
Model of Multipath

\[ \bar{\Gamma}(t, \tau, \Omega_R, \Omega_T) = \sum_{l=1}^{L} \gamma_l(t, \tau, \Omega_R, \Omega_T) \]
Ray-Based Channel Response Model

\[ h(t, \tau) = \iiint e_R(\Omega_R) \cdot \bar{\Gamma}(t, \tau, \Omega_R, \Omega_T) \cdot e_T^*(\Omega_T) d\Omega_R d\Omega_T \]

\[ = \sum_{l=1}^{L} \begin{bmatrix} e_{R\theta}(\Omega_{Rl}) & e_{R\phi}(\Omega_{Rl}) \end{bmatrix} \begin{bmatrix} \gamma_{i\theta} & \gamma_{i\phi} \\ \gamma_{i\phi} & \gamma_{i\phi} \end{bmatrix} \begin{bmatrix} e_{T\theta}^*(\Omega_{Tl}) \\ e_{T\phi}^*(\Omega_{Tl}) \end{bmatrix} \]
Ray-Based Channel Response Model

\[ h(t, \tau) = \iiint e_R(\Omega_R) \cdot \overline{\Gamma}(t, \tau, \Omega_R, \Omega_T) \cdot e^*_T(\Omega_T) d\Omega_R d\Omega_T \]

\[ = \sum_{l=1}^{L} \begin{bmatrix} e_{R\theta}(\Omega_{Rl}) & e_{R\varphi}(\Omega_{Rl}) \end{bmatrix} \begin{bmatrix} \gamma_{\theta\theta}^l & \gamma_{\theta\varphi}^l \\ \gamma_{\varphi\theta}^l & \gamma_{\varphi\varphi}^l \end{bmatrix} \begin{bmatrix} e_{T\theta}(\Omega_{Tl}) \\ e_{T\varphi}(\Omega_{Tl}) \end{bmatrix} \]

Receiver antenna vector complex directivity
Ray-Based Channel Response Model

\[ h(t, \tau) = \int \int \int \int \mathbf{e}_R(\Omega_R) \cdot \mathbf{\Gamma}(t, \tau, \Omega_R, \Omega_T) \cdot \mathbf{e}^*_T(\Omega_T) \, d\Omega_R \, d\Omega_T \]

\[ = \sum_{l=1}^{L} \begin{bmatrix} e_{R\theta}(\Omega_{RL}) & e_{R\phi}(\Omega_{RL}) \end{bmatrix} \begin{bmatrix} \gamma_{i\theta} & \gamma_{i\phi} \\ \gamma_{i\phi} & \gamma_{i\phi} \end{bmatrix} \begin{bmatrix} e_{T\theta}(\Omega_{TL}) \\ e_{T\phi}(\Omega_{TL}) \end{bmatrix} \]

Receiver antenna vector complex directivity
Transmitter antenna vector complex directivity
Treatment of Phase

Effect of phase can be found when bandwidth and baamwidth are finite.
Treatment of Phase

- Effect of phase can be found when bandwidth and baudwidth are finite.
- Four different approaches
Treatment of Phase

Effect of phase can be found when bandwidth and baamwidth are finite.

Four different approaches

Deterministic phase: Raytracing phase is used. Not meaningful; limited position accuracy and terminal motion
Treatment of Phase

Effect of phase can be found when bandwidth and baamwidth are finite.

Four different approaches

**Deterministic phase** : Raytracing phase is used. Not meaningful; limited position accuracy and terminal motion

**Power summing** : Rays are incoherently summed. Estimation of average; no fading fluctuation
Treatment of Phase

Effect of phase can be found when bandwidth and bandwidth are finite.

Four different approaches

Deterministic phase: Raytracing phase is used.
   Not meaningful; limited position accuracy and terminal motion

Power summing: Rays are incoherently summed.
   Estimation of average; no fading fluctuation

Random phase: Each ray has a random value of phase.
   Model of fading instant; analytical PDF
Treatment of Phase

Effect of phase can be found when bandwidth and baamwidth are finite.

Four different approaches

Deterministic phase: Raytracing phase is used. Not meaningful; limited position accuracy and terminal motion

Power summing: Rays are incoherently summed. Estimation of average; no fading fluctuation

Random phase: Each ray has a random value of phase. Model of fading instant; analytical PDF

Dynamic phase: Motion of terminal is considered. Phase rotation due to Doppler; similar to “Jakes model”
Effect of Finite Beam/Bandwidth

Impulse response of system shall be convolved to the ray-tracing channel model.
Field Test

- PN correlation sounder ⇒ delay spectrum
- Rotating parabolic antenna ⇒ angular spectrum
- Smoothing over 30cm × 30cm area to remove fading

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<table>
<thead>
<tr>
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<td>frequency</td>
<td>8.45 GHz</td>
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<tr>
<td>bandwidth</td>
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<td>delay resolution</td>
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<td>Tx antenna</td>
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<td>Rx antenna</td>
<td>V-pol 50 cm parabola</td>
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<td>beamwidth</td>
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Test Site

Yokosuka Highland area, Japan

Residential area with wooden houses and concrete walls

Average Building Height: 8 m

Rx: height 4.4 m  Tx: height 2.7 m
Both results are in agreement w.r.t. dominant signals.

Non-specular components are observed in experiment.
Conclusion and Future Works

Conclusion
- Ray-based model is flexibly applied to SIMO and MIMO transmission.
- Ray tracing simulator for microcell environment is presented.
- The simulator is validated by field test.
- Commercial softwares are available; rather few validation data.

Future works
- Modeling of non-specular scattering effect
- 3D propagation mechanism (e.g. path over the roof top)
- Birth and death of ray ⇒ shadowing