Antenna De-embedding in Propagation Simulation using FDTD Method

D2 Jun-ichi Naganawa

2013/06/27 MCRG Seminar

Based on: IEICE General Conf. (Mar. 2013)

MCRG Tokyo Tech
東京工業大学
Tokyo Institute of Technology
Department of International Development Engineering (IDE)
Tokyo Institute of Technology

Outline

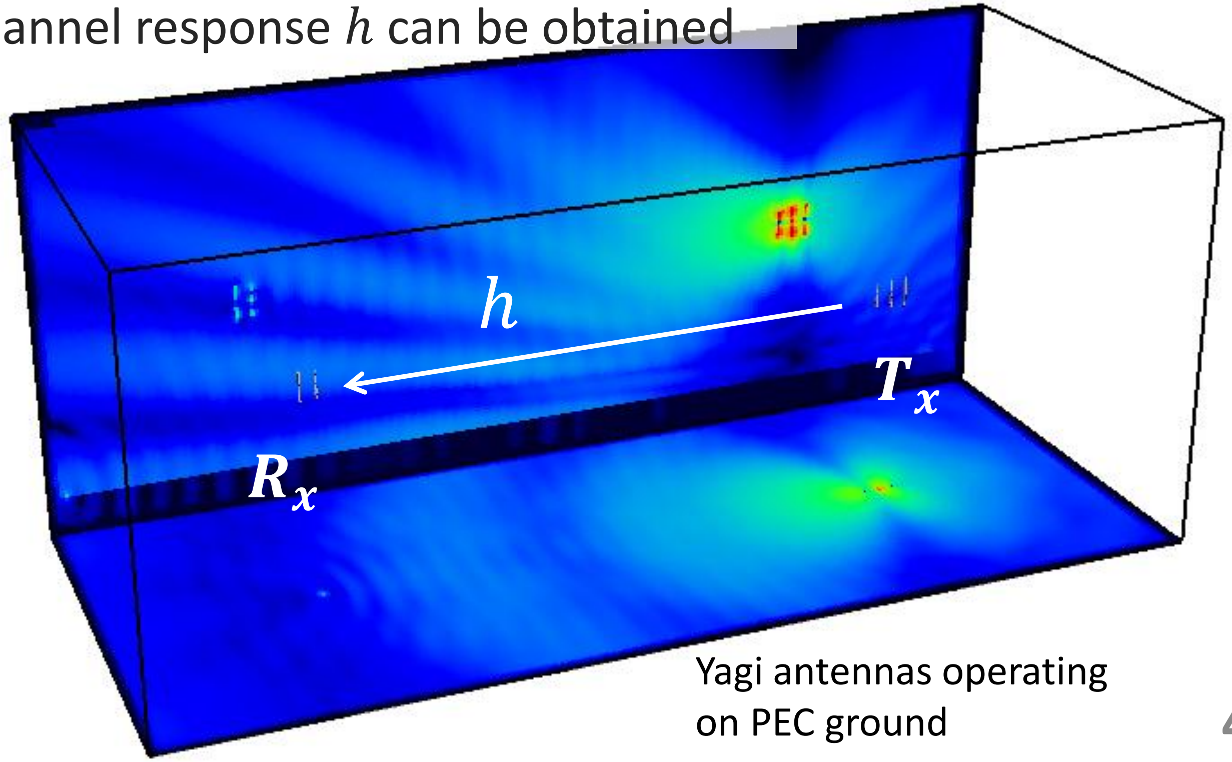
- Background and Purpose
  - Antenna De-embedding in Propagation simulation
- Approach
  - Antenna and Channel Modeling by Spherical Wave
- Technical challenges
  - How to get $\boldsymbol{R}, \boldsymbol{M}, \boldsymbol{T}$ using FDTD method
- Result
  - Numerical examples
- Summary and Future work

Background

Propagation Simulation using FDTD Method

FDTD(Finite-Difference Time-domain) Method

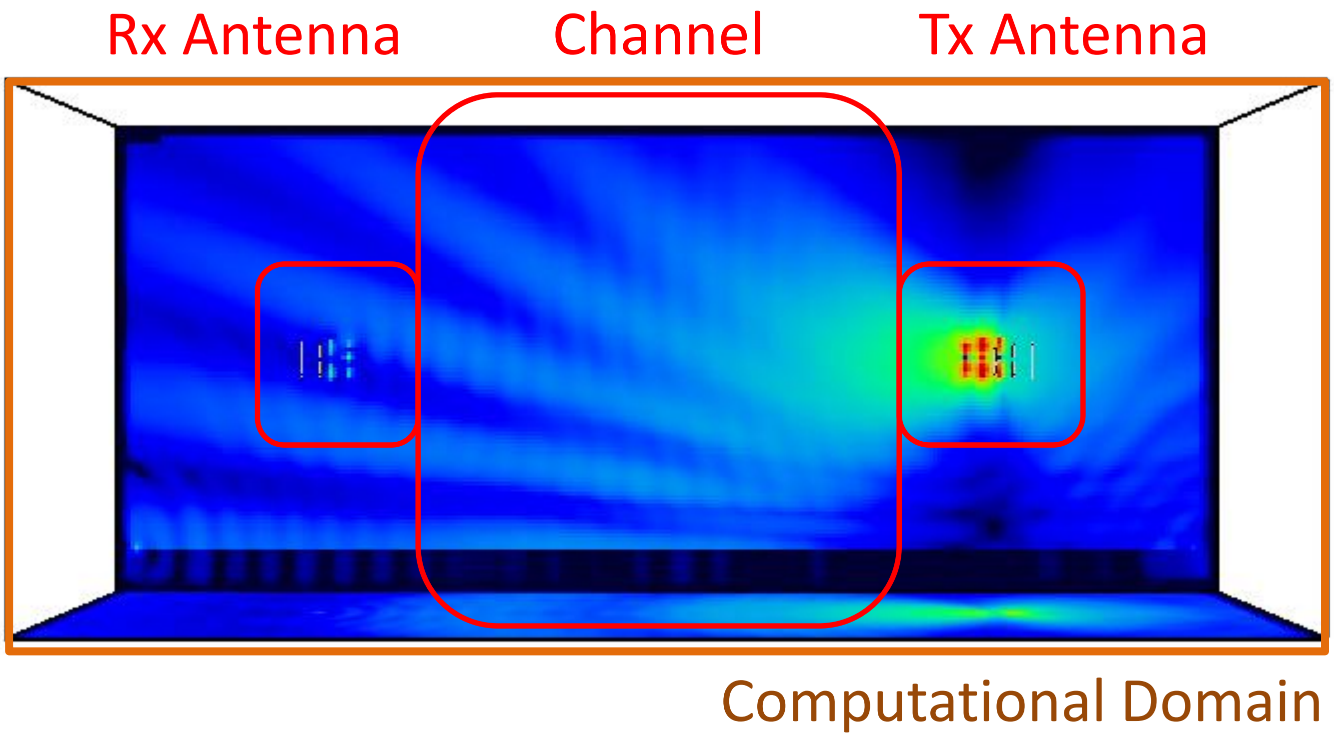
- Antenna and channel is modeled by cells
  - Modeling is flexible
  - Various propagation mechanism is included
    - Reflection, Transmission, Diffraction, etc.
- From E-field, channel response h can be obtained
- e.g.



Yagi antennas operating on PEC ground

Problem

- Antenna is embedded
  - i.e. The computational domain includes both antennas and channel

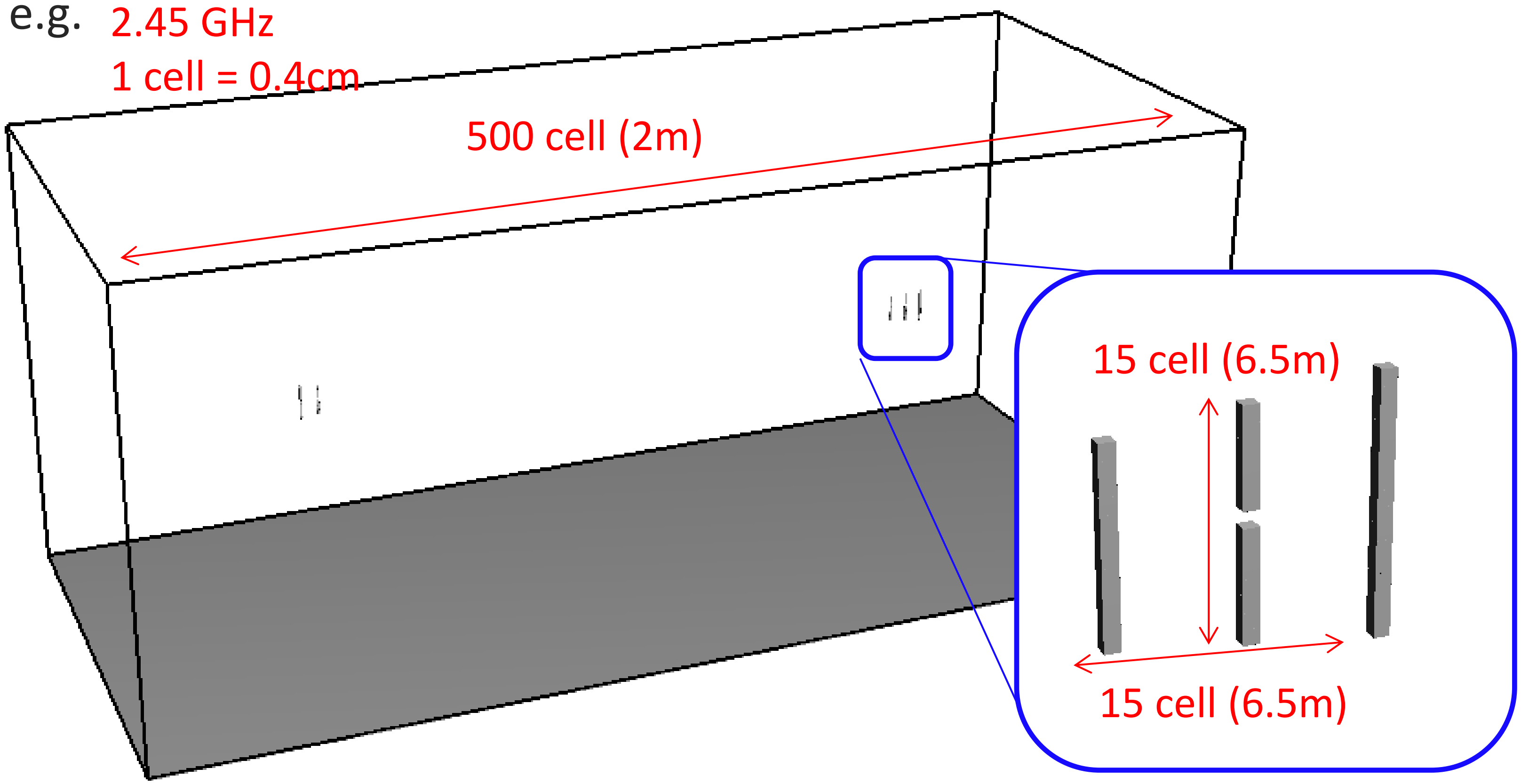


Problem

■ Antenna is embedded

→Antenna modeling become inaccurate

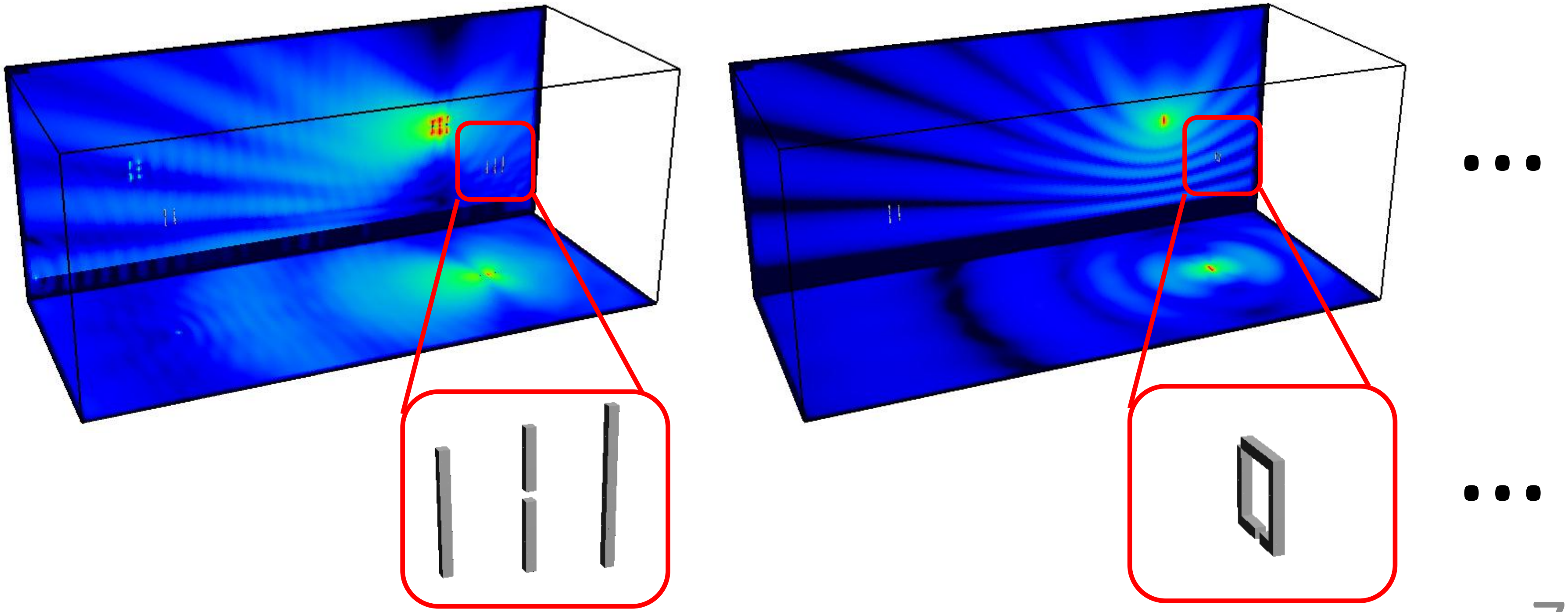
- Channel = large ⇔ Antenna = small
- e.g.



Problem

- Antenna is embedded

→Antenna optimization become difficult
Simulation should be repeated for different antennas

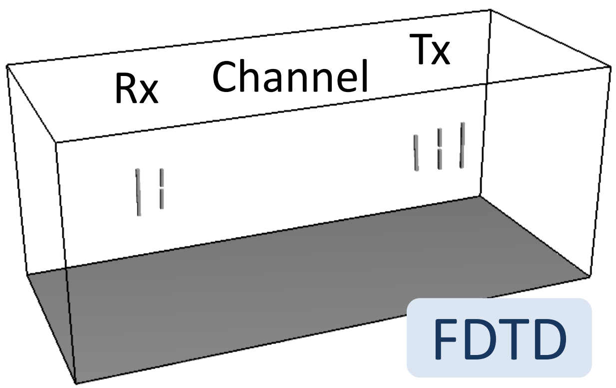


Purpose

Antenna De-embedding

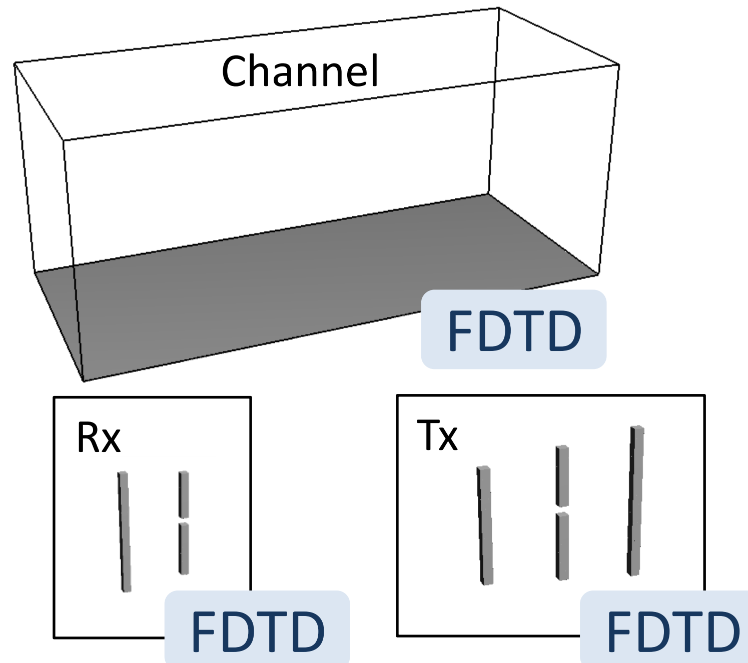
Antenna De-embedding should be achieved

- Embedded simulation (Conventional Approach)



Channel response $\boldsymbol{h}$

- De-embedded simulation



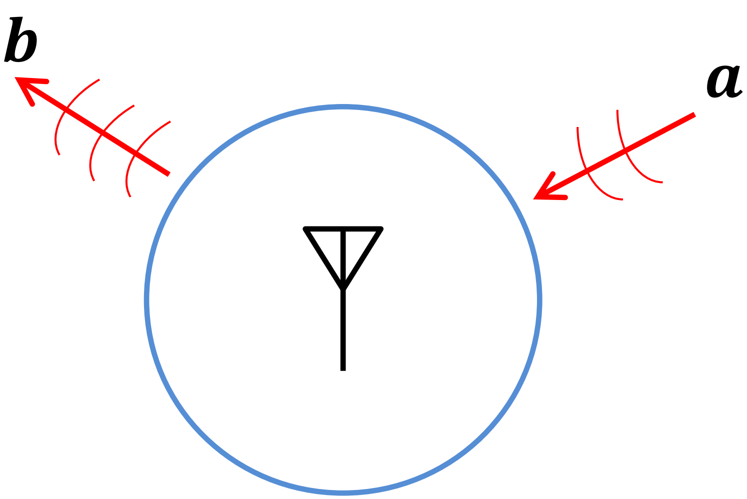
Channel response $\boldsymbol{h}$

Approach

Approach: Spherical waves

Spherical wave

- It is know that any E-field can be approximated by the finite summation of spherical waves



$$\boldsymbol{E}(r,\theta,\phi) = k\sqrt{\eta}\sum_{j}^{J} b_j \boldsymbol{F}_j^{(3)} + a_j \boldsymbol{F}_j^{(4)}(r,\theta,\phi)$$

j ... mode index

J ... the number of mode

$\boldsymbol{b}$ ... incoming wave coefficients

$$\boldsymbol{b} = \left[b_1\ b_2\ \ldots b_J\right]^T \in J \times 1$$

$\boldsymbol{a}$ ... outgoing wave coefficients

$$\boldsymbol{a} = \left[a_1\ a_2\ \ldots a_J\right]^T \in J \times 1$$

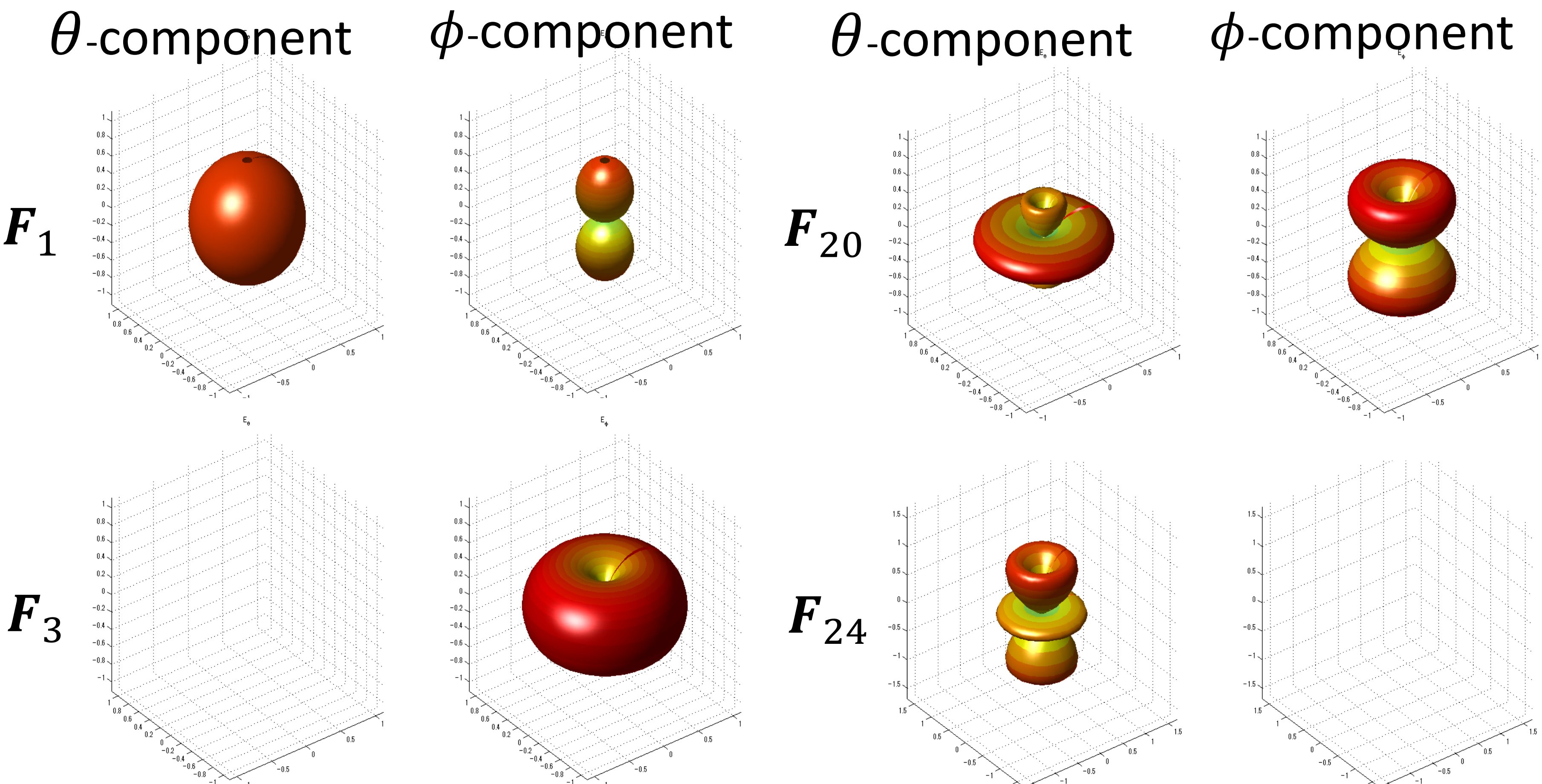
$\boldsymbol{F_j}^{(3)}$ ... incoming spherical wave function

$\boldsymbol{F_j}^{(4)}$ ... outgoing spherical wave function

k, η ... Wave number and impedance

Approach: Spherical waves

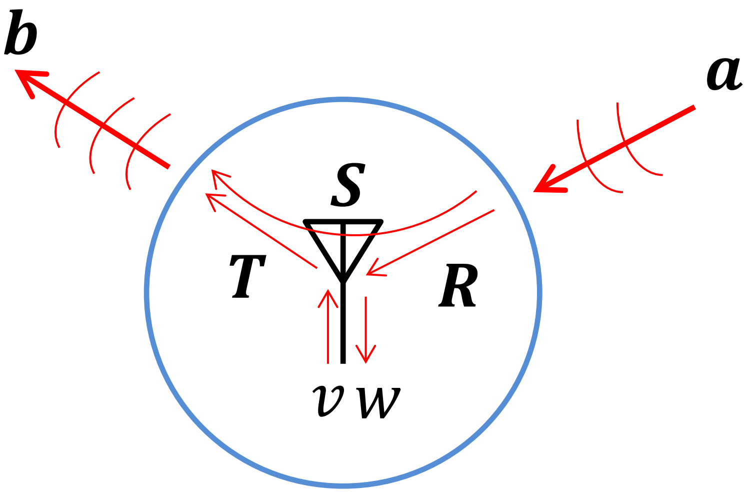
■ Spherical wave: e.g.



Observation: Higher mode means complex shape → Provide more accuracy

Antenna Modeling by Spherical Waves

- To model antennas in the domain of spherical waves, $\boldsymbol{S}, \boldsymbol{R}, \boldsymbol{T}$ are utilized.

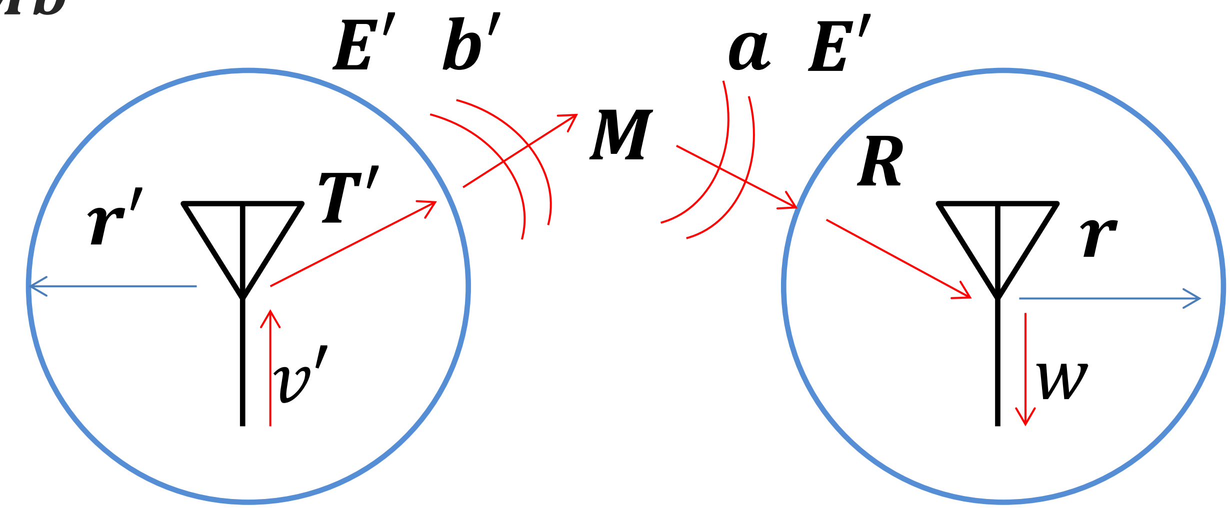


w … Received power
v … Input power
$\boldsymbol{R}$ … Receiving coefficient $\mathbf{R} \in C^{1\times J}$
$\boldsymbol{T}$ … Transmitting coefficient $\boldsymbol{T} \in C^{J\times 1}$
$\boldsymbol{S}$ … Scattering matrix $\mathbf{S} \in C^{J\times J}$

$$w = \boldsymbol{Ra}$$
$$\boldsymbol{b} = \boldsymbol{T}v + \boldsymbol{Sa}$$

Channel Representation by Spherical Waves

- Channel is represented by the relationship between radiated mode $\boldsymbol{b}'$ and incoming mode $\boldsymbol{a}$:
  - a$= \boldsymbol{M}\boldsymbol{b}'$



- Channel response h is given by
  - $h = \frac{w}{v\prime} = \frac{\boldsymbol{R}\boldsymbol{a}}{v\prime} = \frac{\boldsymbol{R}\boldsymbol{M}b'}{v\prime} = \frac{\boldsymbol{R}\boldsymbol{M}\boldsymbol{T}v'}{v\prime} = \boldsymbol{R}\boldsymbol{M}\boldsymbol{T}$

Channel Representation by Spherical Waves

- Channel response is given by
  - $h = \boldsymbol{RMT}$

Rx Antenna (R) — Channel (M) — Tx Antenna (T)

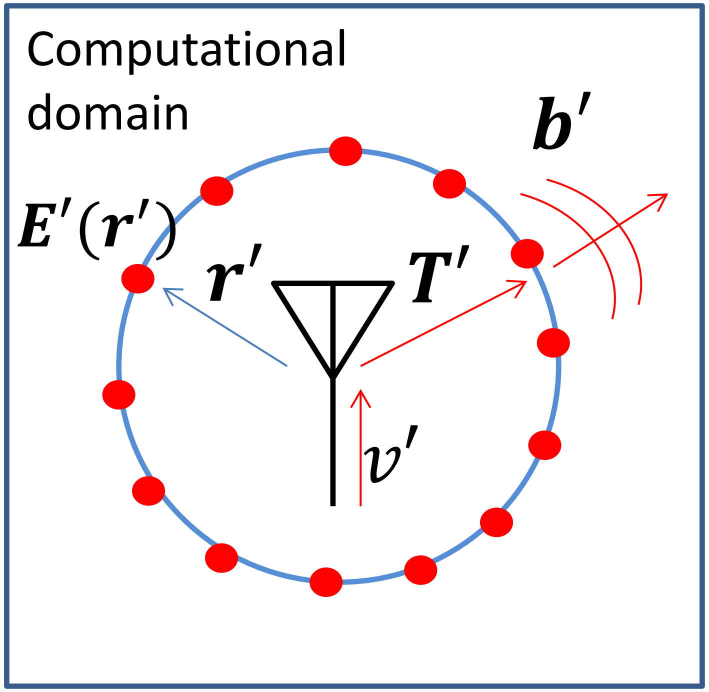
- If R, M, T can be obtained by separated simulation, Antenna De-embedding is achieved.

- How to get $R, M,$ and T using FDTD Method?

Technical challenges

How to get $\boldsymbol{T}'$

- $\boldsymbol{T}'$ can be obtained by simulation of radiation pattern



- $\boldsymbol{b}' = v'\boldsymbol{T}' \rightarrow \boldsymbol{T}' = \boldsymbol{b}'/v'$
- $\boldsymbol{b}'$ can be obtained by radiation pattern $\boldsymbol{E}$
  - At single point

$$\boldsymbol{E}(\boldsymbol{r}') = k\sqrt{\eta}\sum_j b_j \boldsymbol{F}_j^{(3)}(\boldsymbol{r}')$$

  - For all points

$$\boldsymbol{E} = k\sqrt{\eta}\boldsymbol{b}\boldsymbol{F}^{(3)}$$

  - Therefore,

$$\boldsymbol{b} = \frac{1}{k\sqrt{\eta}}\left\{\boldsymbol{F}^{(3)}\right\}^{-1}\boldsymbol{E}$$

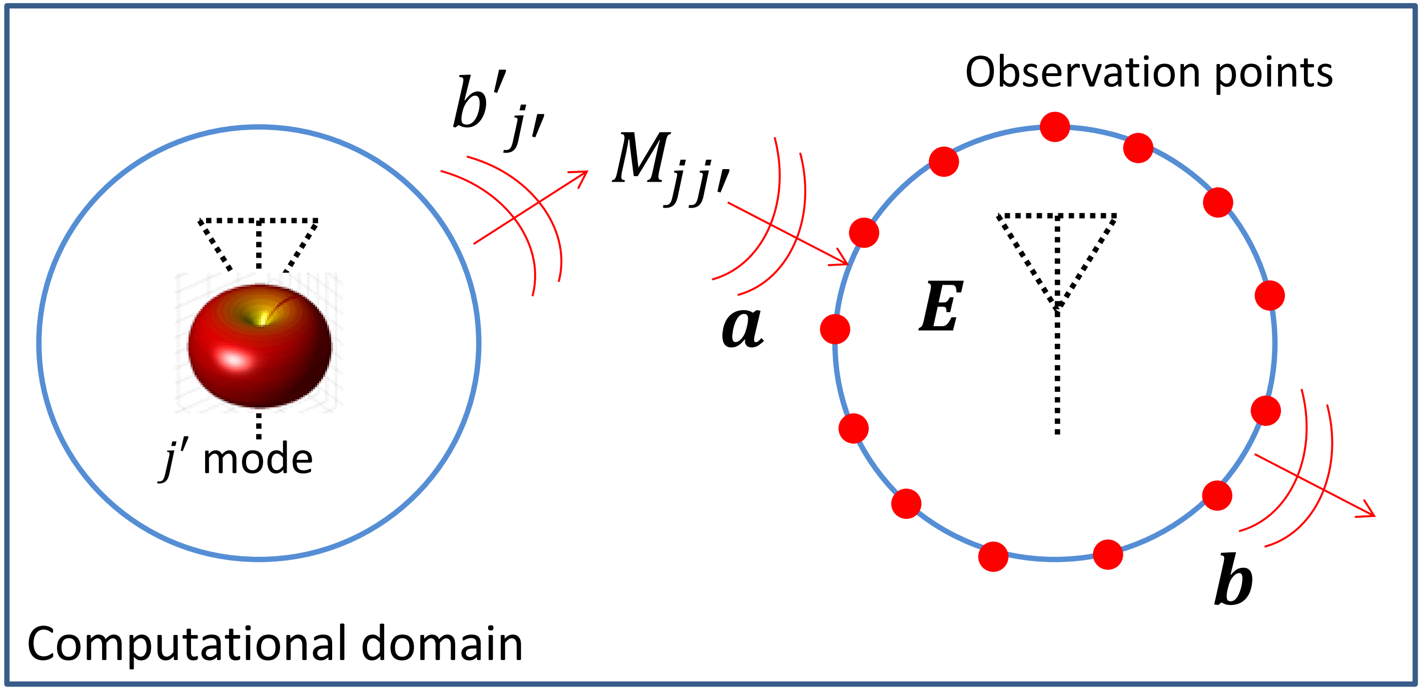
N_s … The number of samples
$\boldsymbol{E}' \in C^{J\times 2N_s}$ … E_θ and E_ϕ at observation points
$\boldsymbol{F}^{(3)} \in C^{J\times N_s}$ … Spherical wave for modes and observation points

How to get $\boldsymbol{R}$

- R can be obtained by reciprocal relationship
  - $R_j = R_{smn} = (-1)^m T_{s-mn}$
  - n, m, s are indexes
    - $j = 2\{n(n+1) + m - 1\} + s$
    - j is actually a simplified index.

How to get $\boldsymbol{M}$

- $\boldsymbol{a} = \boldsymbol{M}\boldsymbol{b}' \rightarrow M_{jj'} = \dfrac{a_j}{b'_{j'}}$
  - $\boldsymbol{M}$ can be obtained by simulation without antenna
  - Instead, single mode source and observation points are set
  - $\boldsymbol{a}$ can be obtained from E-field around receiving antenna



Numerical Example

Numerical Examples

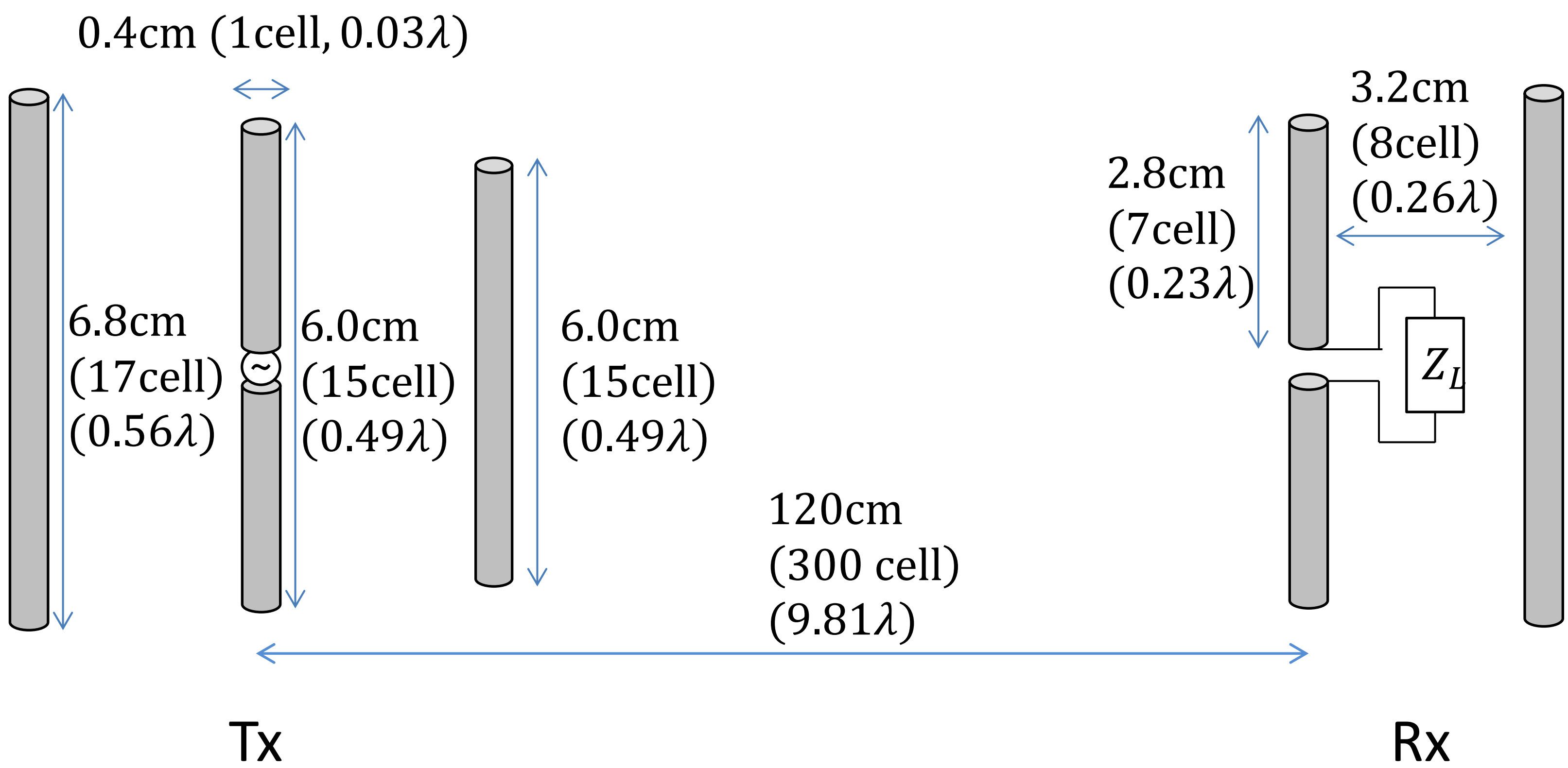
- In order to validate our approach, two numerical examples are performed

1. Yagi antennas
2. $\lambda/2$ dipole on human body tissue

Yagi-Uda antennas in Freespace

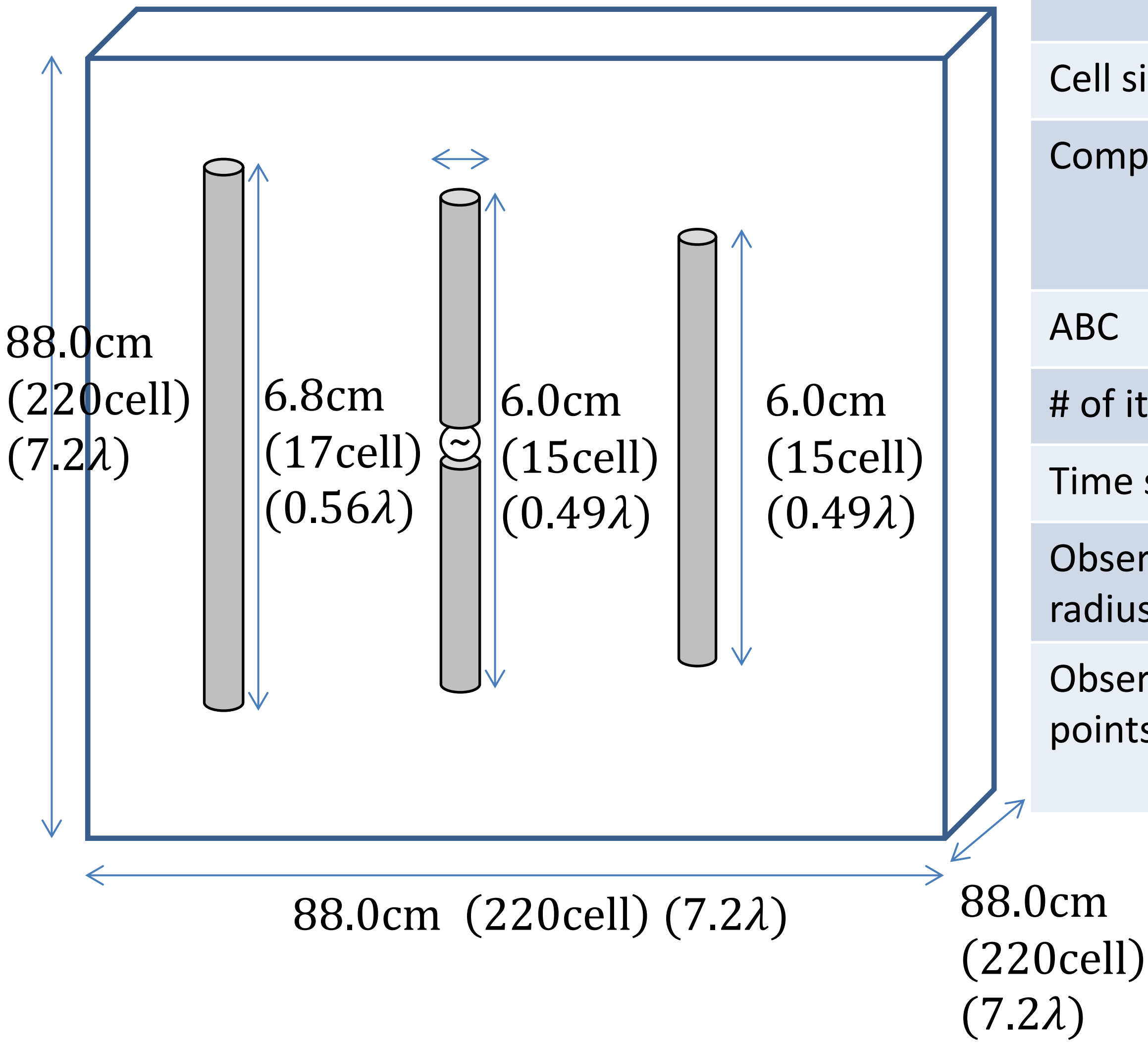
Configuration

- 2.45 GHz



T'

Simulation setup

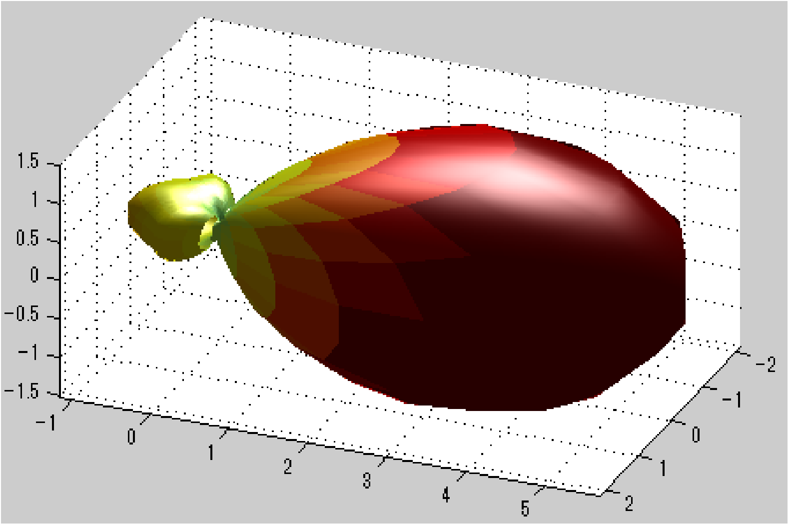


Source	2.4 GHz CW Delta-gap feed
Cell size	0.4 cm (0.03λ)
Comp. space	220x220x220 ($7.2\lambda \times 7.2\lambda \times 7.2\lambda$) (88 cm × 88 cm × 88 cm)
ABC	10 layers PML
# of iteration	3000
Time step	4 psec
Observation radius	90 cell (2.9λ)
Observation points	800 20 (elevation) x 40(azimuth)

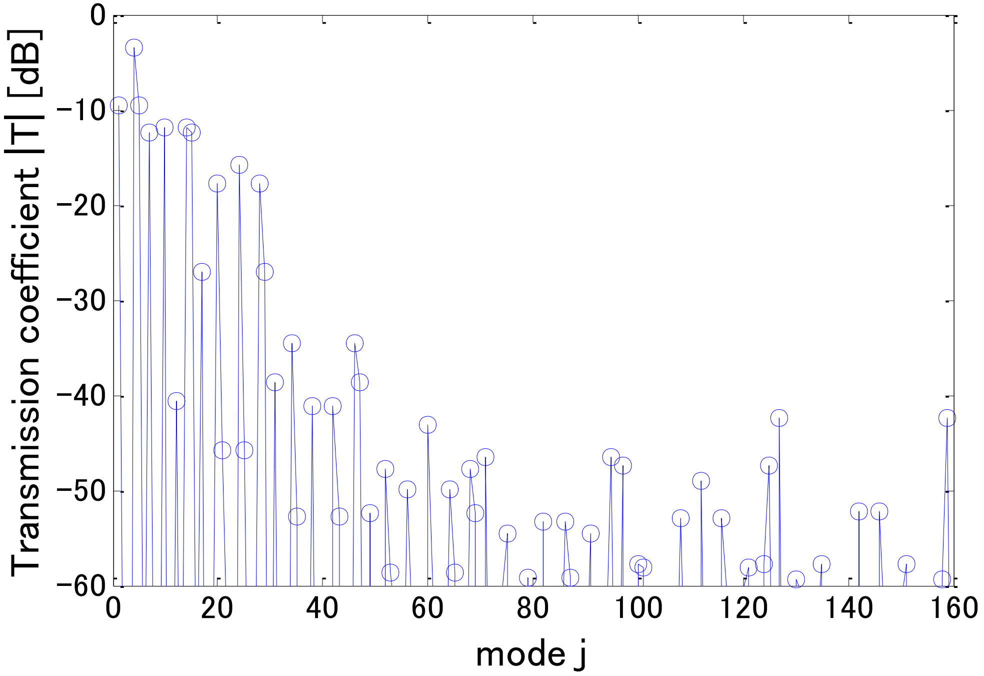
T'

■ Simulation result

Radiation Pattern



Transfer coefficient T'

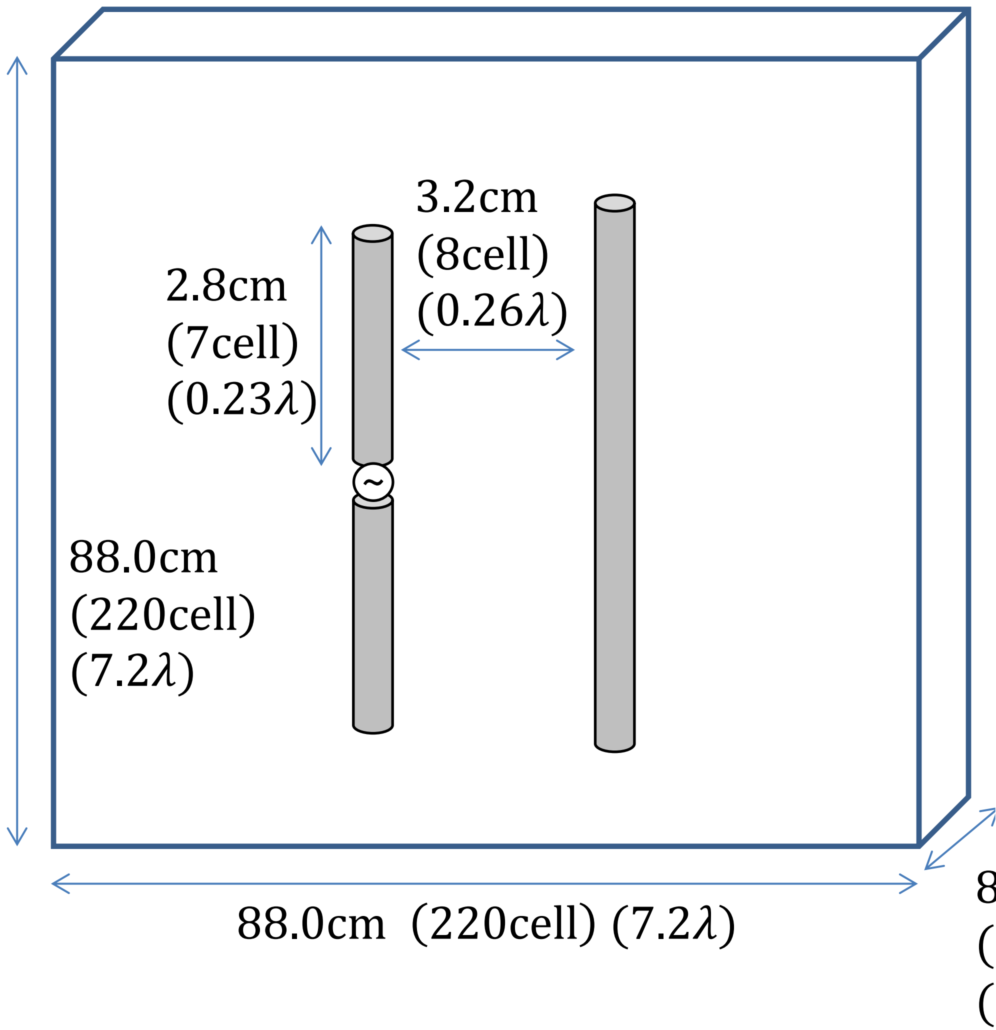


Gain: 7.59 dB

Input impedance: 70.10 + j86.60

R

Simulation setup

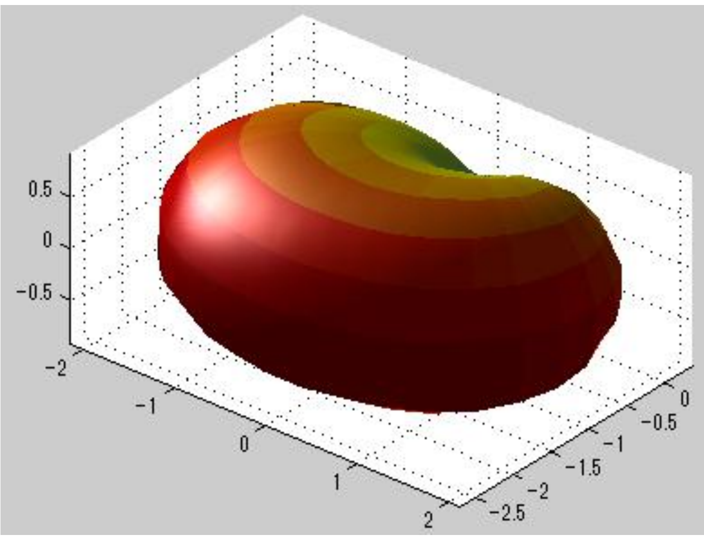


Source	2.4 GHz CW Delta-gap feed
Cell size	0.4 cm (0.03λ)
Comp. space	220x220x220 ($7.2\lambda \times 7.2\lambda \times 7.2\lambda$) (88 cm × 88 cm × 88 cm)
ABC	10 layers PML
# of iteration	3000
Time step	4 psec
Observation radius	90 cell (2.9λ)
Observation points	800 20 (elevation) x 40(azimuth)

R

■ Simulation result

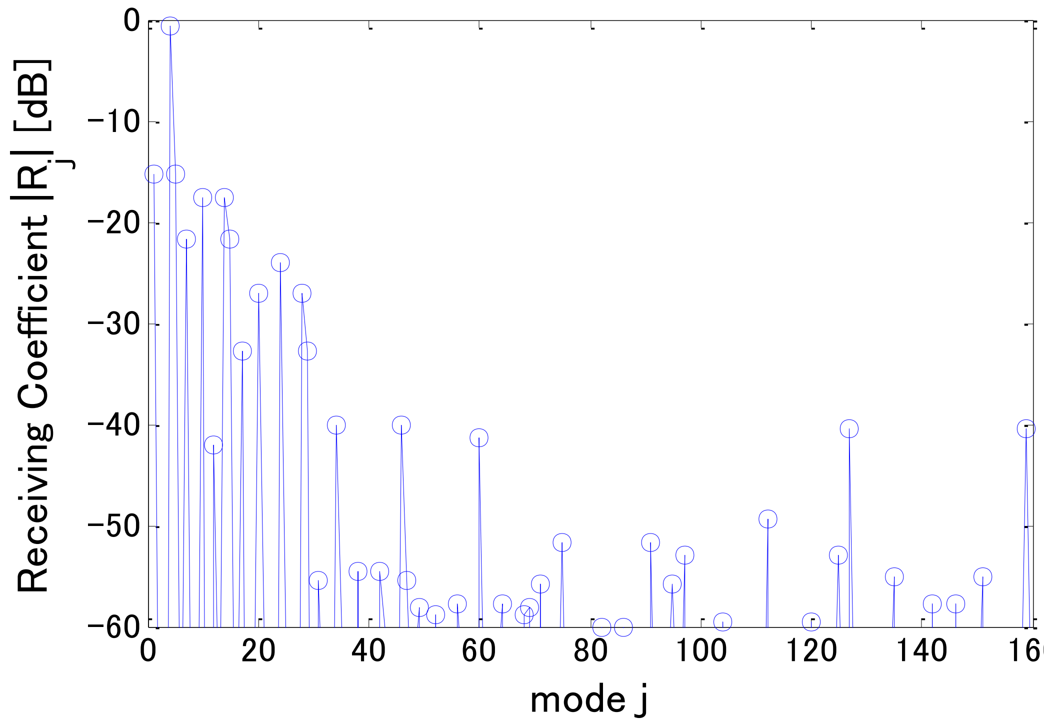
Radiation Pattern



Gain: 4.35 dB

Input impedance: 107.97 + j44.48

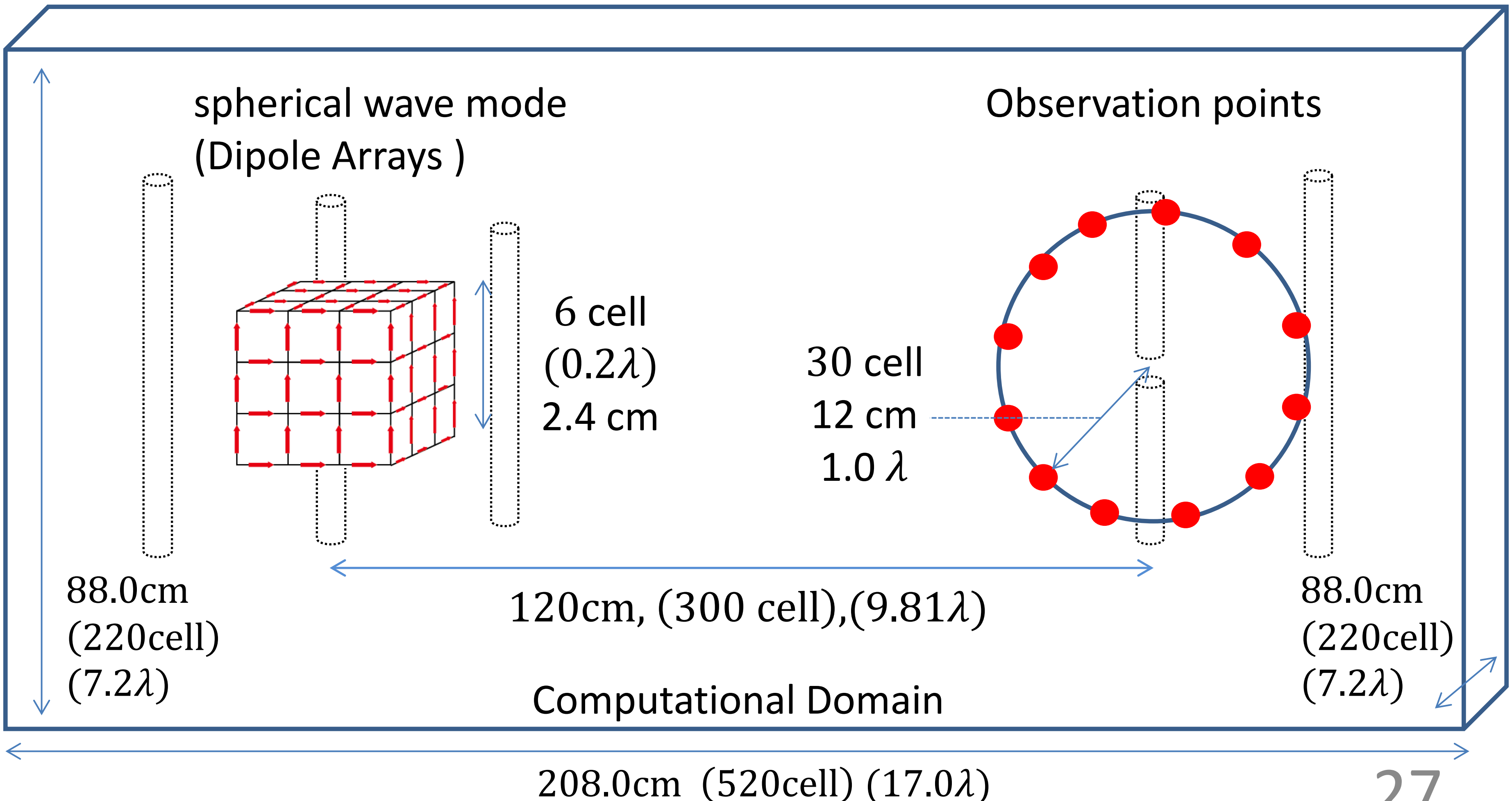
Receiving coefficient $\boldsymbol{R}$



M

Simulation setup

- Instead of antennas, source and observation points are set.



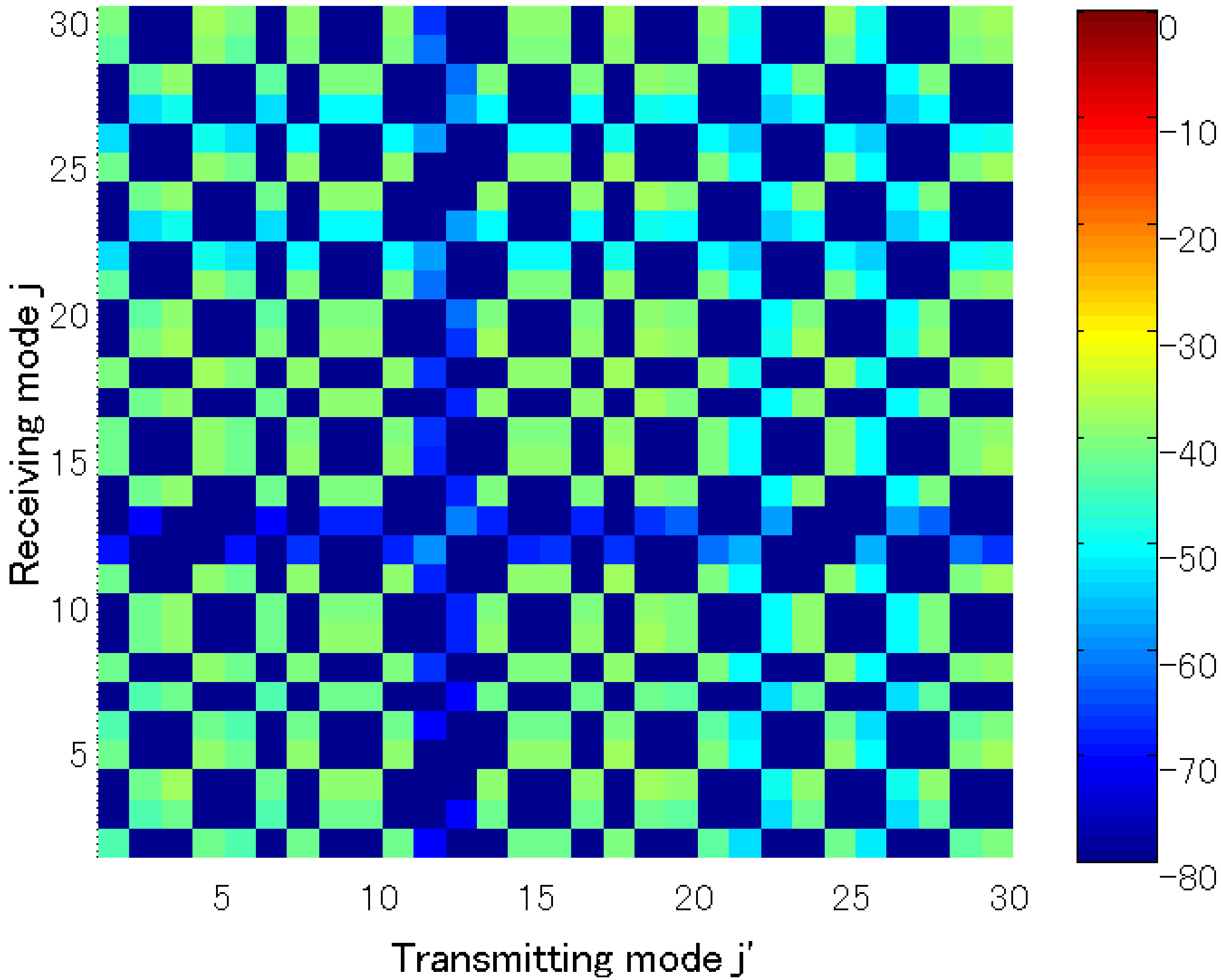
M

Simulation setup

Source	Single mode spherical wave - Realized by dipole arrays - Size of the array: 6x6x6 2.45 GHz CW
Cell size	0.4 cm (1λ)
Computational domain	220x520x220 ($7.2\lambda \times 17.0\lambda \times 7.2\lambda$) ($88.0\ \text{cm} \times 208\ \text{cm} \times 88.0\ \text{cm}$)
# of iterations	5000
Time step	4.0 psec
# of observation points	800 (20 in elevation and 40 in azimuth)
Observation radius	30 cell (12 cm) (1.0λ)
ABC	10 layers of PML

M

■ Simulation Result $|M_{jj'}|$ [dB]



Result

Pathgain $|\boldsymbol{h}|$

- Proposed approach … -29.91 dB
- Embedded simulation
  (conventional approach) … -28.98 dB
- Friis transmission formula … -29.87 dB

Numerical Examples

- In order to validate our approach, two numerical examples are performed

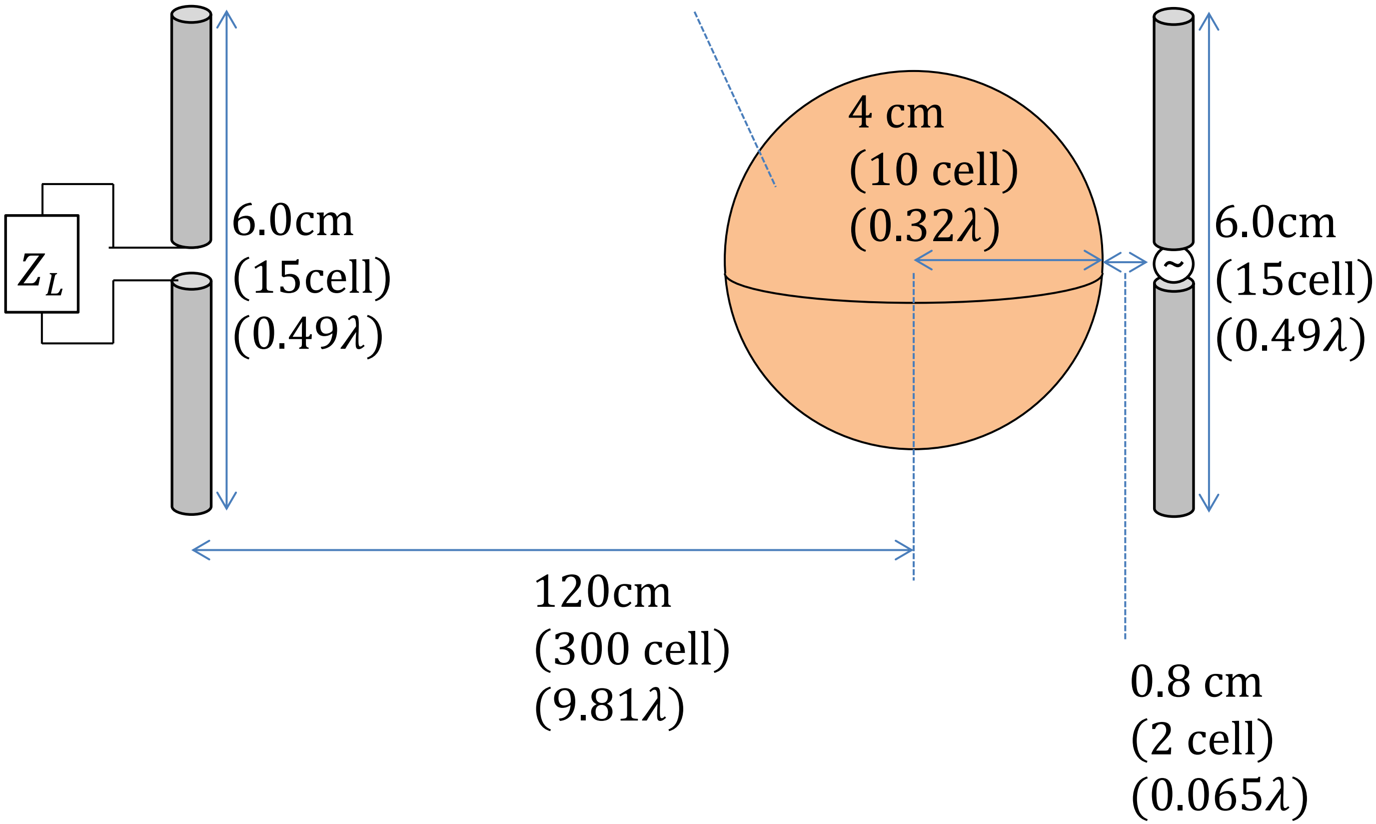
1. Yagi antennas
2. $\lambda/2$ dipole on human body tissue

λ/2 dipole on human body tissue

Configuration

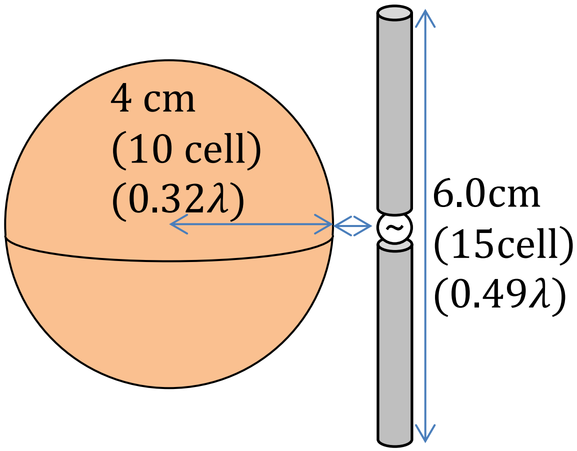
- 2.45 GHz

Body tissue
Lossy dielectric sphere
$\epsilon_r = 53.57, \sigma = 1.81$ S/m
(Value of muscle at 2.45 GHz)

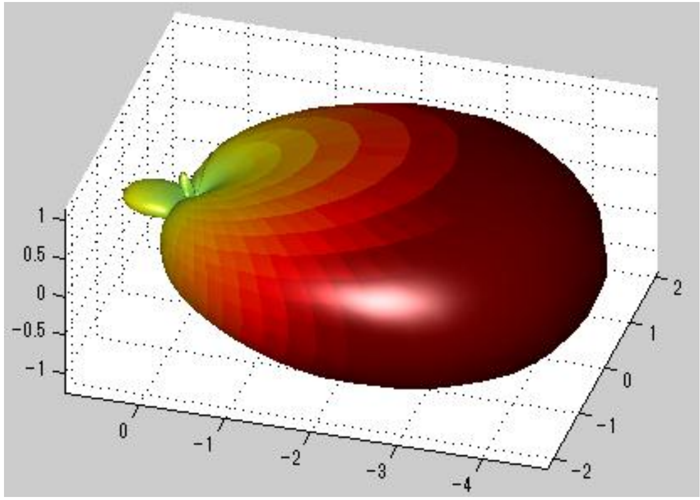


T'

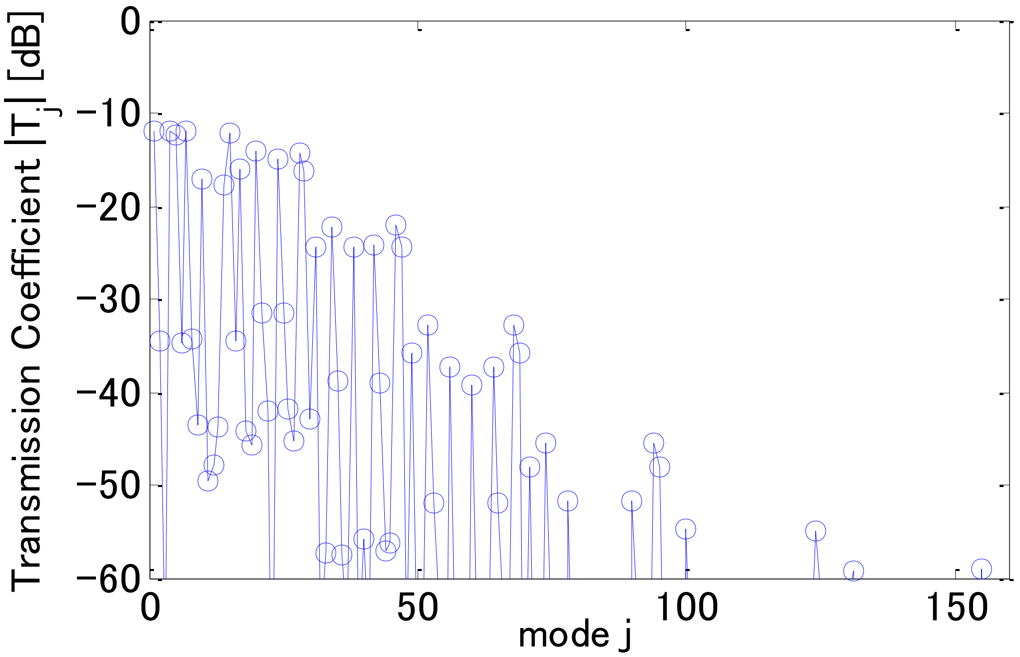
Simulation result



Radiation Pattern



Transmission Coefficient T'

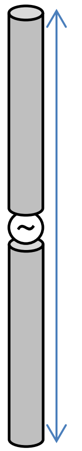


Gain: -3.47 dB (direction to Rx)

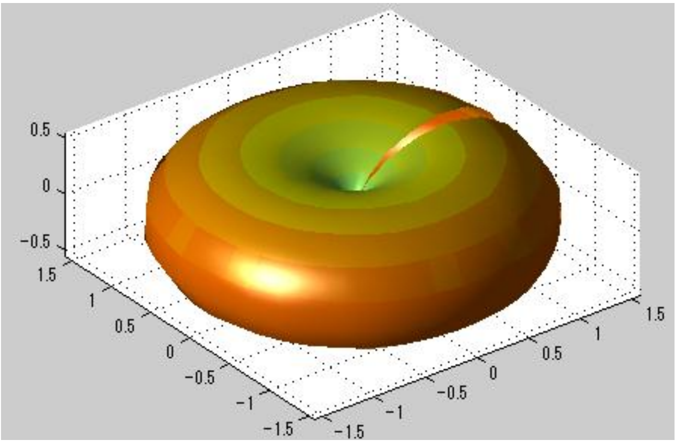
Input impedance: 58.24 + j37.64

R

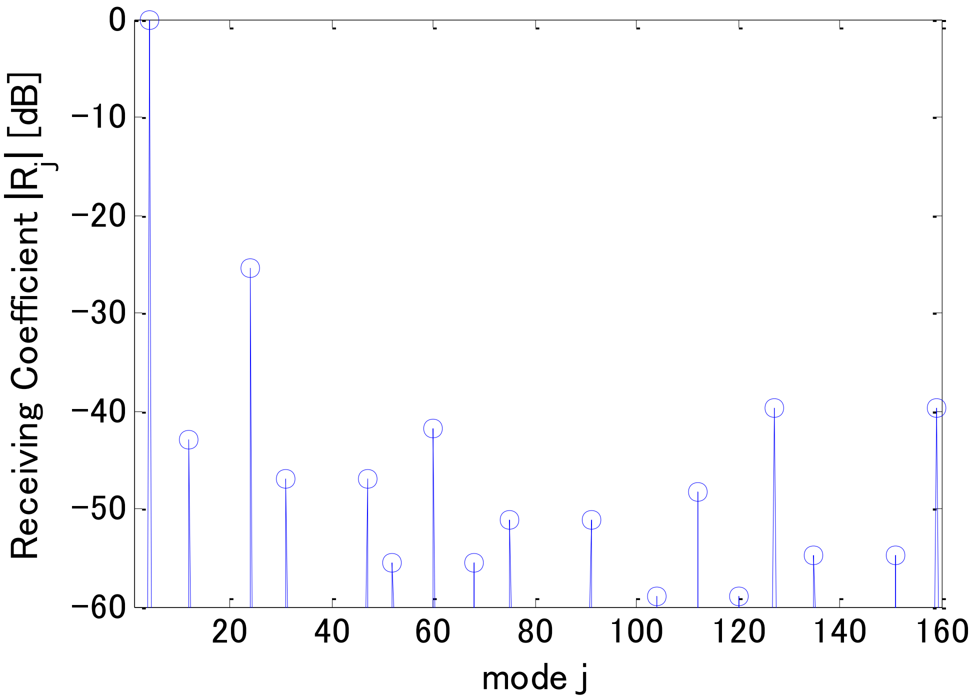
Simulation result



Radiation Pattern



Receiving Coefficient R'



Input impedance: 88.25 + j28.50
Gain: 2.09 dB

M

- Regarding M, same result can be used to the case of Yagi-Uda antenna
  - Channel is same: free space with distance of 120 cm

Result

- Pathgain $|\boldsymbol{h}|$
  - Proposed approach … -41.67 dB
  - Embedded simulation (conventional approach) … -42.30 dB
  - Friis transmission formula … -43.21 dB

Summary and Future Work

Summary

Background

- Antennas and channel are included in the same computational domain of propagation simulation

Purpose

- Antenna de-embedding should be achieved: Performing simulation separately for antennas and channel

Approach

- Modeling channel and antennas by spherical wave

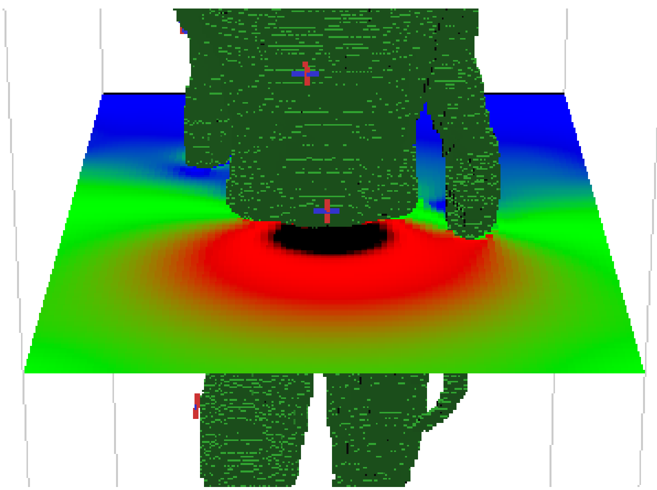
Result

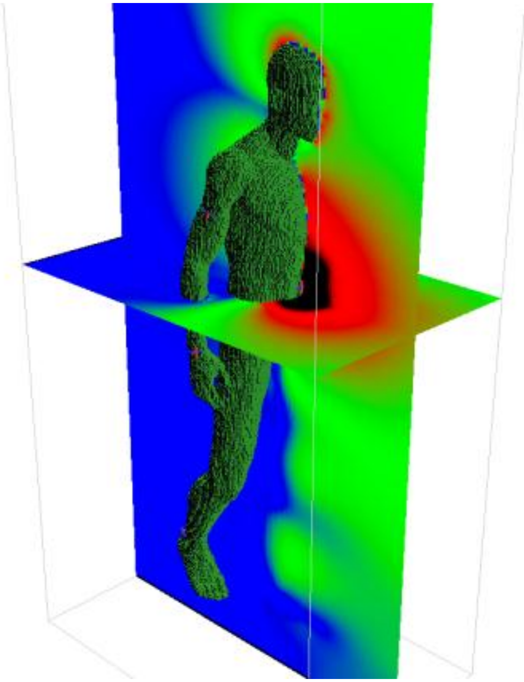
- Numerical examples are presented
- Proposed approach is validated by comparison to Friis transmission formula and embedded simulation

Future work

Extension to Body Area Network

- Validation in the more realistic channel.
- Including the effect of human body to antenna characteristic





Thank you for your kind attention.

Appendix A. Spherical Wave Theory

Spherical Wave

- It is know that any E-field can be expressed by using the summation of spherical waves.

$$\boldsymbol{E}(r,\theta,\phi) = k\sqrt{\eta}\sum_{c=1}^{4}\sum_{n=1}^{N}\sum_{m=-n}^{n}\sum_{s=1}^{2} Q_{smn}^{(c)}\boldsymbol{F}_{smn}^{(c)}(r,\theta,\phi)$$

- Definition

  F_{smn}^{c*} … complex conjugate of spherical waves
  Q_{smn}^{c}… coefficient
  k… wave number
  η… wave impedance

- In stead of $n, m,$ and s, j can be used.

$$\boldsymbol{E}(r,\theta,\phi) = k\sqrt{\eta}\sum_{c=1}^{4}\sum_{j=1}^{J} Q_{j}^{(c)}\boldsymbol{F}_{j}^{(c)}(r,\theta,\phi)$$

$$j = 2\{n(n+1)+m-1\}+s$$

$$J = 2N(N+2)$$

Exact expression

$$\boldsymbol{F}^{(c)}_{1mn}(r,\phi,\theta) = \frac{1}{\sqrt{2\pi}}\frac{1}{\sqrt{(n+1)}}\left(-\frac{m}{|m|}\right)$$
$$\left\{z_n^{(c)}(kr)\frac{im\bar{P}_n^{|m|}\cos(\theta)}{\sin(\theta)}e^{im\phi}\hat{\theta} - z_n^{(c)}(kr)\frac{\mathrm{d}\bar{P}_n^{|m|}(\cos(\theta))}{\mathrm{d}\theta}e^{im\phi}\hat{\phi}\right\}$$

$$\boldsymbol{F}^{(c)}_{2mn}(r,\phi,\theta) = \frac{1}{\sqrt{2\pi}}\frac{1}{\sqrt{n(n+1)}}\left(-\frac{m}{|m|}\right)$$
$$\left\{\frac{n(n+1)}{kr}z_n^c(kr)\bar{P}_n^{|m|}\cos(\theta)e^{im\phi}\hat{r}\right.$$
$$+\frac{1}{kr}\frac{\mathrm{d}}{\mathrm{d}(kr)}\{z_n^c(kr)\}\frac{\mathrm{d}\bar{P}_n^{|m|}(\cos(\theta))}{\mathrm{d}\theta}\hat{\theta}$$
$$\left.+\frac{1}{kr}\frac{\mathrm{d}}{\mathrm{d}(kr)}\{z_n^c(kr)\}\frac{im\bar{P}_n^{|m|}\cos(\theta)}{\sin(\theta)}\hat{\phi}\right\}$$

$$z_n^{(1)} = j_n(kr)$$
$$z_n^{(2)} = n_n(kr)$$
$$z_n^{(3)} = h_n(kr) = j_n(kr) + in_n(kr)$$
$$z_n^{(4)} = h_n(kr) = j_n(kr) - in_n(kr)$$

Exact expression

Choice of c depends on the type of wave:

- Standing wave
  - $c = 1{,}2$ is sufficient

$$\boldsymbol{E}(r,\theta,\phi) = k\sqrt{\eta}\sum_{j=1}^{J} Q_{smn}^{(1)}\boldsymbol{F}_{smn}^{(1)}(r,\theta,\phi) + Q_{smn}^{(2)}\boldsymbol{F}_{smn}^{(2)}(r,\theta,\phi)$$

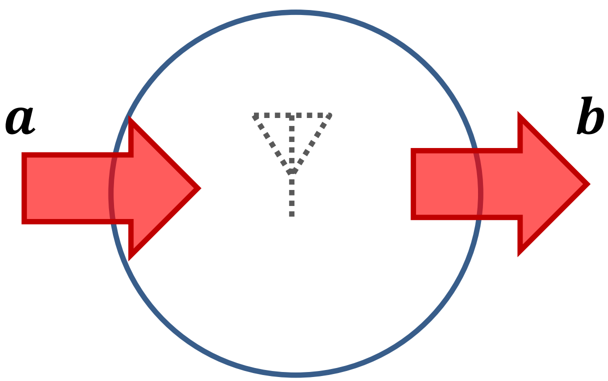
- Traveling wave
  - $c = 3{,}4$ is sufficient
    $c = 4$ … incoming wave
    $c = 3$ … outwarding wave

$$\boldsymbol{E}(r,\theta,\phi) = k\sqrt{\eta}\sum_{j=1}^{J} Q_{smn}^{(3)}\boldsymbol{F}_{smn}^{(3)}(r,\theta,\phi) + Q_{smn}^{(4)}\boldsymbol{F}_{smn}^{(4)}(r,\theta,\phi)$$

Appendix B. Expansion at Rx

4. Obtaining incoming wave $\boldsymbol{a}$ from observed E-field $\boldsymbol{E}$

- Without receiving antenna $\boldsymbol{a} = \boldsymbol{b}$



$$\boldsymbol{E}(r,\theta,\phi) = k\sqrt{\eta}\sum_{j}^{J} b_j \boldsymbol{F}_j^{(3)} + a_j \boldsymbol{F}_j^{(4)}(r,\theta,\phi)$$

$$= k\sqrt{\eta}\sum_{j}^{J} a_j \left\{ \boldsymbol{F}_j^{(3)} + \boldsymbol{F}_j^{(4)}(r,\theta,\phi) \right\}$$

↓ #1

$$= k\sqrt{\eta}\sum_{j}^{J} 2a_j \boldsymbol{F}_j^{(1)}(r,\theta,\phi)$$

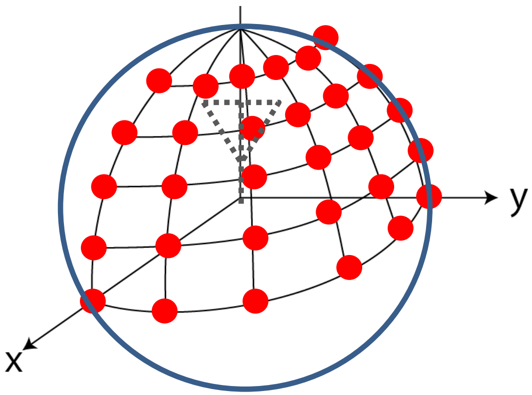
#1

$$z_n^{(1)} = j_n(kr)$$
$$z_n^{(2)} = n_n(kr)$$
$$z_n^{(3)} = h_n(kr) = j_n(kr) + in_n(kr)$$
$$z_n^{(4)} = h_n(kr) = j_n(kr) - in_n(kr)$$

How to obtain receiving mode

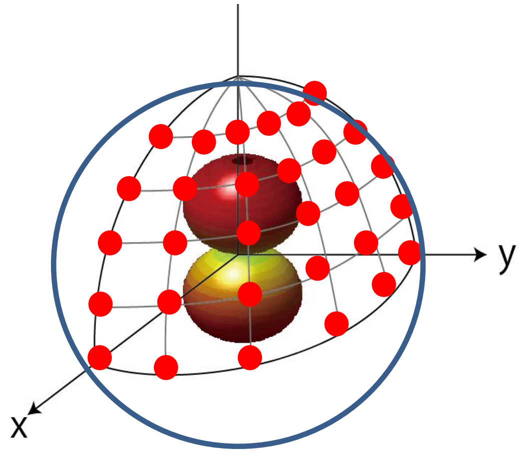
Spherical Wave Expansion

(1) E-field at observation points



$$\boldsymbol{E} = \begin{bmatrix} \boldsymbol{E}(\theta_1,\phi_1)\cdot\hat{\theta} \\ \boldsymbol{E}(\theta_2,\phi_2)\cdot\hat{\theta} \\ \vdots \\ \boldsymbol{E}(\theta_{N_s},\phi_{N_s})\cdot\hat{\theta} \\ \boldsymbol{E}(\theta_1,\phi_1)\cdot\hat{\phi} \\ \boldsymbol{E}(\theta_2,\phi_2)\cdot\hat{\phi} \\ \vdots \\ \boldsymbol{E}(\theta_{N_s},\phi_{N_s})\cdot\hat{\phi} \end{bmatrix}$$

(2) E-field by mode *j*



$$\boldsymbol{F}_j = \begin{bmatrix} \boldsymbol{F}_j^{(1)}(\theta_1,\phi_1)\cdot\hat{\theta} \\ \boldsymbol{F}_j^{(1)}(\theta_2,\phi_2)\cdot\hat{\theta} \\ \vdots \\ \boldsymbol{F}_j^{(1)}(\theta_{N_s},\phi_{N_s})\cdot\hat{\theta} \\ \boldsymbol{F}_j^{(1)}(\theta_1,\phi_1)\cdot\hat{\phi} \\ \boldsymbol{F}_j^{(1)}(\theta_2,\phi_2)\cdot\hat{\phi} \\ \vdots \\ \boldsymbol{F}_j^{(1)}(\theta_{N_s},\phi_{N_s})\cdot\hat{\phi} \end{bmatrix}$$

(3) Expansion

$$\boldsymbol{E}' = k\sqrt{\eta} \sum_{j=1} b_j \boldsymbol{F}_j$$

$$\boldsymbol{E}' = k\sqrt{\eta} \left[\boldsymbol{F}_1 \ \boldsymbol{F}_2 \ \ldots \boldsymbol{F}_J\right] \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_J \end{bmatrix}$$

$$\boldsymbol{E}' = k\sqrt{\eta}\, \boldsymbol{F}\boldsymbol{b}'$$

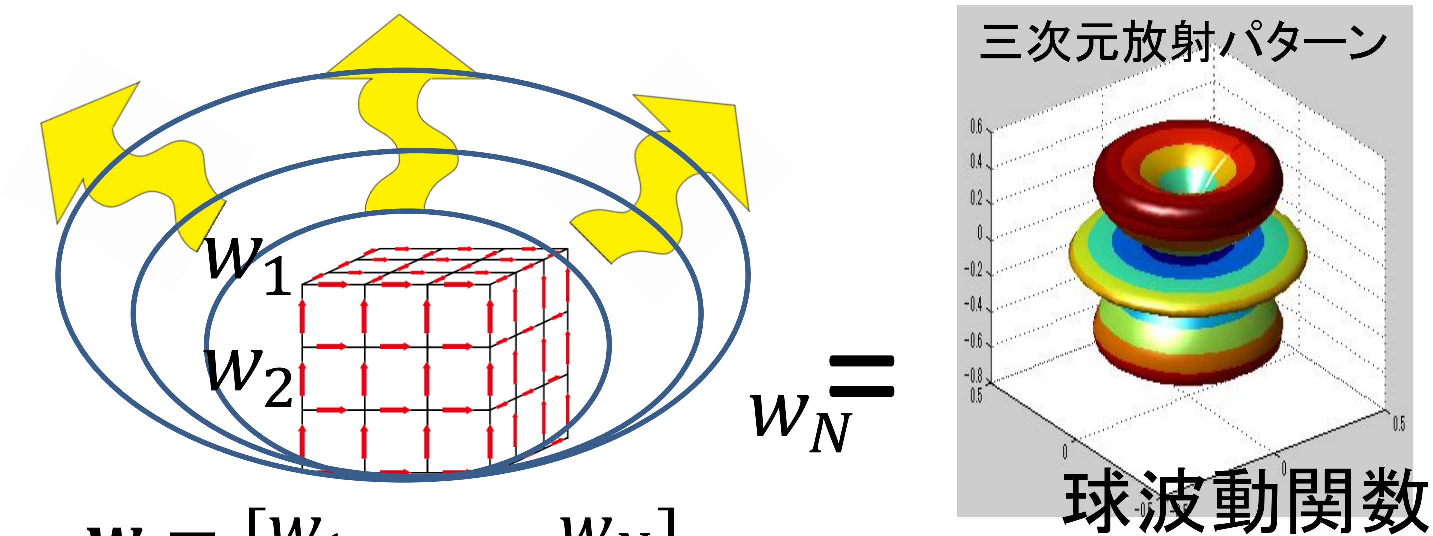
$$\boldsymbol{b}' = \frac{1}{k\sqrt{\eta}} \boldsymbol{F}^{-1}\boldsymbol{E}'$$

Pseudo inverse

Appendix C. Excitation of spherical wave

アプローチ

- FDTDグリッド上に構成された微小ダイポールアレイの励振電流を制御して所望のモードを生成
  - 微小ダイポールはFDTD上で点電流源として実現される



$$\boldsymbol{w} = [w_1 \quad \cdots \quad w_N]$$

- 励振電流の決定方法は点整合法

点整合法による励振電流の取得

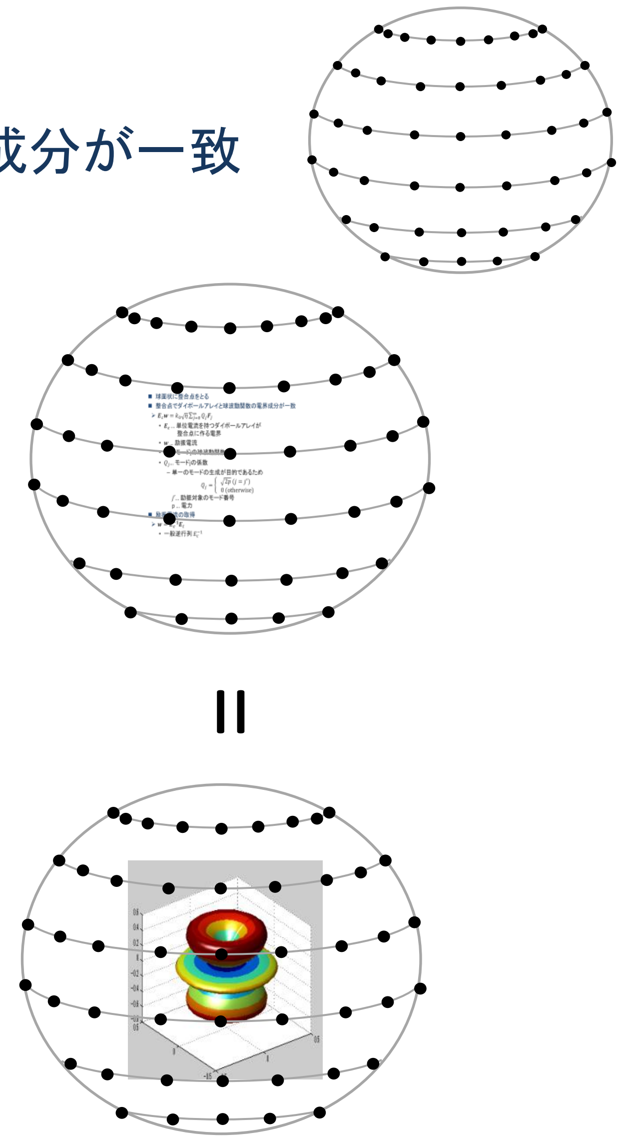
- 球面状に整合点をとる
- 整合点でダイポールアレイと球波動関数の電界成分が一致
  - $\boldsymbol{E}_c \boldsymbol{w} = k_0 \sqrt{\eta} \sum_{j=0}^{\infty} Q_j \boldsymbol{F}_j$
    - $\boldsymbol{E}_c$ ... 単位電流を持つダイポールアレイが整合点に作る電界
    - $\boldsymbol{w}$ ... 励振電流
    - $\boldsymbol{F}_j$ ... モードjの球波動関数
    - Q_j... モードjの係数
      - 単一のモードの生成が目的であるため

$$Q_j = \begin{cases} \sqrt{2p} \ (j = j') \\ 0 \ (\text{otherwise}) \end{cases}$$

j'... 励振対象のモード番号

p ... 電力

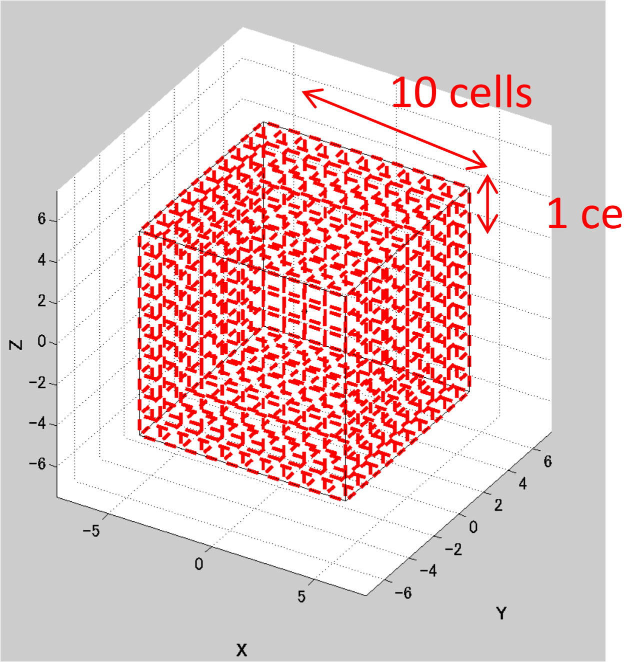
- 励振電流の取得
  - $\boldsymbol{w} = \boldsymbol{E}_c^{-1} \boldsymbol{E}_t$
    - 一般逆行列 E_c^{-1}



励振例

■ パラメータ

周波数	2.4GHz
FDTDセルサイズ	1/25λ (5mm)
ダイポールアレイのサイズ	各方向 10 cells (5cm)
観測半径	3.6λ
整合点および観測点	θ方向の分割数 20 φ方向の分割数 40
ダイポール数	1200
時間ステップ	5psec
ステップ数	3000

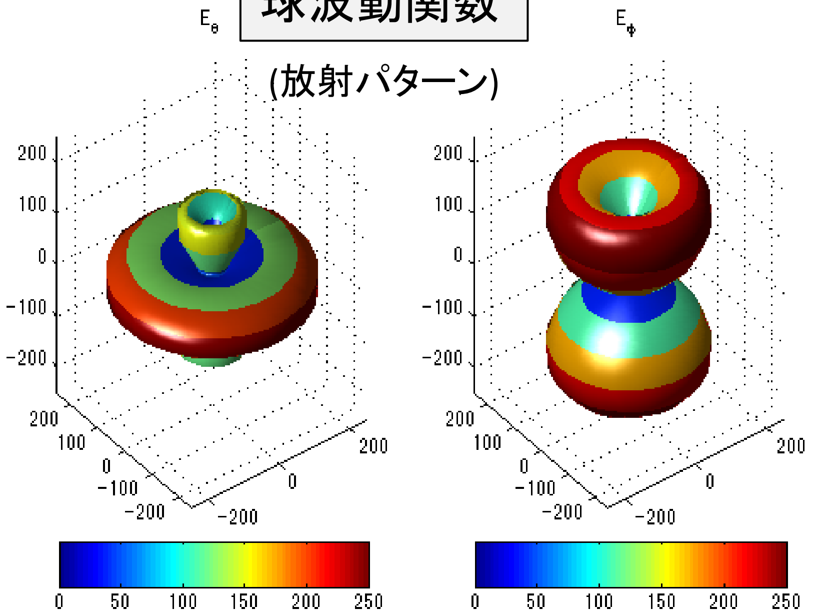


ダイポールアレイ

励振例 (j’ = 20 モード)

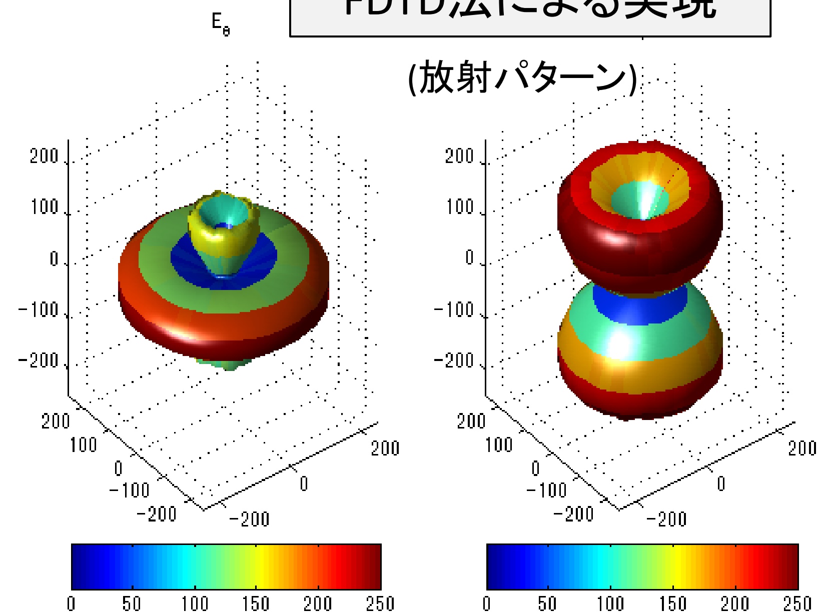
球波動関数

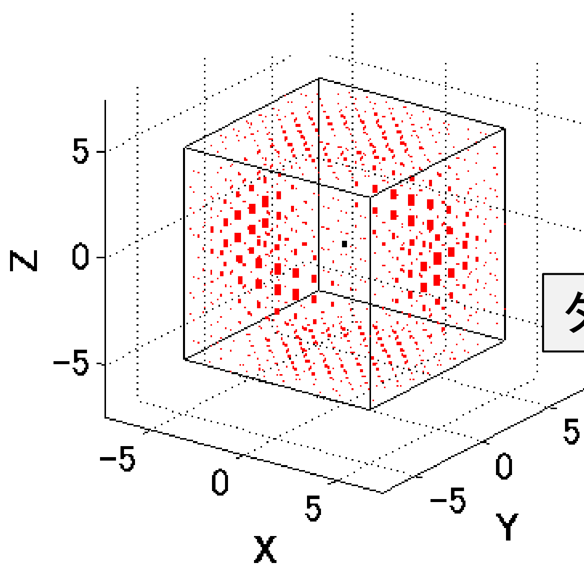
(放射パターン)



FDTD法による実現

(放射パターン)





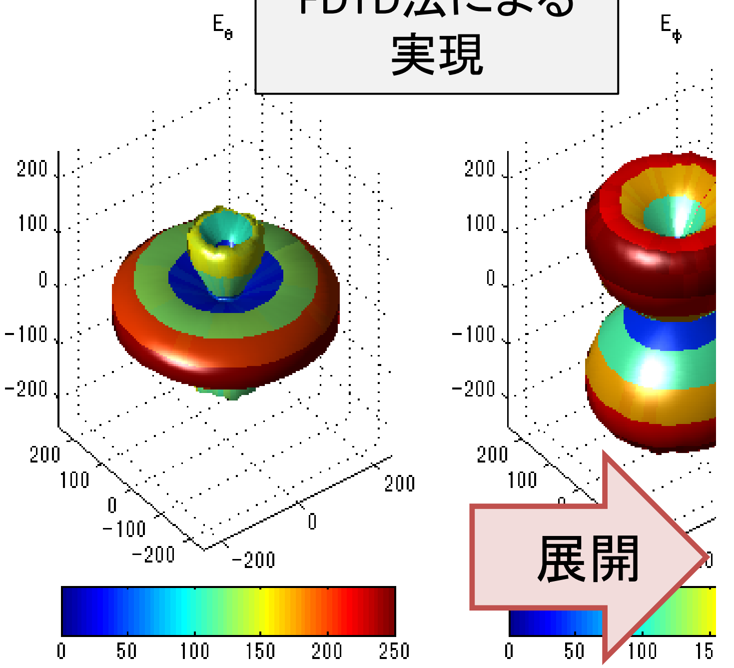
ダイポールアレイ

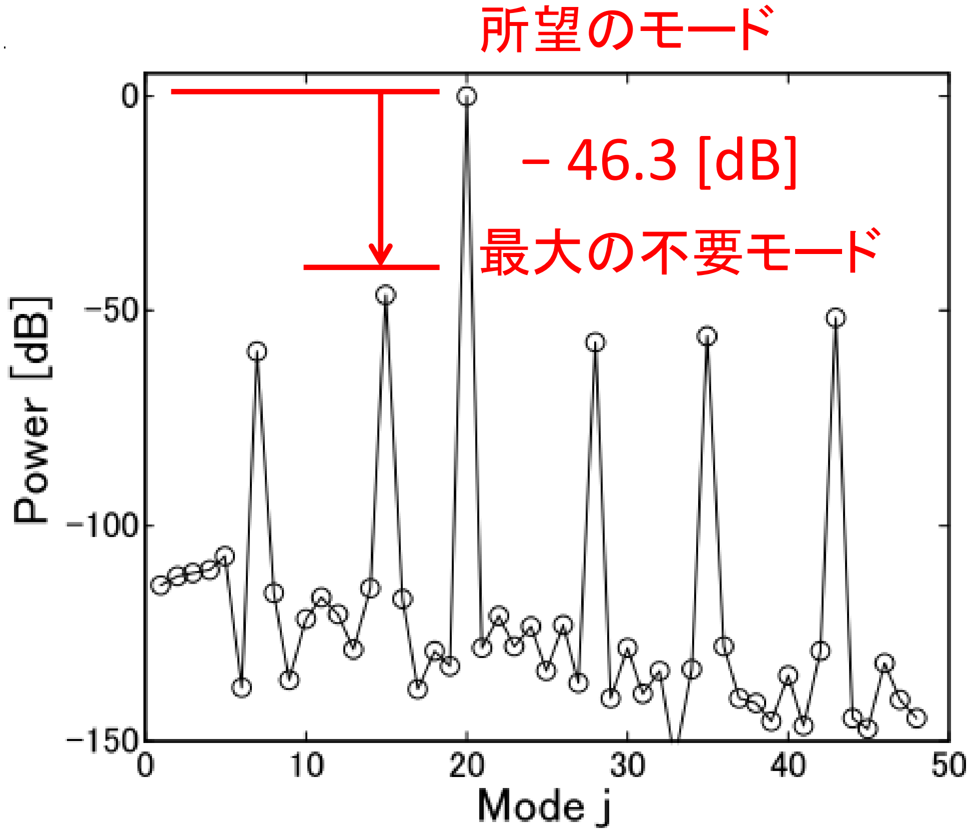
励振例

■ 誤差の評価

➢ 励振された電界を展開し，最大の不要モードの大きさを評価

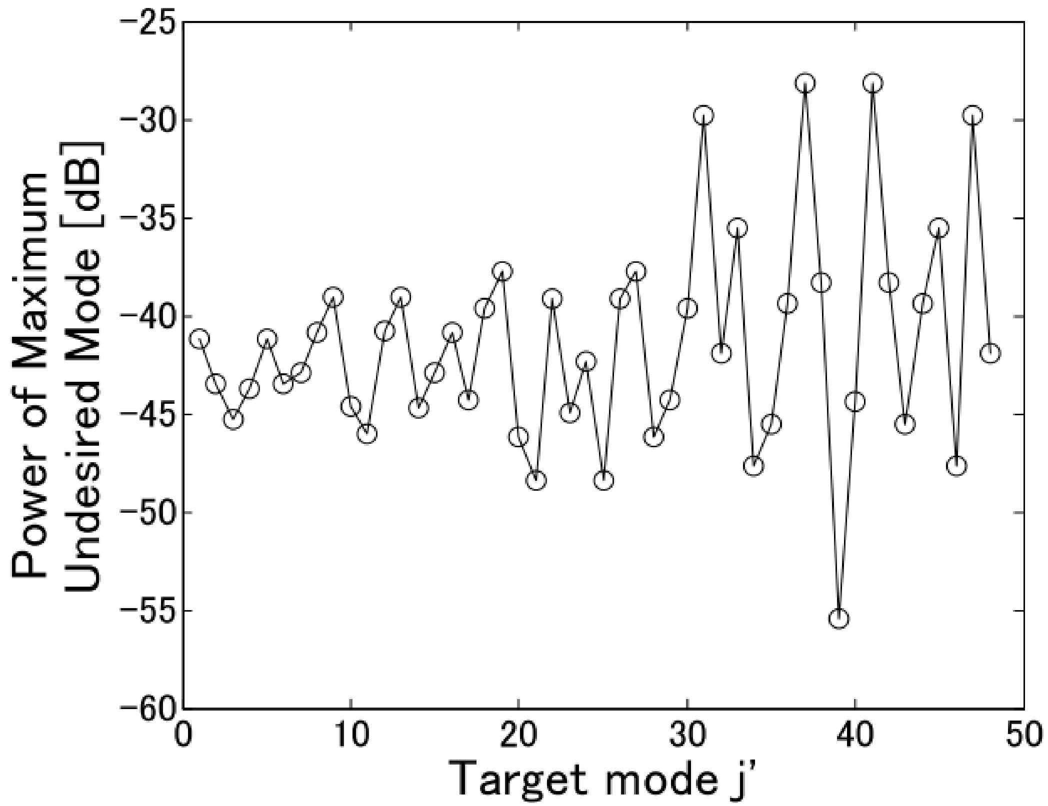
FDTD法による実現





評価

- j'=1 ... 48 のモードに対して同様の評価を実行
  - 励振 → 展開 → 最大の不要モードの大きさを評価
  - BAN用の小型アンテナのモデル化には十分と想定



- 全てのモードで-25dB以下を達成

Appendix D.

- J = 48
- Spherical 42.275150
- Embed 42.297497
- Friis 43.219244