Accelerated FDTD Computation Applied to Antenna Shape Optimization

Graduate School of Information Science and Technology
Hokkaido University

Yuta Watanabe
Kota Watanabe
Hajime Igarashi

Outline

I. Background

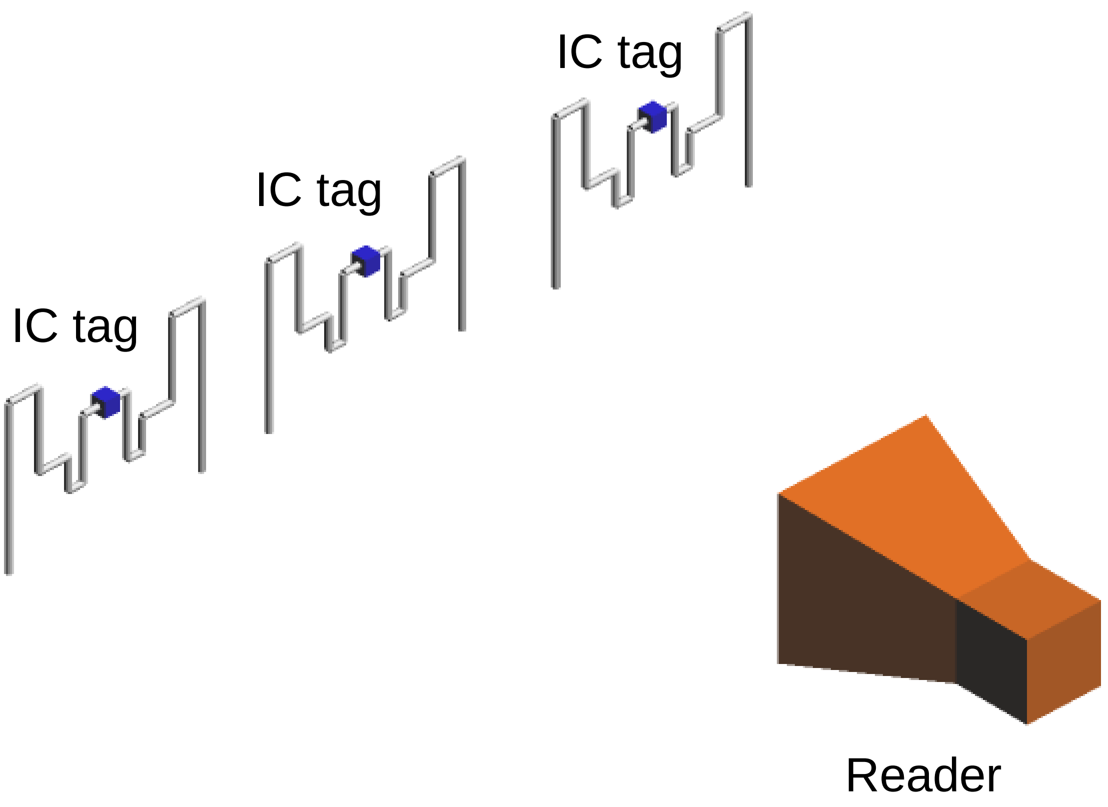
II. Coupling analysis accelerated TP-EEC method

III. Optimization of patch antenna

IV. Conclusions

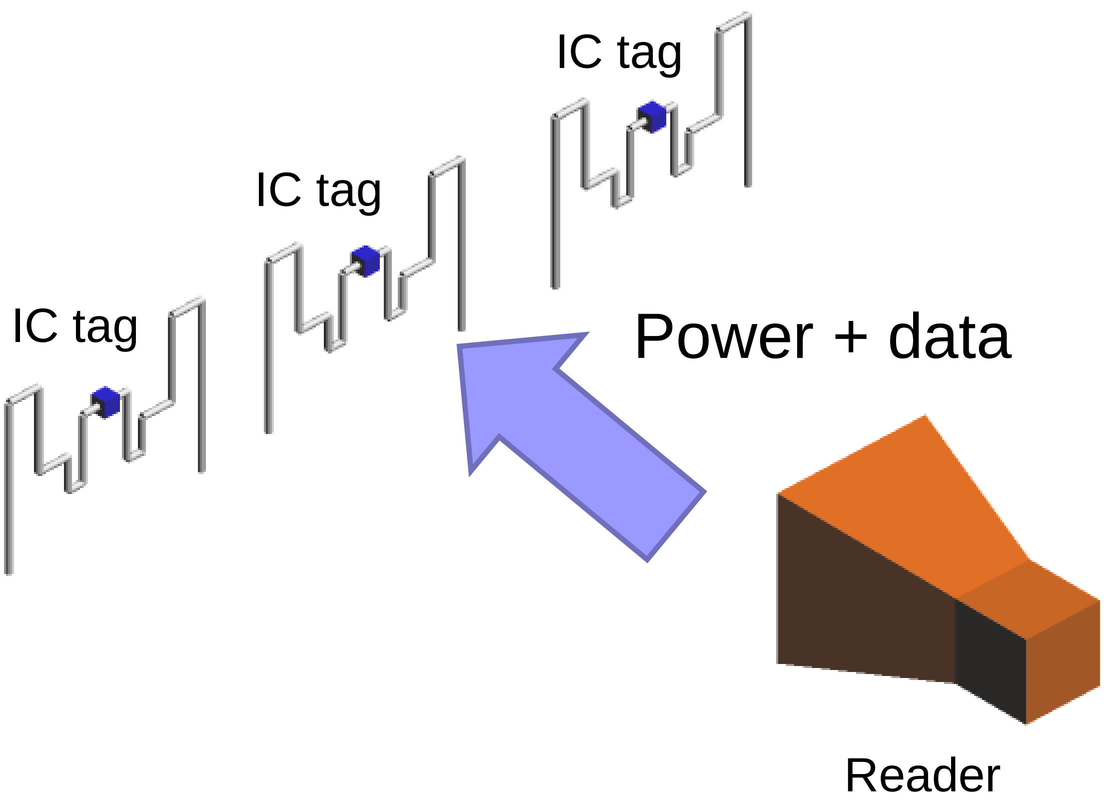
Background

The Radio Frequency Identification (RFID) system is composed of the RFID tag and reader.



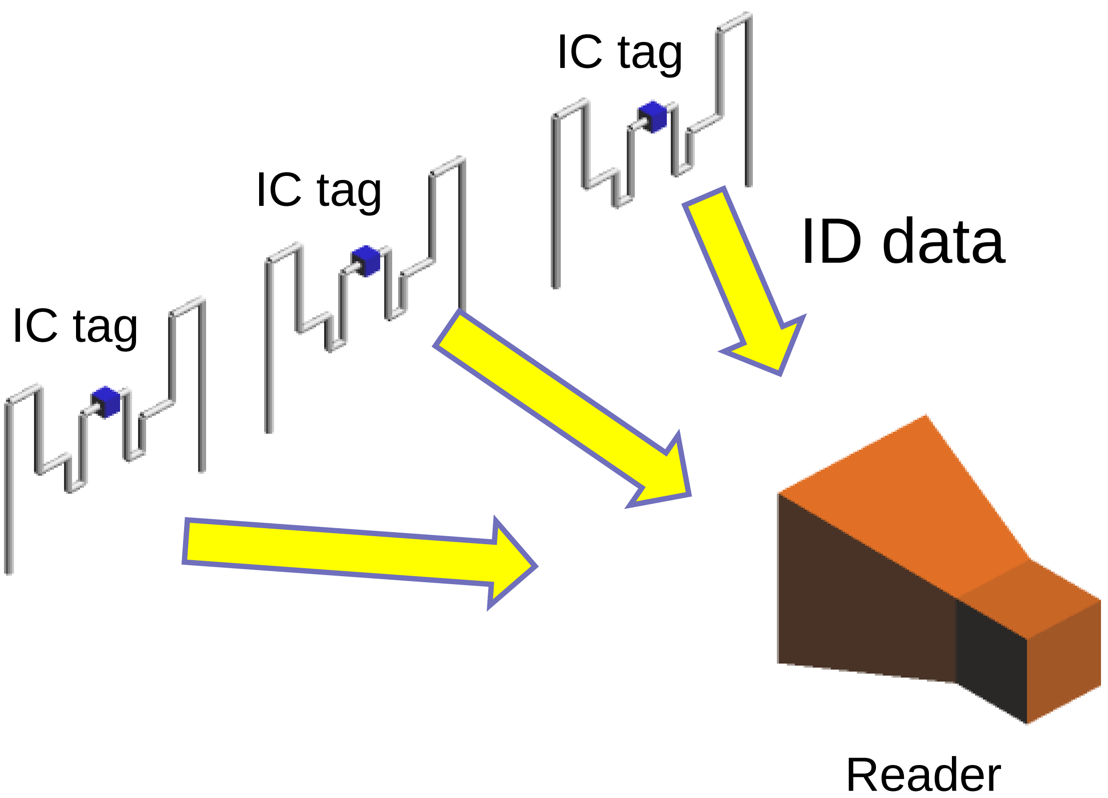
Background

The Radio Frequency Identification (RFID) system is composed of the RFID tag and reader.



Background

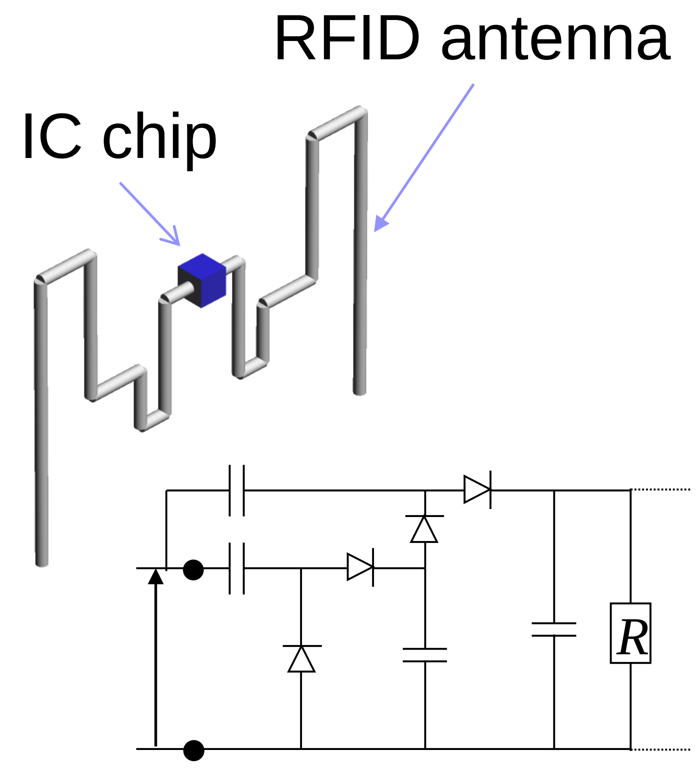
The Radio Frequency Identification (RFID) system is composed of the RFID tag and reader.



Background

The RFID system is promising for various applications, such as remote sensing and retail management.

Optimization of the RFID antenna and IC chip is of importance.



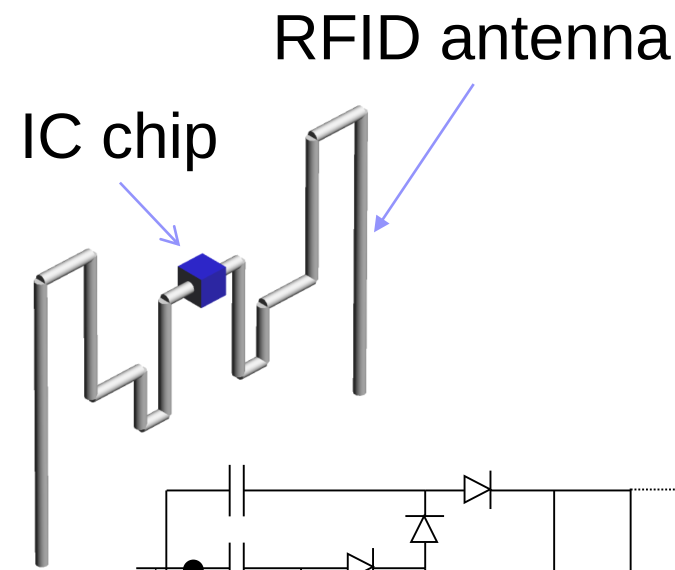
Example of IC chip

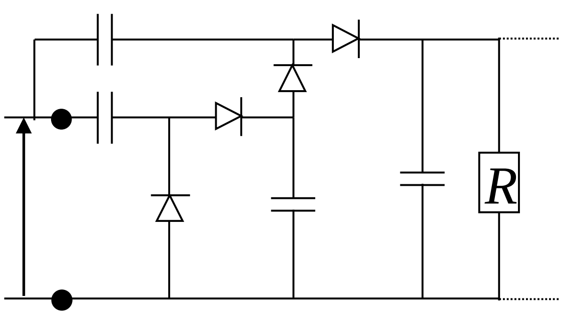
Background

Optimization of the RFID tag is difficult because of analysis of RFID tag.

- Takes into account between RFID antenna and IC chip
- Requires time domain computation

Optimization of the RFID tag requires high computational cost.





Example of IC chip

Background

To overcome these problems, we accelerate the coupling analysis of electromagnetic field and nonlinear circuit.

TP-EEC[1] method is applied to coupling analysis for acceleration.

[1] Y. Takahashi, T. Tokumasu, A. Kameari, H. Kaimori, M. Fujita, T. Iwashita and S. Wakao, "Convergence acceleration of time periodic electromagnetic field analysis by the singularity decomposition-explicit error correction method," *IEEE Trans. Magn*., vol. 46, no. 6, pp. 946-949.

Outline

I. Background

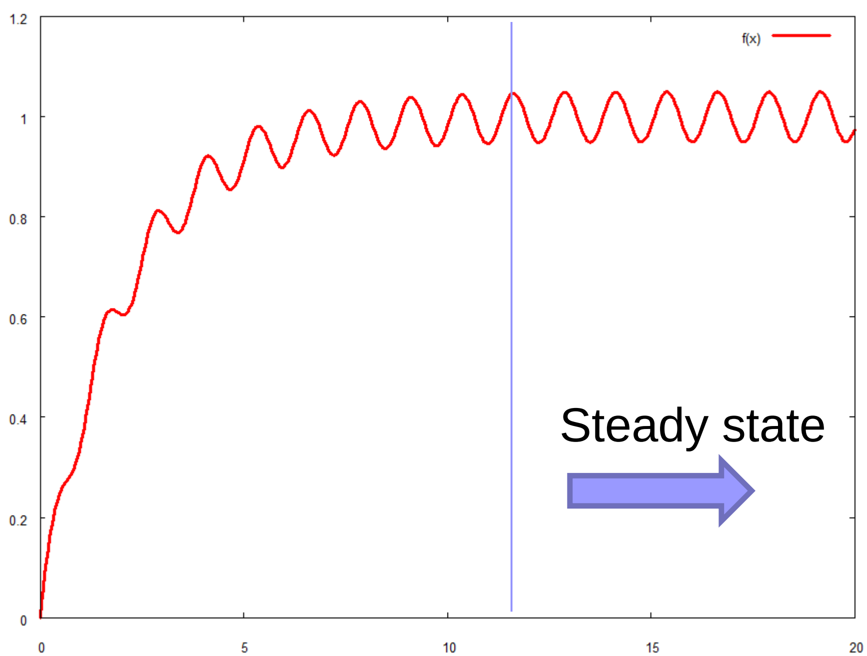
II. Coupling analysis accelerated TP-EEC method

III. Optimization of patch antenna

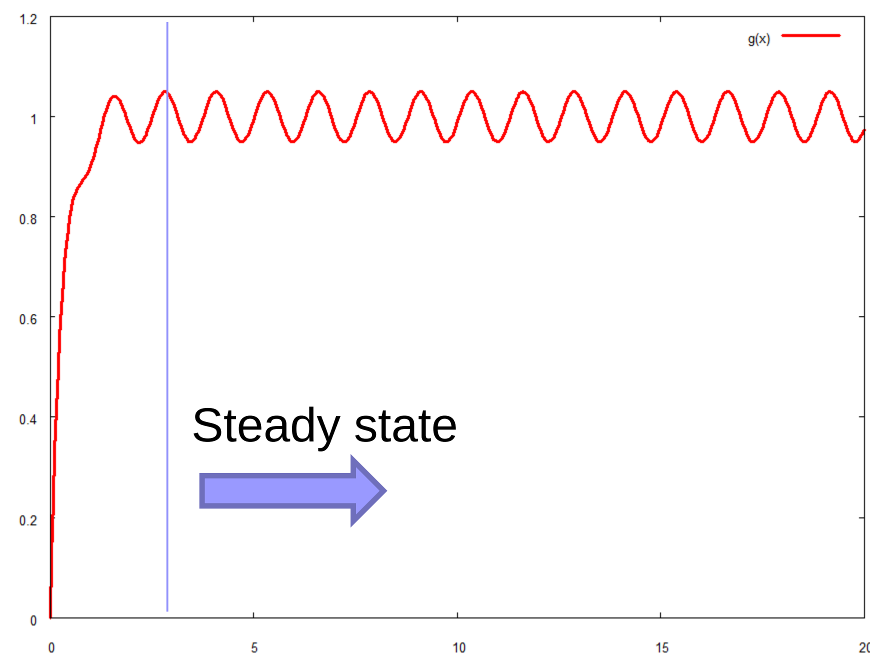
IV. Conclusions

TP-EEC method

The time periodic explicit error correction method accelerates convergence to a steady state.



Slow convergence



Fast convergence

One dimensional example

Let us consider the following equation

$$u + \tau \frac{\mathrm{d}u}{\mathrm{d}t} = f(t). \qquad (1)$$

Equation (1) is discretized by finite difference in time as follows:

$$(C+1)u^n - Cu^{n-1} = F^n. \qquad (2)$$

where

$$C = \theta - 1 + \frac{\tau}{\Delta t}, \quad 0 \le \theta \le 1$$

$$F^n = \theta f^n + (1-\theta) f^{n-1}$$

One dimensional example

Let us consider the following equation

$$u + \tau \frac{\mathrm{d}u}{\mathrm{d}t} = f(t). \qquad (1)$$

Equation (1) is discretized by finite difference in time as follows:

$$(C+1)u^{n} - Cu^{n-1} = F^{n}. \qquad (2)$$

It is assumed that convergence to a steady state is as slow as follows:

$$C \approx \frac{\tau}{\Delta t} >> 1.$$

One dimensional example

The stationary solution of (2) is denoted by $u^*(t)$. Error $e^n = u^*(n\Delta t) - u^n$ obeys

$$(C+1)e^n = Ce^{n-1}$$

Therefore, the error e^n is given by

$$e^n = \frac{1}{1+\varepsilon} e^{n-1}, \ \varepsilon = \frac{1}{C} \approx \frac{\Delta t}{\tau} << 1.$$

We introduce error vectors $\boldsymbol{e}$ defined for each period as

$$\boldsymbol{e} = \begin{bmatrix} 1/(1+\varepsilon) \\ 1/(1+\varepsilon)^2 \\ \vdots \\ 1/(1+\varepsilon)^N \end{bmatrix} e^0 \approx \begin{bmatrix} 1-\varepsilon \\ 1-2\varepsilon \\ \vdots \\ 1-N\varepsilon \end{bmatrix} e^0 = \left(1 - \varepsilon \frac{N+1}{2}\right) \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} e^0 - \frac{\varepsilon}{2} \begin{bmatrix} -(N-1) \\ \vdots \\ N-2 \\ N-1 \end{bmatrix} e^0$$

One dimensional example

The error vectors are composed of the 0th and 1st order components.

$$\boldsymbol{e} \approx \left(1 - \varepsilon \frac{N+1}{2}\right) \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} e^0 - \frac{\varepsilon}{2} \begin{bmatrix} -(N-1) \\ \vdots \\ N-2 \\ N-1 \end{bmatrix} e^0$$

0th order component

1st order component

One dimensional example

Equation (2) is expressed for each period as

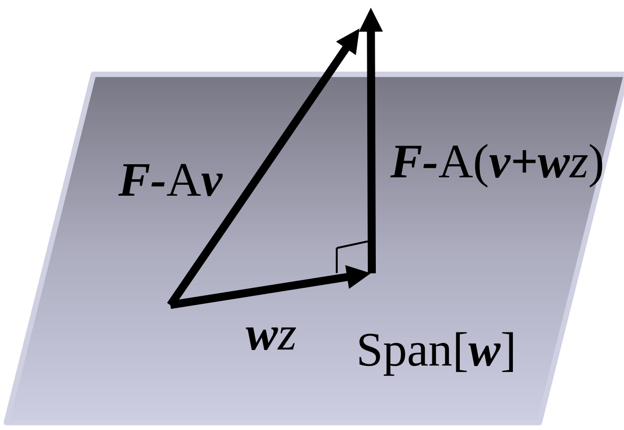
$$\begin{bmatrix} C^1 & 0 & \cdots & C^N \\ C^1 & C^2 & \cdots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & \cdots & C^{N-1} & C^N \end{bmatrix} \begin{bmatrix} u^1 \\ u^2 \\ \vdots \\ u^N \end{bmatrix} = \begin{bmatrix} F^1 \\ F^2 \\ \vdots \\ F^N \end{bmatrix} \Rightarrow \mathrm{A}\boldsymbol{u} = \boldsymbol{F}$$

Approximate solution $\boldsymbol{u}^{\text{new}}$ is decomposed into fast and slowly converging components;

$$\boldsymbol{u}^{\text{new}} = \boldsymbol{u} + \boldsymbol{w}z = \boldsymbol{u} + \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} z$$

z is obtained from the orthogonal condition

$$\left(\boldsymbol{F} - \mathrm{A}\left(\boldsymbol{u} + \boldsymbol{w}z\right), \boldsymbol{w}\right) = 0$$



TP-EEC method

We obtain the correction equation

$$\boldsymbol{w}^{\mathrm{t}}\mathrm{A}\boldsymbol{w}\mathrm{z} = \boldsymbol{w}^{\mathrm{t}}(\boldsymbol{F} - \mathrm{A}\boldsymbol{u})$$

by solving the correction equation, u is corrected as follows:

$$\boldsymbol{u}^{\mathrm{new}} = \boldsymbol{u} + \boldsymbol{w}(\boldsymbol{w}^{\mathrm{t}}\mathrm{A}\boldsymbol{w})^{-1}\boldsymbol{w}^{\mathrm{t}}(\boldsymbol{F} - \mathrm{A}\boldsymbol{u})$$

Because $\boldsymbol{u}=\boldsymbol{u}^{*}+\boldsymbol{e}$ and $\boldsymbol{F}=\mathrm{A}\boldsymbol{u}^{*}$, we have

$$\boldsymbol{e}^{\mathrm{new}} = \mathrm{P}\boldsymbol{e}$$

$$\mathrm{P} = \mathrm{I} - \boldsymbol{w}(\boldsymbol{w}^{\mathrm{t}}\mathrm{A}\boldsymbol{w})^{-1}\boldsymbol{w}^{\mathrm{t}}\mathrm{A}$$

TP-EEC method

Projection matrix P given by

$$\mathrm{P} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & & \\ \vdots & & \ddots & \\ 0 & & & 1 \end{bmatrix} - \frac{1}{N} \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & 1 & & \\ \vdots & & \ddots & \\ 1 & & & 1 \end{bmatrix}$$

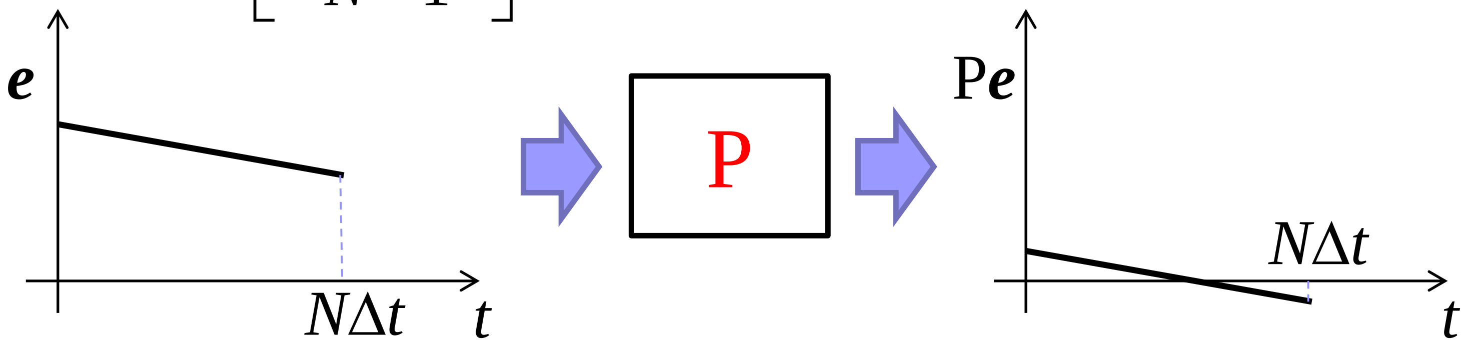
This suggests that the bias component in error $\boldsymbol{e}$ is eliminated by the correction.

$$\boldsymbol{e}^{\mathrm{new}} = \mathrm{P}\boldsymbol{e} = \begin{bmatrix} e_1 - \sum_n e_n / N \\ \vdots \\ e_N - \sum_n e_n / N \end{bmatrix}$$

Projection matrix P

P works as an error filter which eliminate the bias component.

$$\mathrm{P}\boldsymbol{e} \approx -\frac{\varepsilon}{2}\begin{bmatrix} -(N-1) \\ \vdots \\ N-2 \\ N-1 \end{bmatrix} e^0$$



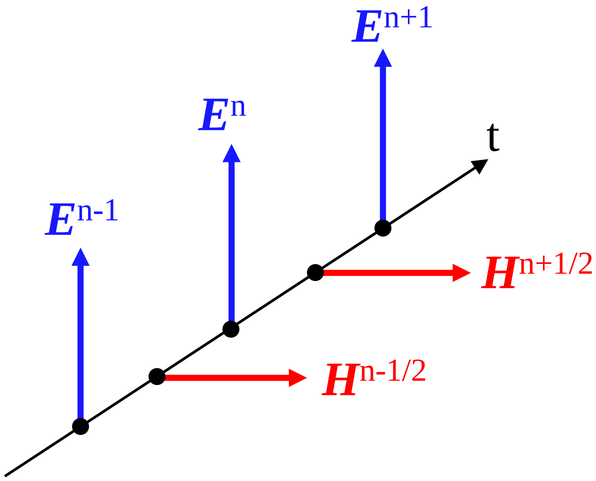
Similarly the first order component in the error can be eliminated by the TP-EEC method

Computational method - FDTD -

Maxwell equation

$$\varepsilon \frac{\partial \boldsymbol{E}(\boldsymbol{r},t)}{\partial t} + \boldsymbol{J}(\boldsymbol{r},t) = \nabla \times \boldsymbol{H}(\boldsymbol{r},t)$$

$$\mu \frac{\partial \boldsymbol{H}(\boldsymbol{r},t)}{\partial t} = -\nabla \times \boldsymbol{E}(\boldsymbol{r},t)$$



Finite difference in time

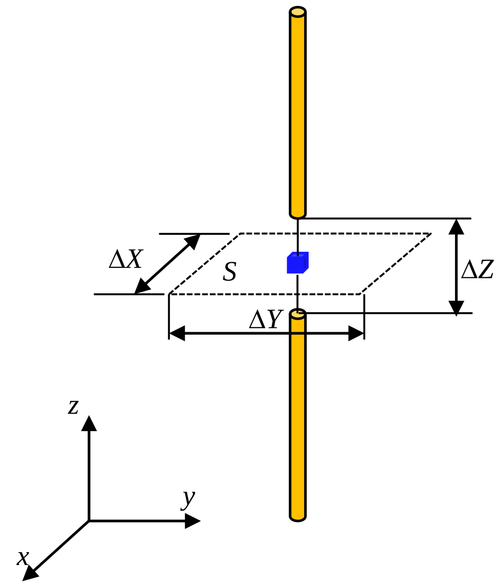
$$\boldsymbol{E}(\boldsymbol{r})^{n} = \frac{1-\sigma\Delta t/2\varepsilon}{1+\sigma\Delta t/2\varepsilon}\boldsymbol{E}^{n\text{-}1}(\boldsymbol{r}) + \frac{\Delta t/\varepsilon}{1+\sigma\Delta t/2\varepsilon}\nabla \times \boldsymbol{H}^{n\text{-}1/2}(\boldsymbol{r},t)$$

$$\boldsymbol{H}(\boldsymbol{r})^{n+1/2} = \boldsymbol{H}(\boldsymbol{r})^{n-1/2} - \frac{\Delta t/\mu}{1+\sigma\Delta t/2\varepsilon}\nabla \times \boldsymbol{E}^{n}(\boldsymbol{r},t)$$

Coupling analysis

Ampere law

$$\varepsilon \frac{\partial \boldsymbol{E}(\boldsymbol{r},t)}{\partial t} + \boldsymbol{J}(\boldsymbol{r},t) = \nabla \times \boldsymbol{H}(\boldsymbol{r},t)$$

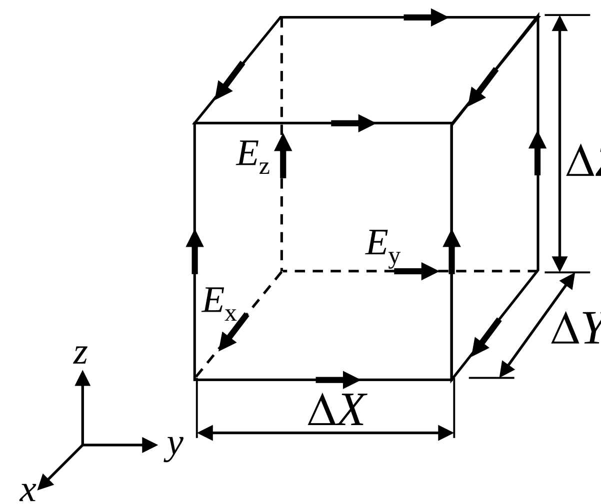


Integral of Maxwell equation on *S*

$$C_0 \frac{\partial V_L}{\partial t} + I_L(V_L) = I$$

$$C_0 = \varepsilon \frac{\Delta X \Delta Y}{\Delta Z} \qquad I_L = \Delta X \Delta Y J_z(E_z)$$

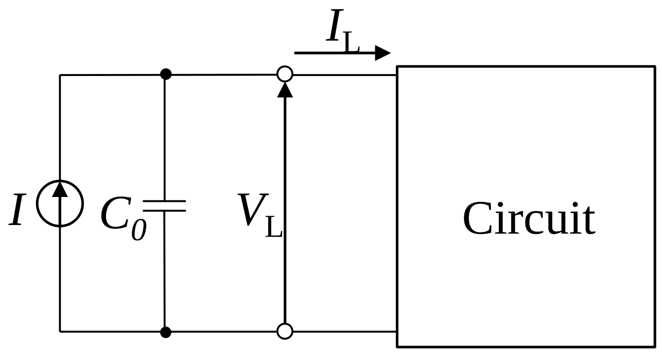
$$v_{in} = E_z \Delta Z \qquad I = \int_{\partial S} \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{s}$$

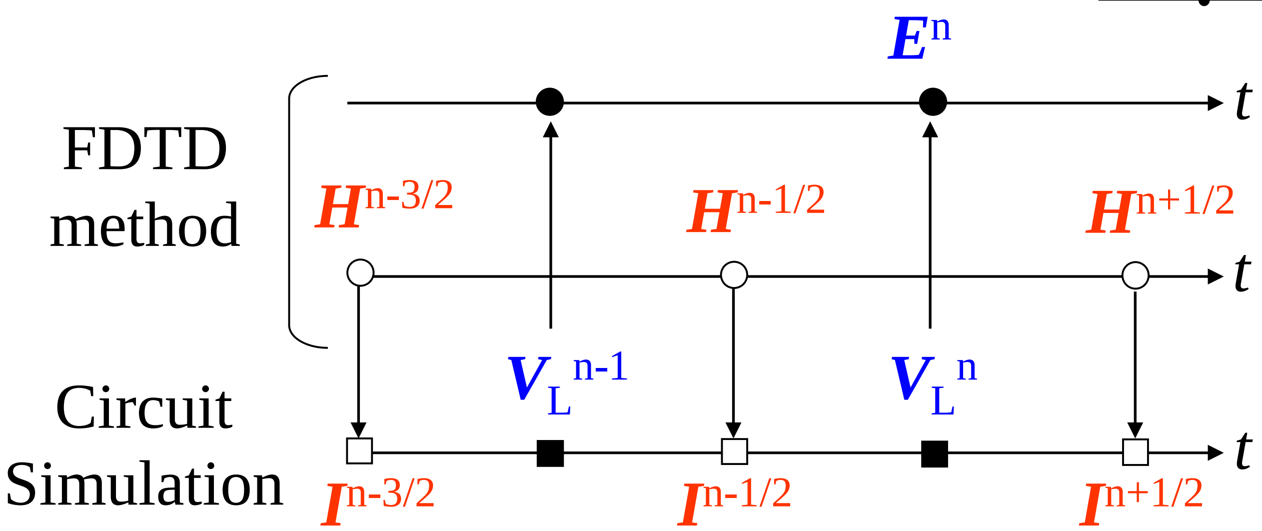


Coupling analysis

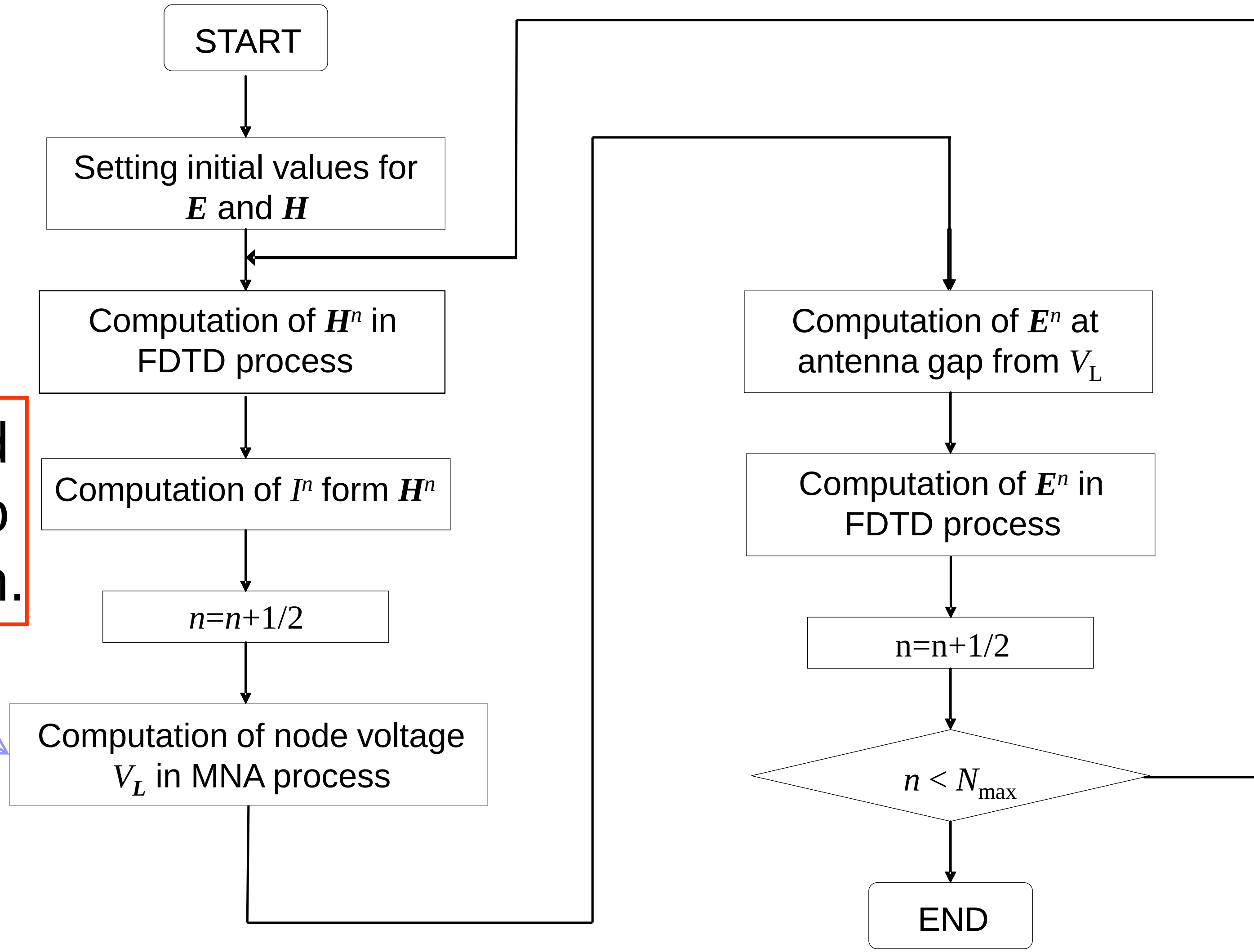
Coupling equation of FDTD and circuit simulation

$$C_0 \frac{\partial V_L}{\partial t} + I_L(V_L) = I$$



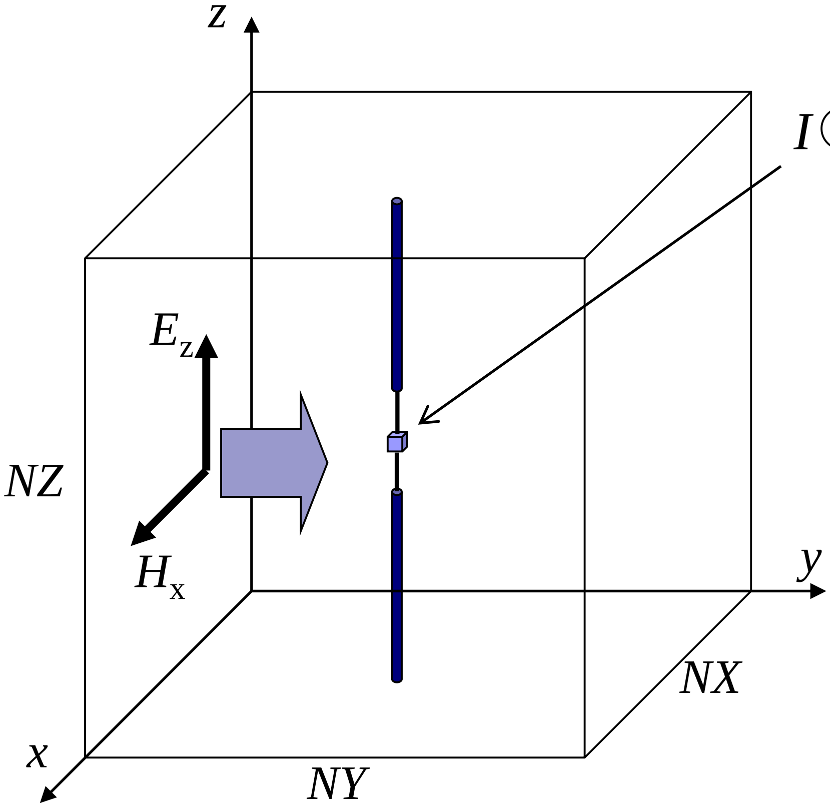


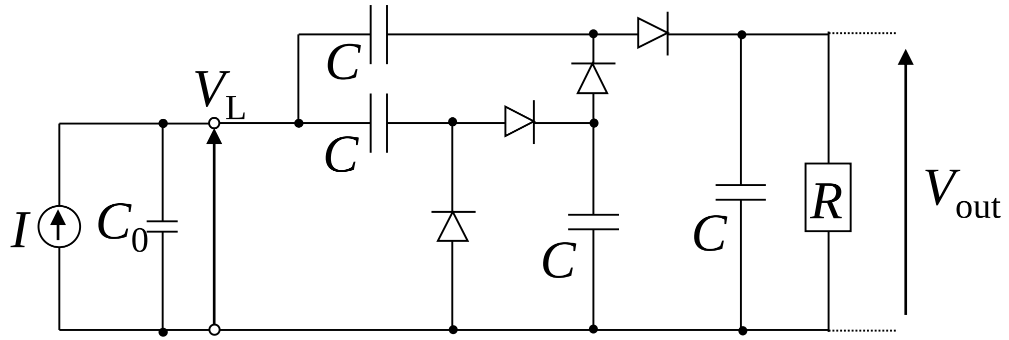
Flow chart



TP-EEC method is applied to Circuit simulation.

Analysis model





$\Delta X = \Delta Y = \Delta Z = 3\text{mm}$

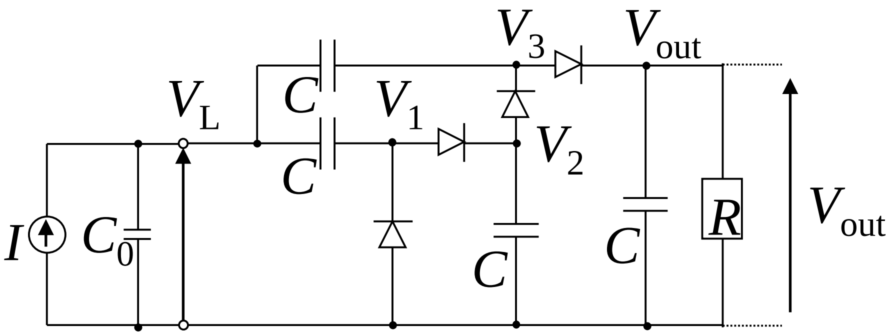
$NX = NY = NZ = 120$

Open boundary condition : PML

$f = 1\text{GHz}$

$E_z = 20\text{V/m}$

Nodal equation



Cockcroft-Walton circuit

$$C = 10\text{pF}$$

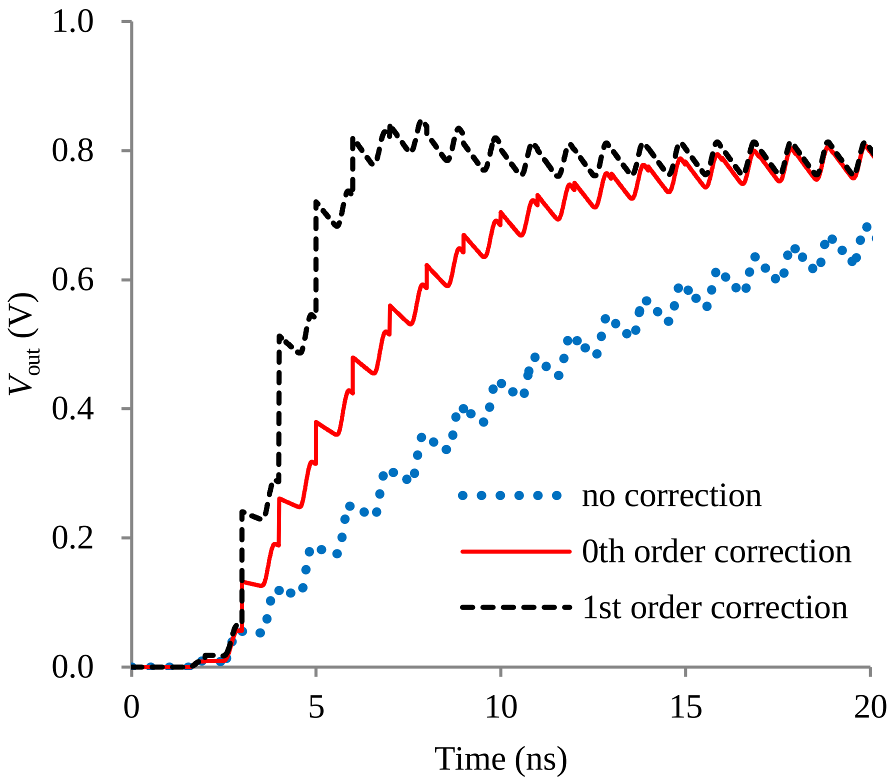
$$R = 1\text{k}\Omega$$

$$I_d(v) = 10^{-11}\{\exp(-40v) - 1\}\text{A}$$

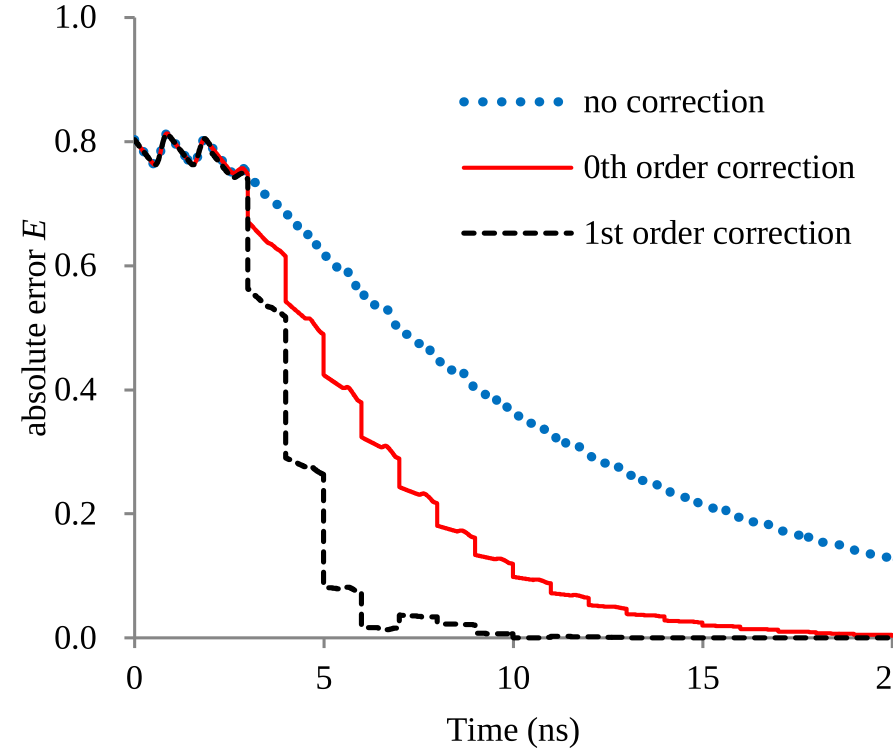
Nodal equation of CW circuit

$$\begin{cases} I - C_0 \dfrac{\mathrm{d}}{\mathrm{d}t} V_L + C \dfrac{\mathrm{d}}{\mathrm{d}t}(V_1 - V_L) + C \dfrac{\mathrm{d}}{\mathrm{d}t}(V_3 - V_L) = 0 \\ C \dfrac{\mathrm{d}}{\mathrm{d}t}(V_L - V_1) + I_\mathrm{d}(-V_1) - I_\mathrm{d}(V_1 - V_2) = 0 \\ I_\mathrm{d}(V_1 - V_2) - C \dfrac{\mathrm{d}}{\mathrm{d}t} V_2 - I_\mathrm{d}(V_2 - V_3) = 0 \\ C \dfrac{\mathrm{d}}{\mathrm{d}t}(V_L - V_3) + I_\mathrm{d}(V_2 - V_3) - I_\mathrm{d}(V_3 - V_\mathrm{out}) = 0 \\ I_\mathrm{d}(V_3 - V_\mathrm{out}) - C \dfrac{\mathrm{d}}{\mathrm{d}t} V_\mathrm{out} - \dfrac{V_\mathrm{out}}{R} = 0 \end{cases}$$

Numerical results



Output voltage of CW circuit



Error of node vector

The TP-EEC method provides convergence to the steady state 4.9 times faster than for non-corrected computation.

Outline

I. Background

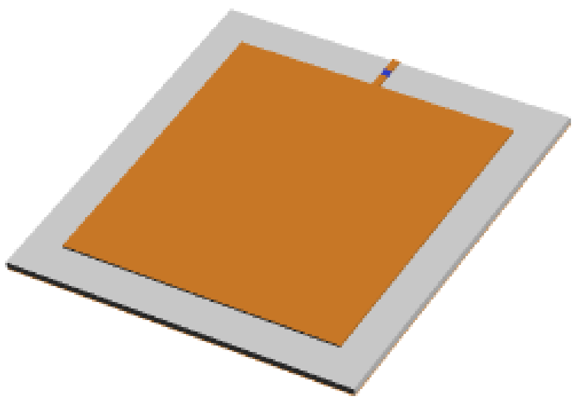
II. Coupling analysis accelerated TP-EEC method

III. Optimization of patch antenna

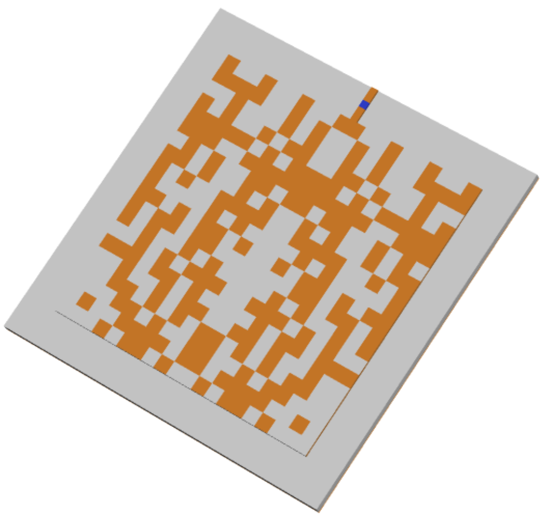
IV. Conclusions

Optimization of patch antenna

The shape of patch antenna is optimized by μ-GA based on coupling analysis accelerated by the TP-EEC method.



Example of patch antenna



Example of optimized patch antenna

Optimization method

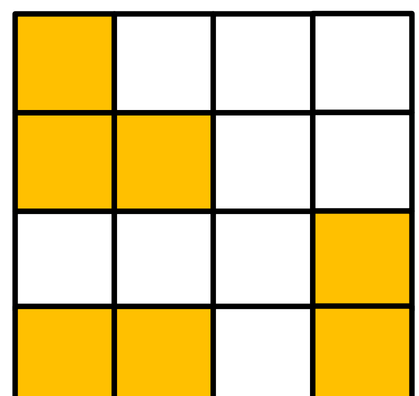
We use m-GA and on-off method for the topology optimization of patch antennas.

Advantages of μ-GA
- Small individual
- Reinitialization
- Global solution search.

Advantages of On-off method
- Representation of topology shape

1	0	0	0
1	1	0	0
0	0	0	1
1	1	0	1

Genotype of μ-GA

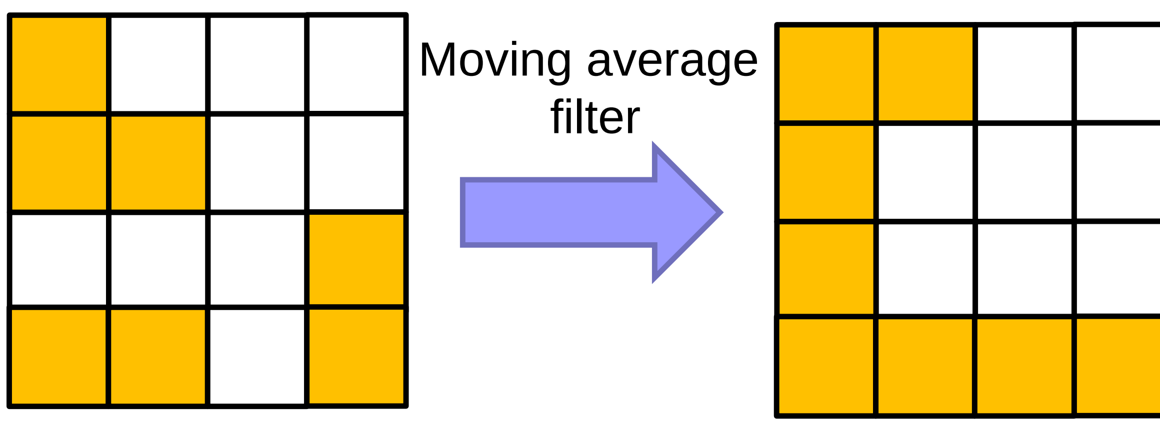


Phenotype of μ-GA

Optimization method

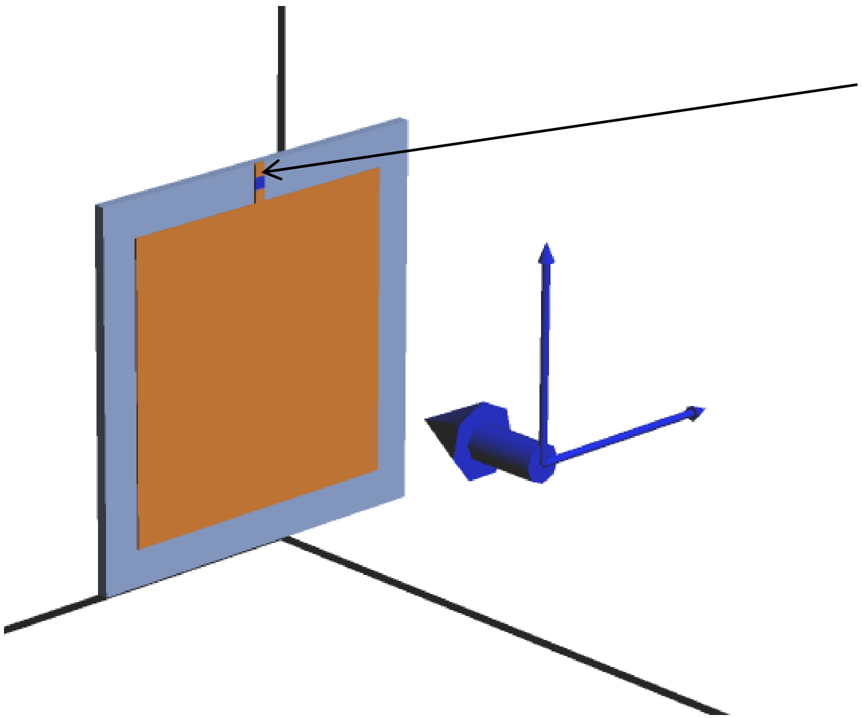
To obtain optimized solutions that are robust against shape changes, we introduce a moving average filter.

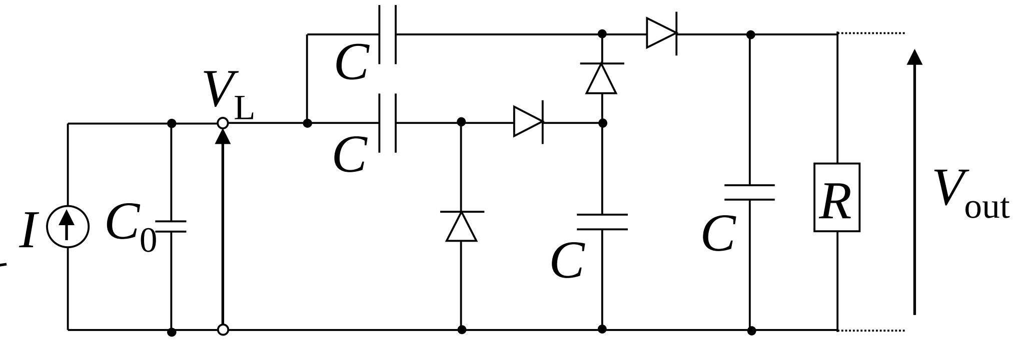
N_1	N_2	N_3
N_4	N_5	N_6
N_7	N_8	N_9



$$N_5 = \begin{cases} 1 & x \geq 0.5 \\ 0 & x < 0.5 \end{cases}, \qquad x = \frac{1}{9}\sum_{i=1}^{9} N_i$$

Problem definition





$\Delta X = \Delta Y = \Delta Z = 3\text{mm}$

$NX = NY = NZ = 120$

Open boundary condition : PML

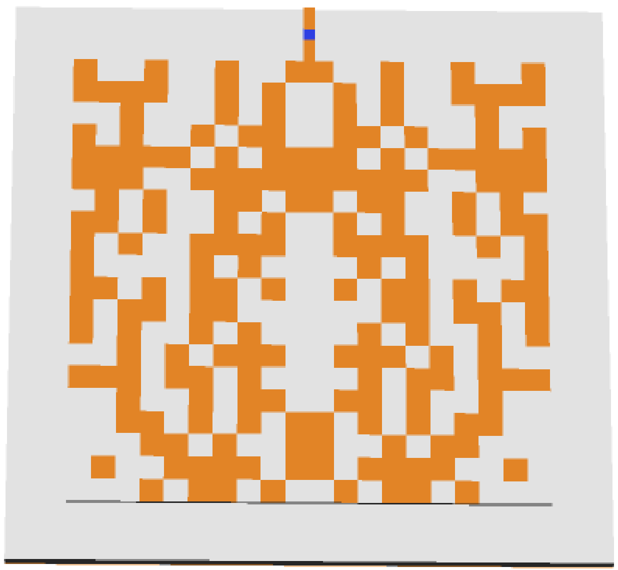
$f = 1\text{GHz}$

$E_z = 20\text{V/m}$

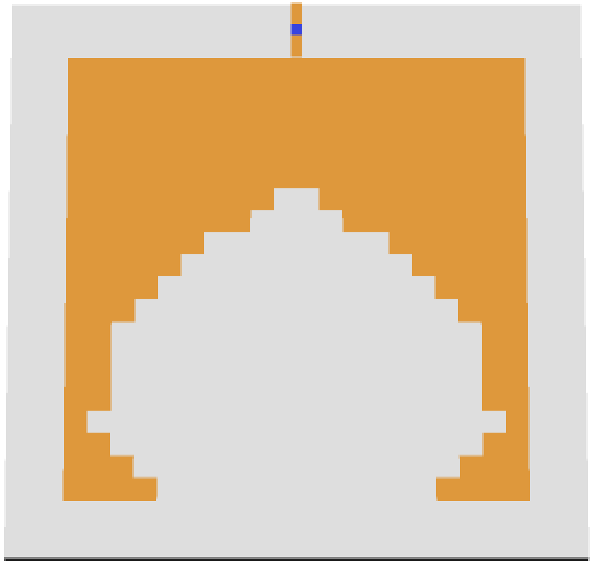
$$V_{out} + w\left(1 - \frac{N}{N_{max}}\right) \rightarrow \max$$

N denotes number of cells whose states are ON.

Results

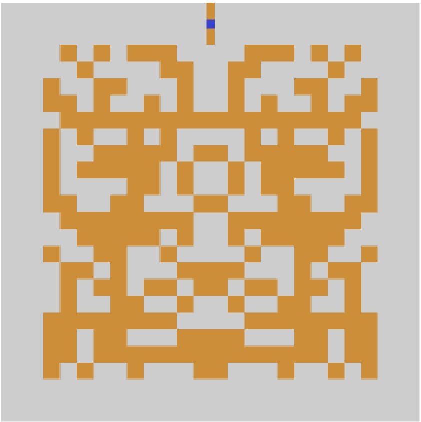


Optimized shape without filter

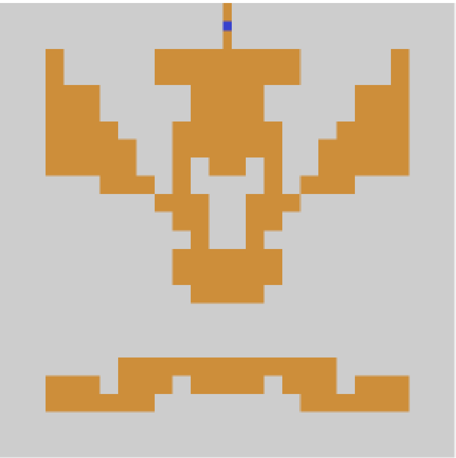


Optimized shape

Results

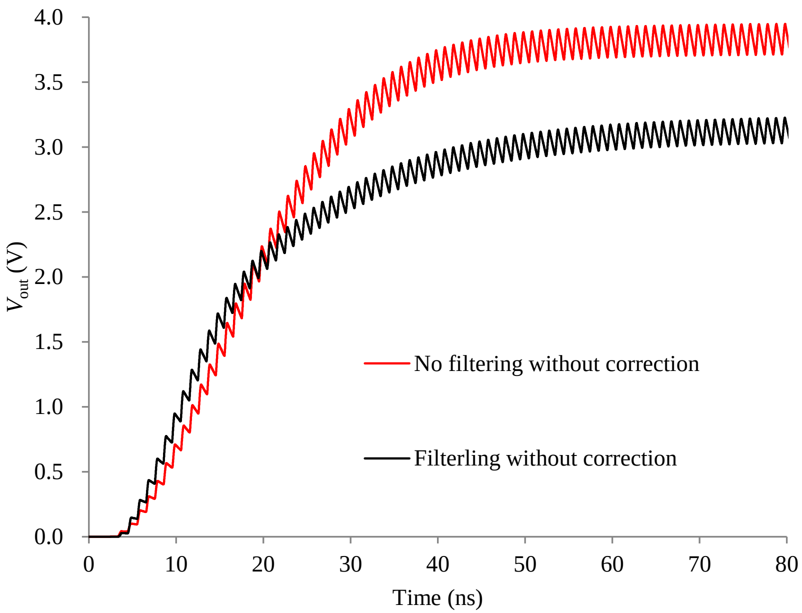


Optimized shape without filter



Optimized shape

Results



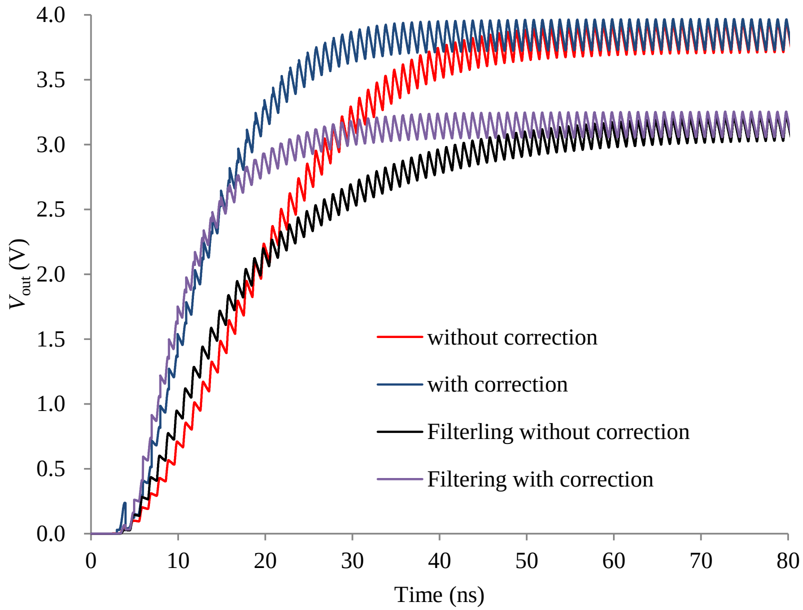
Time evolution of output voltage

Maximum and expected output voltage

	Vout (V)	E[Vout] (V)
No filtering	3.8	1.6
filtering	3.1	1.9

E[Vout] is evaluated by the Monte Carlo method where the statuses of 5% cells are varied randomly.

Results



Time evolution of output voltage

Maximum and expected output voltage

	Vout (V)	E[Vout] (V)
No filtering	3.8	1.6
filtering	3.1	1.9

E[Vout] is evaluated by the Monte Carlo method where the statuses of 5% cells are varied randomly.

Outline

I. Background

II. Coupling analysis accelerated TP-EEC method

III. Optimization of patch antenna

IV. Conclusions

Conclusions

- The convergence to a steady state of coupling analysis is accelerated by the TP-EEC method. It is shown that the TP-EEC method effectively eliminates slowly converging components in error.
- The patch antenna is optimized by μ-GA and accelerated coupling analysis. The computation time for the optimization is reduced to 1/2 that of the conventional optimization method.
- The patch antenna obtained by optimization with a filter has high robustness.

Recommended questions

1. Can the error correction eliminate higher error components?
2. Does the efficiency of the error correction depends on the type of circuit?
3. Do you have different antenna shape when you change the random seed?
4. How long does it takes to obtain an optimization result?
5. Why do you need the regularization term in the objective function?

Higher error components

The error vectors are composed of the 0th, 1st and 2nd order components.

$$\boldsymbol{e} = \begin{bmatrix} 1/(1+\varepsilon) \\ 1/(1+\varepsilon)^2 \\ \vdots \\ 1/(1+\varepsilon)^N \end{bmatrix} e^0 \approx \begin{bmatrix} 1-\varepsilon+\varepsilon^2 \\ 1-2\varepsilon+3\varepsilon^2 \\ \vdots \\ 1-N\varepsilon+\frac{N(N+1)}{2}\varepsilon^2 \end{bmatrix} e^0$$

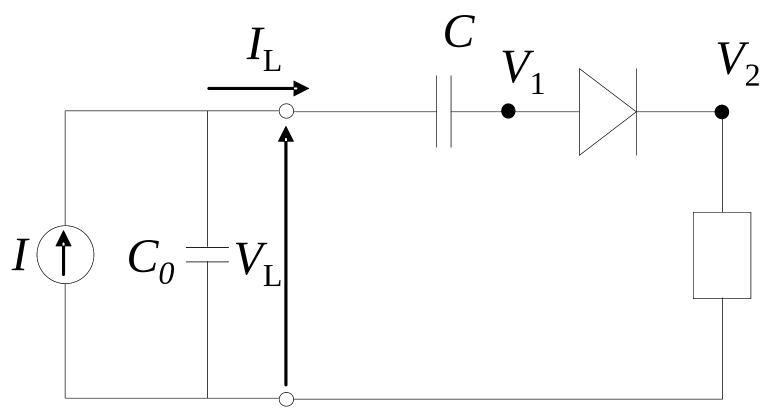
$$\boldsymbol{e} \approx \left(1 - \left(\varepsilon - \frac{\varepsilon^2}{2}\right)\frac{N+1}{2}\right)\begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} e^0 - \left(\frac{\varepsilon}{2} - \frac{\varepsilon^2}{4}\right)\begin{bmatrix} -(N-1) \\ \vdots \\ N-2 \\ N-1 \end{bmatrix} e^0 + \frac{\varepsilon^2}{2}\begin{bmatrix} 1^2 \\ \vdots \\ (N-1)^2 \\ N^2 \end{bmatrix}$$

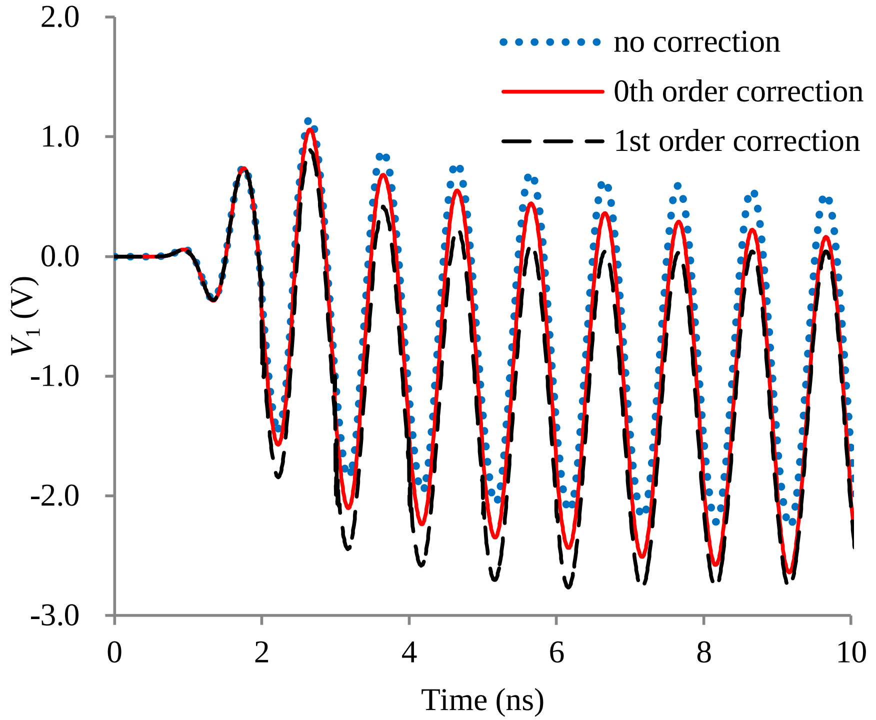
0th order component

1st order component

2nd order component

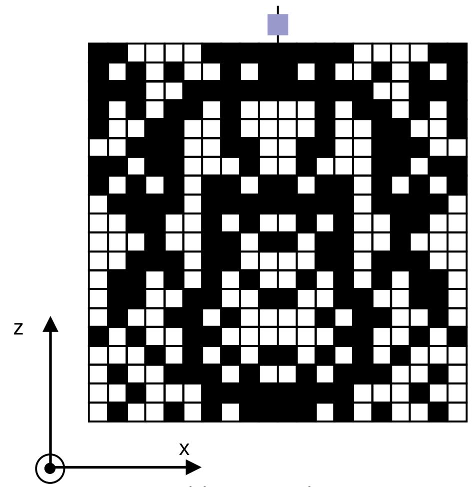
TP-EEC method



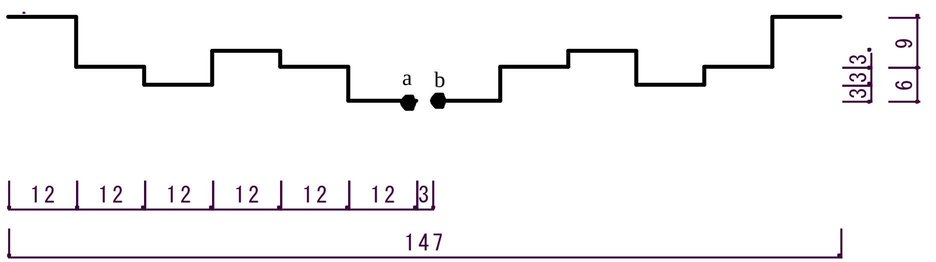


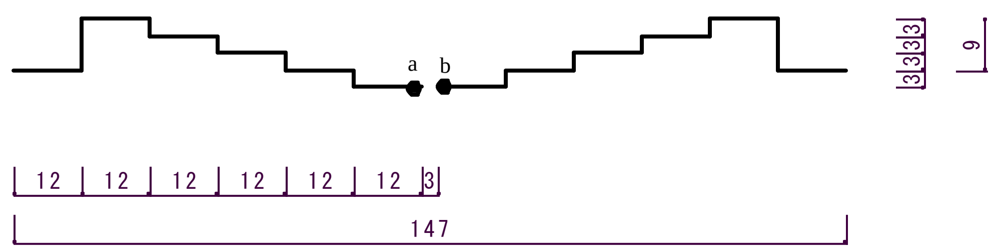
The TP-EEC method provides convergence to the steady state 128.1 times faster than for non-corrected computation.

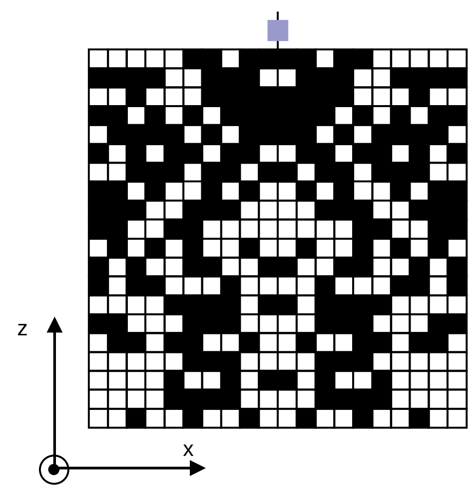
Antenna shape



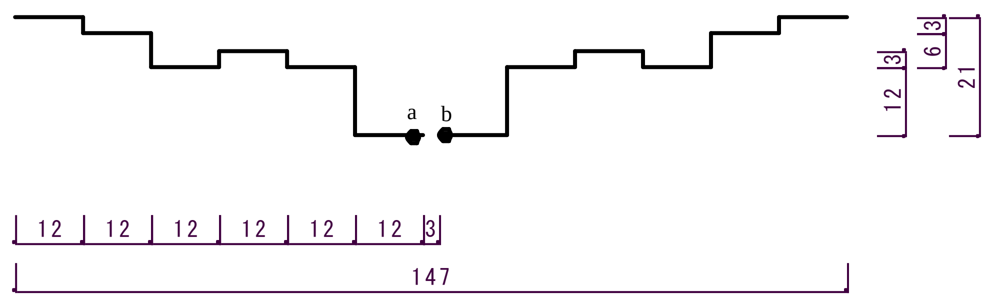
(a) Best result







(b) Second best reuslt



Computation time

Conventional optimization

→ Approximately 1 week.

Presented optimization

→ Approximately 3 days

Regularization term

Objective function

$$V_{\mathrm{out}} + w\left(1 - \frac{N}{N_{\mathrm{max}}}\right) \to \max$$

N denotes number of cells whose states are ON.

Regularization term prevents shape of patch antenna from scattering.

TP-EEC method

Let us consider one dimensional problem

$$u + \tau \frac{\mathrm{d}u}{\mathrm{d}t} = f(t)$$

$$\tau = 0.01$$

$$f(t) = 1 + \sin(10\pi t).$$

Uの結果

Uの誤差

TP-EEC method

Let us consider one dimension problem

The TP-EEC method provides convergence to the steady state *** times faster.

Computation of performance of RFID tags

The RFID tag is composed of RFID antenna and IC chip.

Analysis of the IC tag requires coupling analysis of the electromagnetic field and nonlinear circuit.

We use the FDTD method for the electromagnetic field analysis, and perform modified nodal analysis, MNA for nonlinear circuit simulation.