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チャネルの時間相関を利用したアンテナ選択におけるチャネル推定

Channel estimation method for MIMO antenna selection system exploiting temporal correlation of the channel

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Contents of this presentation

(1)
Iterative Channel Estimation in MIMO Antenna Selection Systems for Correlated Gauss-Markov Channel

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(2)
Channel estimation method for MIMO antenna selection system exploiting temporal correlation of the channel

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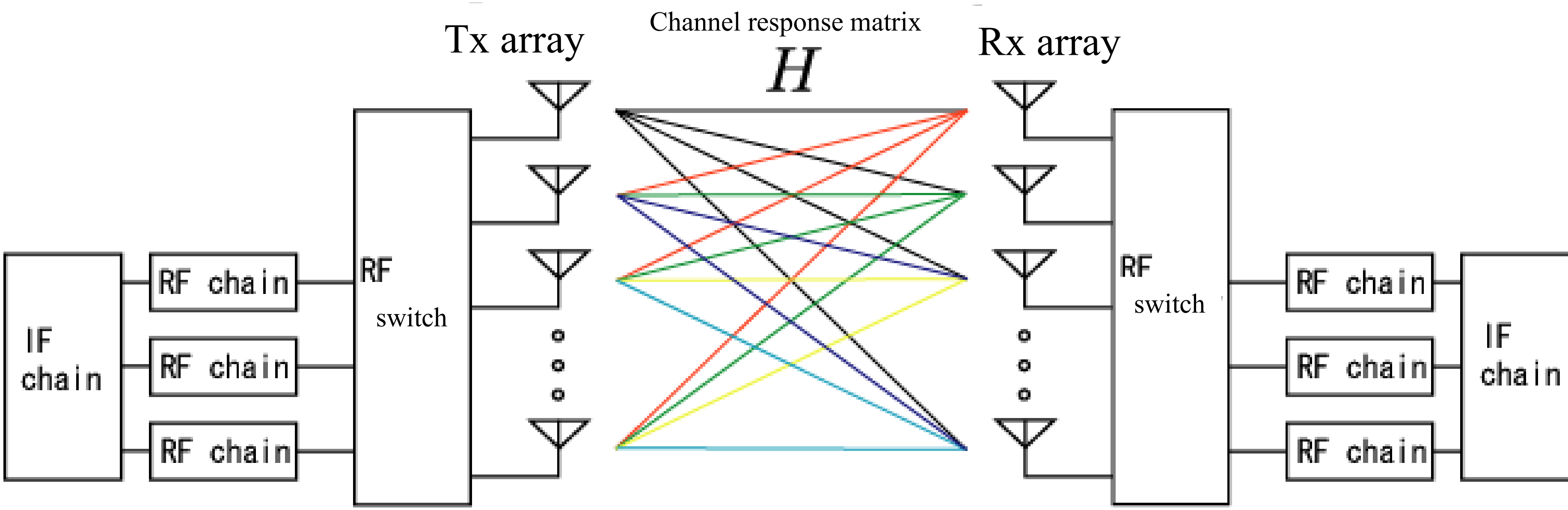
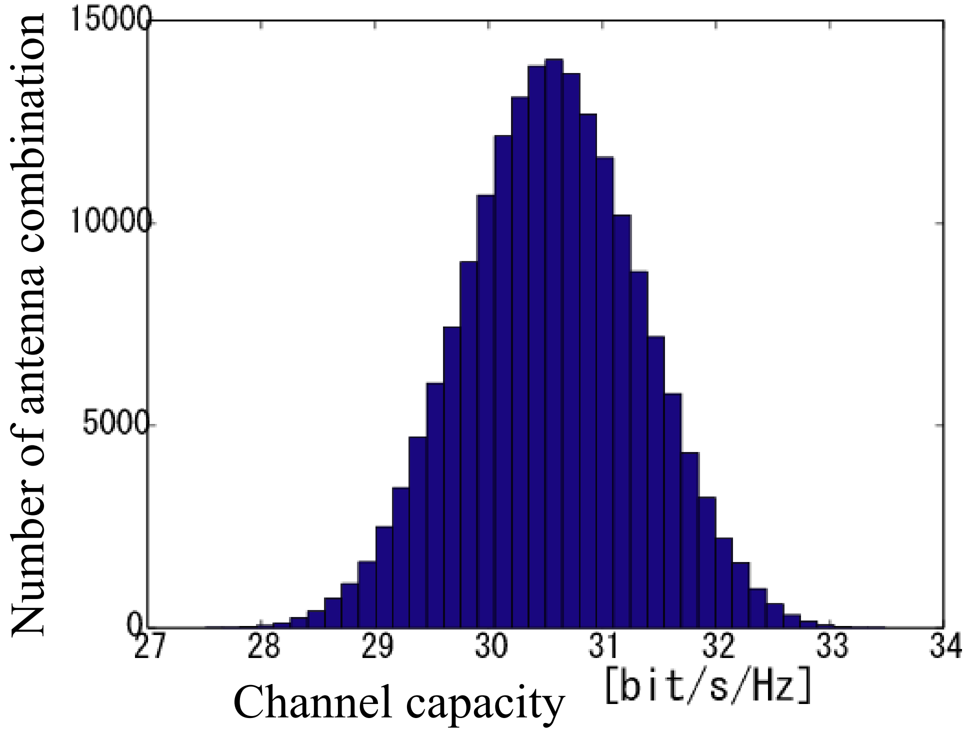
MIMO antenna selection system



- MIMO system performance highly depends on the surrounding scattering conditions
- "MIMO antenna selection systems"
  - Choose antenna elements from many elements
  - Actively change the channel matrix condition
- Cost performance

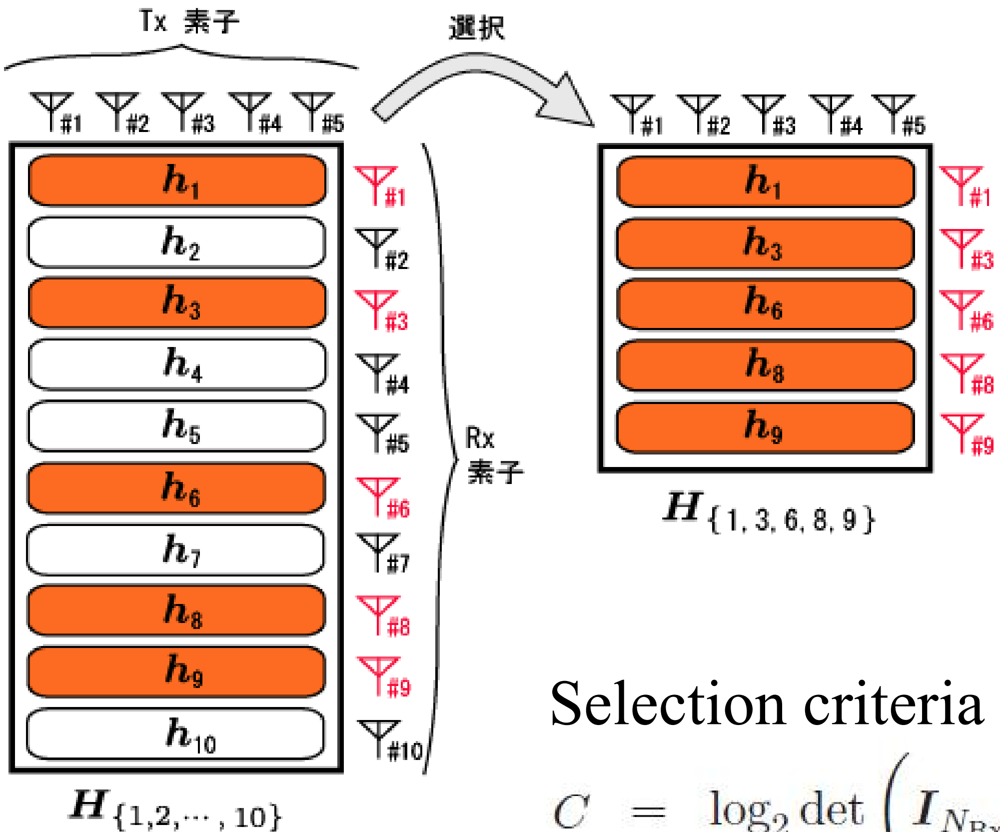
Efficiency of antenna selection

Histogram of channel capacity
for all antenna combinations



- Only Rx side selection, 10 out of 20
- i.i.d. channel
- 20～30% increase of capacity is expected

MIMO antenna selection algorithm



Fast Antenna Subset Selection

- Calculates greedy algorithm quickly
- Finds near-optimal combination

Selection criteria : Maximize channel capacity

$$C = \log_2 \det \left(\boldsymbol{I}_{N_{\mathrm{Rx}}} + \frac{\rho}{N_{\mathrm{Tx}}} \widetilde{\boldsymbol{H}} \widetilde{\boldsymbol{H}}^{\mathrm{H}} \right) \quad [\mathrm{bit/sec/Hz}]$$

- Channel measurement for all elements must precede
- Since channel matrix varies with time, optimal combination changes with time

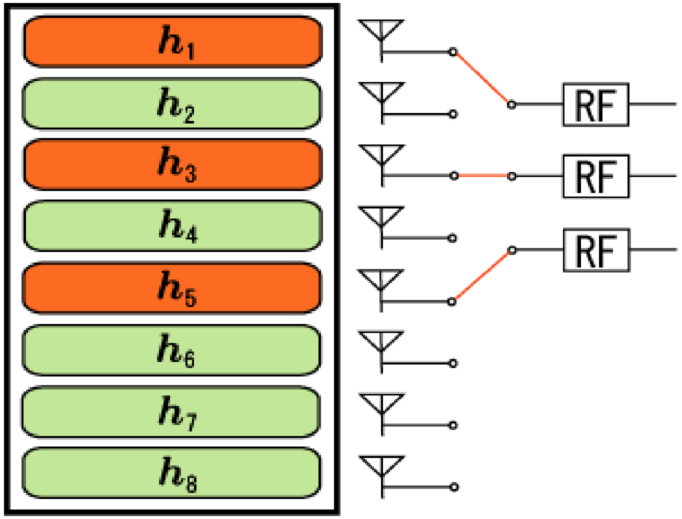
Problem statement

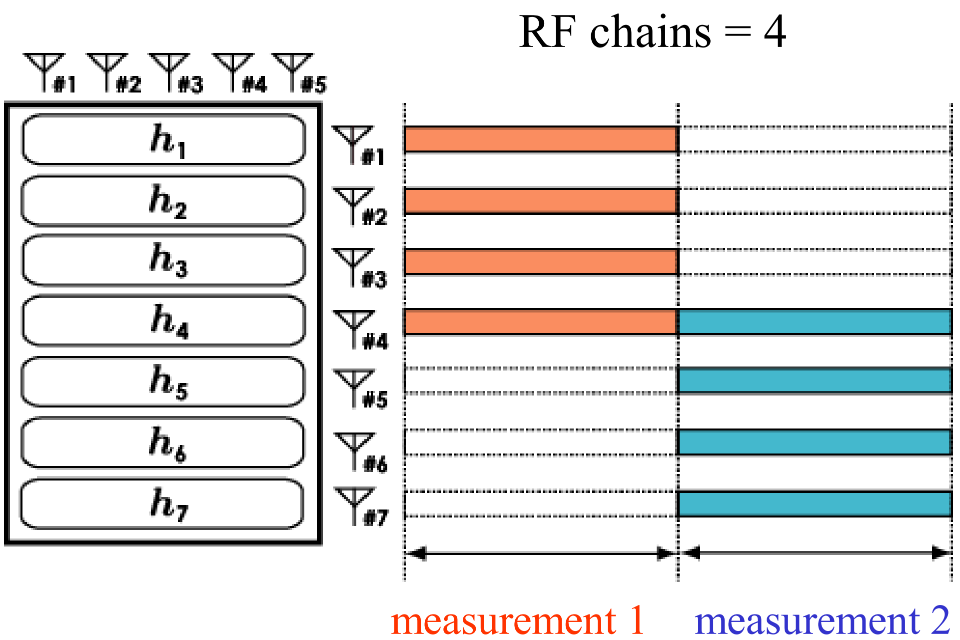
For MIMO antenna selection systems,

design a high precision channel estimation scheme by exploiting a priori channel characteristics

Motivation – Channel estimation for antenna selection

- For each fading block, in order to select the optimal antenna subset, channels for all the element should be measured





Number of RF chains are smaller than number of antenna elements

⇩

Switch antenna connection and measure several times

Matters interested

- Partial channel measurement scheduling
- Exploiting temporal and spatial correlation

Time-varying MIMO channel model

- For estimation, model of time-varying channel matrix is necessary
- Gauss-Markov model
- Simple extension of typical SISO channel model

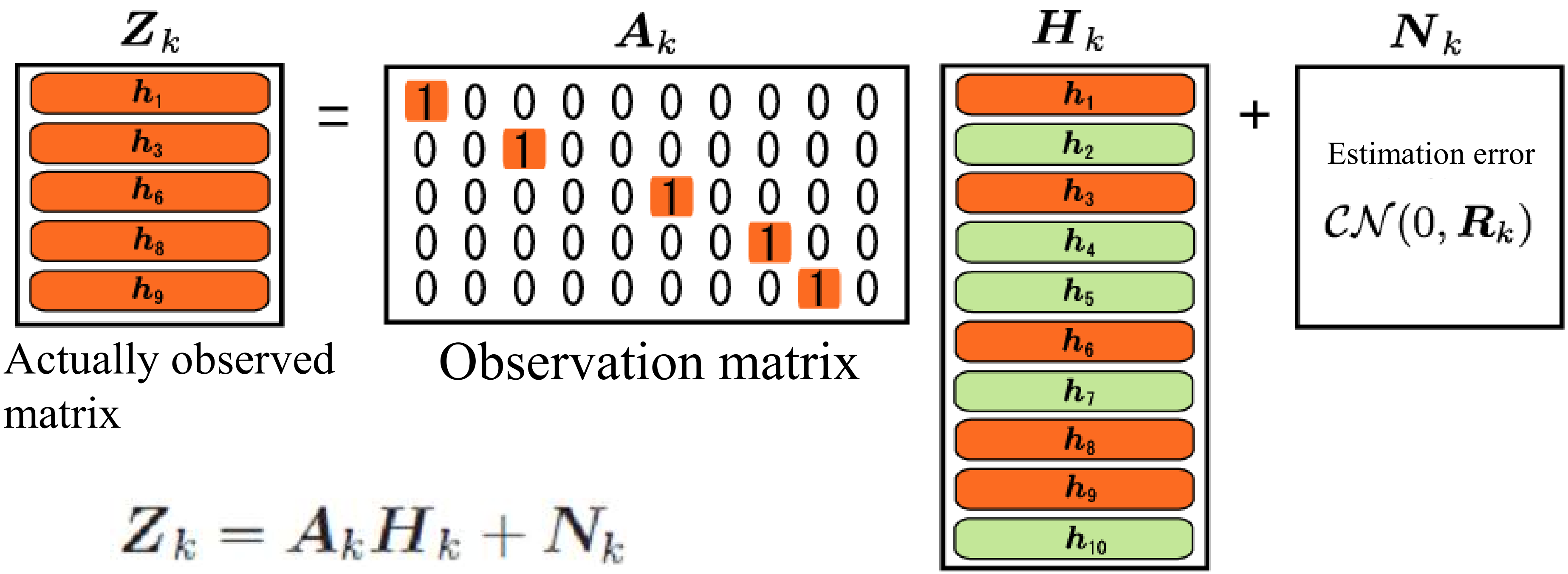
$$\boldsymbol{H}_{k+1} = \rho \boldsymbol{H}_k + \sqrt{1-\rho^2}\, \boldsymbol{R}_{\mathrm{Rx}}^{1/2} \boldsymbol{G} (\boldsymbol{R}_{\mathrm{Tx}}^{1/2})^{\top}$$

ρ : Temporal correlation coefficient
G : Random matrix each element obey CN(0,1)
Rrx : Spatial correlation at Rx side
Rtx : Spatial correlation at Tx side

$$\mathrm{vec}\, \boldsymbol{H}_k \sim \mathcal{CN}\left(0, \boldsymbol{R}_{\mathrm{Tx}} \otimes \boldsymbol{R}_{\mathrm{Rx}}\right)$$

Spatial correlation is assumed as Kronecker model
Spatial correlation remain constant during our interest

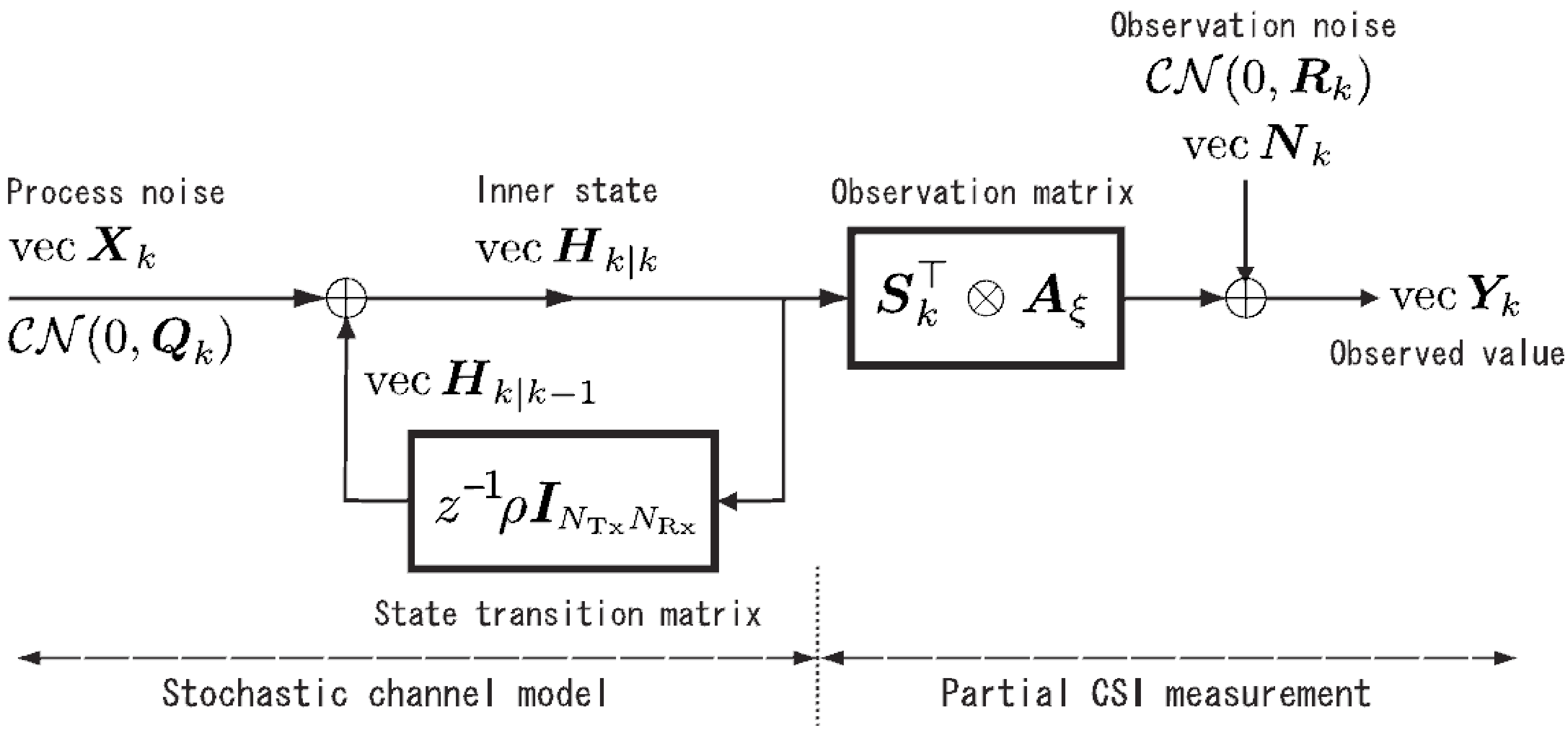
Partial channel observation model



$$Z_k = A_k H_k + N_k$$

- The observation matrix extracts specified row-vectors
- Linear inverse problem which obtains Z from H
- A can be chosen arbitrarily
- If H obeys Gauss-Markov model, Kalman filtering is applicable

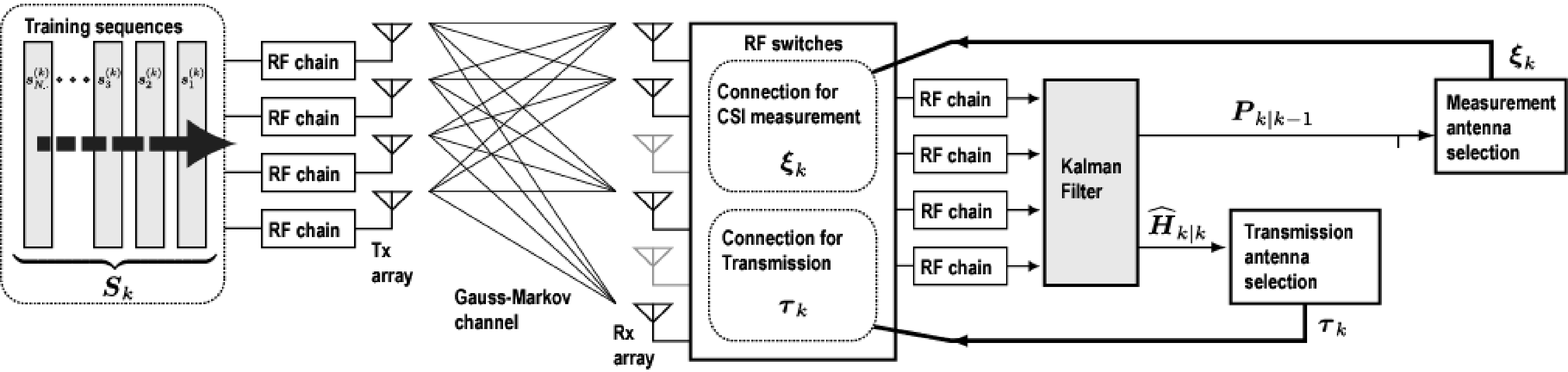
Channel estimation by Kalman filter



- Keep covariance matrix of each point and update every time
- Minimum variance estimation
- For each step, observation matrix is changed→not become RLS algorithm

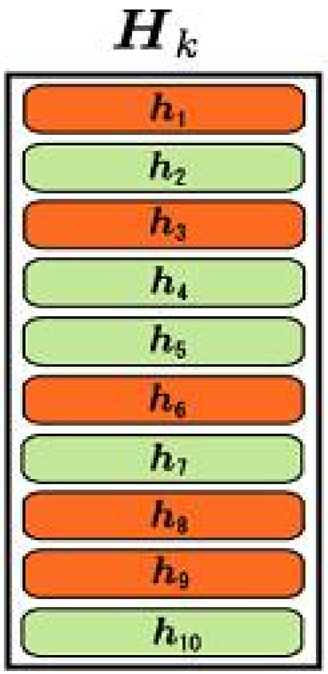
Active enhancement of estimation capability

- Estimation becomes more efficient if we devise measurement taking channel statistics into consideration
- Optimal partial measurement scheduling



Fast antenna subset selection

- Greedy algorithm
- Maximize channel capacity



$$\boldsymbol{H}^{\mathrm{H}}_{\Gamma(k)}\boldsymbol{H}_{\Gamma(k)} = \boldsymbol{H}^{\mathrm{H}}_{\Gamma(k-1)}\boldsymbol{H}_{\Gamma(k-1)} + \boxed{\boldsymbol{h}^{\mathrm{H}}_{i^{(k)}_{\max}}\boldsymbol{h}_{i^{(k)}_{\max}}}$$

Row vector of element to be chosen

By Sherman-Morrison formula for determinant,

Channel capacity

One-rank matrix

$$\boxed{C(\boldsymbol{H}_{\Gamma^k})} = \log_2 \det\left(\boldsymbol{I} + \boldsymbol{H}^{\mathrm{H}}_{\Gamma(k)}\boldsymbol{H}_{\Gamma(k)} + \boxed{\boldsymbol{h}^{\mathrm{H}}_{i^{(k)}_{\max}}\boldsymbol{h}_{i^{(k)}_{\max}}}\right)$$

$$= C(\boldsymbol{H}_{\Gamma(k-1)}) + \log_2\left[1 + \boldsymbol{h}_{i^{(k)}_{\max}}\left(\boldsymbol{I} + \boldsymbol{H}^{\mathrm{H}}_{\Gamma(k-1)}\boldsymbol{H}_{\Gamma(k-1)}\right)^{-1}\boldsymbol{h}^{\mathrm{H}}_{i^{(k)}_{\max}}\right]$$

Antenna element which best contribute to the criteria is chosen such that

$$i^{(k)}_{\max} = \arg\max_{i \notin \Gamma^{(k-1)}} \boldsymbol{h}_i\left(\boldsymbol{I} + \boldsymbol{H}^{\mathrm{H}}_{\Gamma(k-1)}\boldsymbol{H}_{\Gamma(k-1)}\right)^{-1}\boldsymbol{h}^{\mathrm{H}}_i$$

Optimal measurement antenna selection

- Greedy algorithm
- MMSE criteria

$$J_k[\xi, \boldsymbol{S}] \triangleq \mathrm{E}_{\boldsymbol{n}} \mathrm{E}_{\boldsymbol{H}_k} \left\| \boldsymbol{H}_k - \widehat{\boldsymbol{H}}_{k|k} \right\|_F^2 = \operatorname{tr} \boldsymbol{P}_{k|k}$$

$$= \operatorname{tr} \left(\boldsymbol{P}_{k|k-1}^{-1} + \frac{1}{\sigma_n^2} \boldsymbol{S}^* \boldsymbol{S}^\top \otimes \boldsymbol{A}_\xi^{\mathcal{H}} \boldsymbol{A}_\xi \right)^{-1}$$

Error covariance

Training sequence

Antenna selection

Antenna selection matrix

$$\boldsymbol{A}_{\omega_{t+1}}^{\mathcal{H}} \boldsymbol{A}_{\omega_{t+1}} = \boldsymbol{A}_{\omega_t}^{\mathcal{H}} \boldsymbol{A}_{\omega_t} + \mathbf{e}_x \mathbf{e}_x^{\mathcal{H}}$$

Element to be chosen

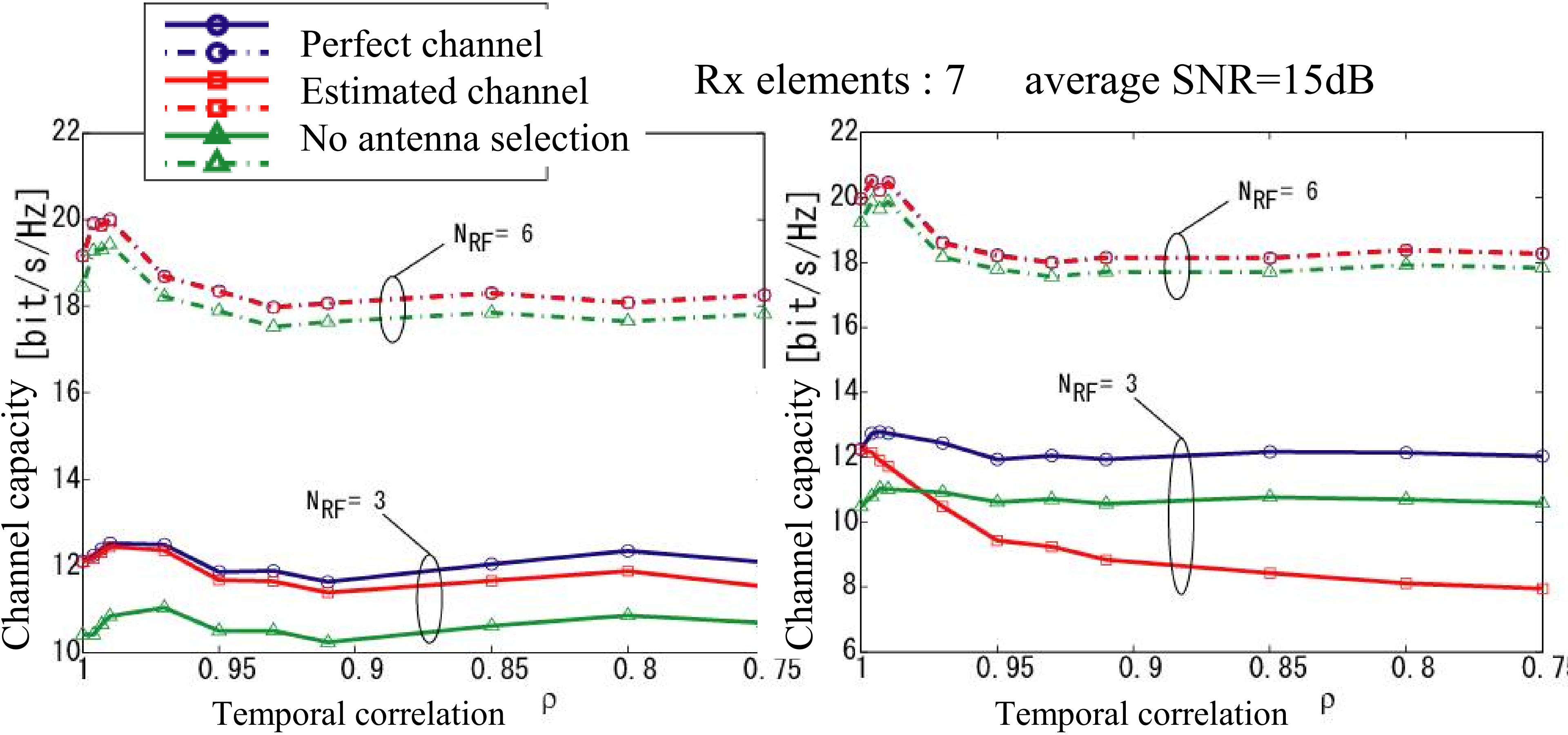
$$\boldsymbol{A}_k = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

By matrix inversion lemma,

Antenna element which best contribute to the criteria is chosen such that

$$x_{\mathrm{opt}} = \arg\max_x \sum_{i=1}^{N_{\mathrm{Tx}}} \frac{\left\| \left[\boldsymbol{\Phi}_{\omega_t}^{(i)} \right]_{:,x} \right\|^2}{\sigma_n^2 / \alpha_i + \left[\boldsymbol{\Phi}_{\omega_t}^{(i)} \right]_{x,x}}$$

Temporal correlation and channel capacity



Estimate is used only for selection

Estimate is used directly for transmission

- As the temporal correlation becomes higher, the antenna selection becomes better
- Estimated channel cannot be used for data transmission unless temporal correlation is larger than 0.97

Effect of correlation model mismatch

- Kronecker model
  - Tx and Rx are independent
  - applicable to NLOS environment
- Mismatch of spatial correlation model may cause degradation of estimation

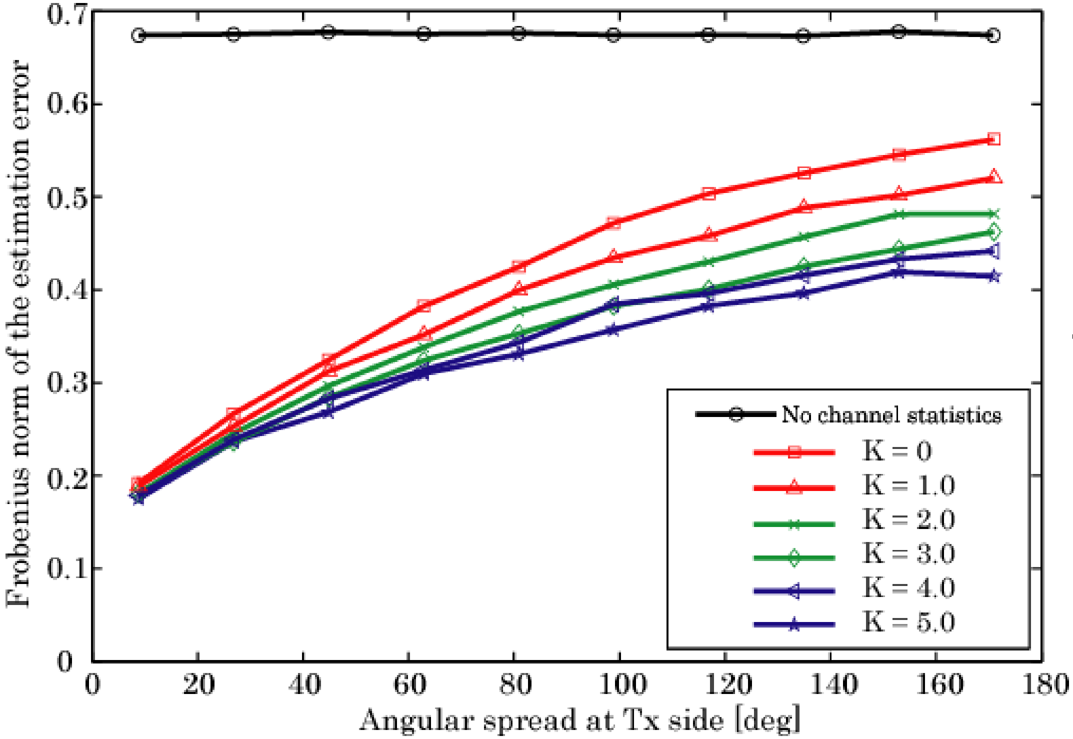
True channel

Specular component

$$\boldsymbol{H} = \sqrt{\frac{K}{K+1}} \sqrt{\frac{1}{N_p}} \sum_{i=1}^{N_p} g_i \cdot \boldsymbol{a}_{\mathrm{Rx}}(\theta_i^{(\mathrm{Rx})}) \left[\boldsymbol{a}_{\mathrm{Tx}}(\theta_i^{(\mathrm{Tx})}) \right]^{\top} + \sqrt{\frac{1}{K+1}} \boldsymbol{R}_{\mathrm{DiffRx}}^{1/2} \boldsymbol{G} \left(\boldsymbol{R}_{\mathrm{DiffTx}}^{1/2} \right)^{\top}$$

Diffuse component

K : Ricean K factor
Np : Number of specular paths
a(･) : steering vector



The presence of specular component yield the strong correlation which is advantageous to the estimation rather than the disadvantage due to model

Summary

- Iterative channel estimation by Kalman filter
- Proposed method can reduce length of training sequence by ½
- Estimate by Kalman filter is precise enough if it is used only for the criteria of antenna selection
- Estimate by Kalman filter is not available as CSI for data transmission unless temporal and spatial correlation of the channel is much stronger

Problems : Validity of the channel model

Assumed channel model

$$\boldsymbol{H}_{k+1} = \rho \boldsymbol{H}_k + \sqrt{1-\rho^2}\, \boldsymbol{R}_{\mathrm{Rx}}^{1/2} \boldsymbol{G} (\boldsymbol{R}_{\mathrm{Tx}}^{1/2})^{\top}$$

- Kronecker model
  - Correlation between Tx and Rx are admissible
- Spatial correlation at Tx and Rx remain constant
  - Does it really hold ?
- Gauss-Markov
  - Does it really hold ?

Design a channel estimation scheme having less dependency on spatial correlation

Basic idea of proposed estimation method

- Generally, increase of training length→increase of precision of channel estimate→increase of capacity
- Eventually, for the antenna elements not being selected, precisely estimated channel state becomes waste

(for the criteria of selection, all elements should be estimated, but it is not necessary to be too precise)

- For elements which are likely to be selected, we want to assign more longer training sequence, and estimate precisely
- <u>How do we choose elements which are likely to be selected ?</u>

Channel estimation enhancement by exploiting temporal correlation

- How can we predict the elements which are likely to be selected ?
- Basically, model of temporal channel transition is necessary to predict

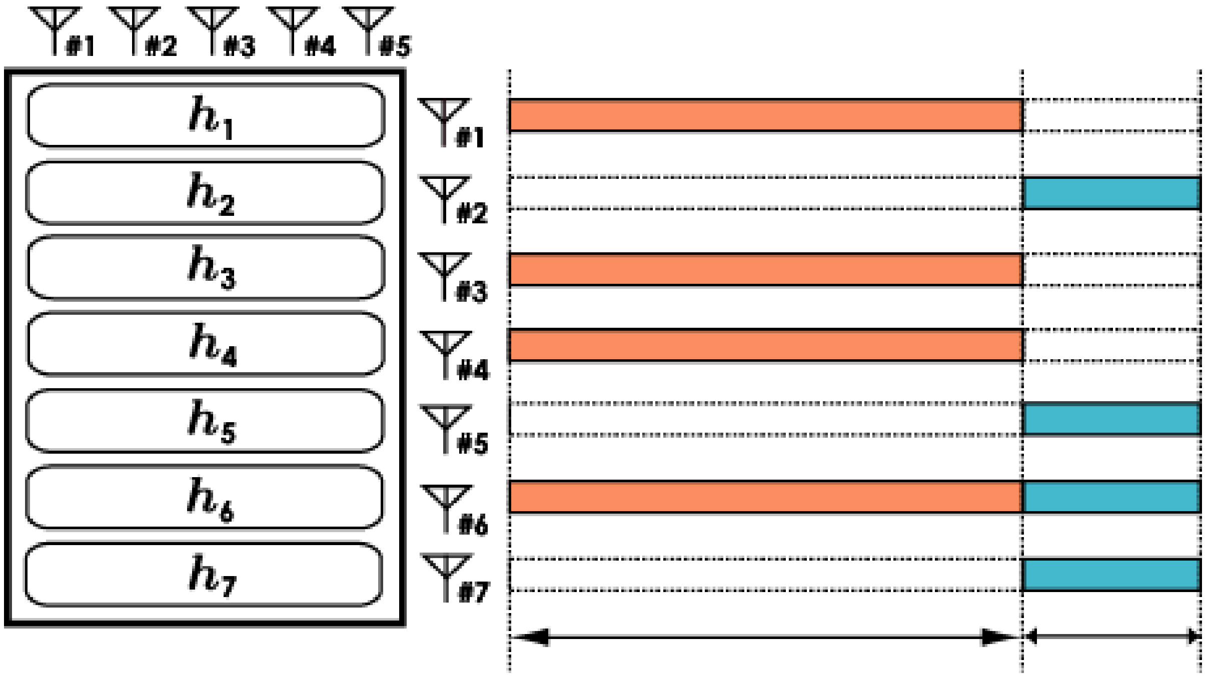
↓ Assume temporally correlated channel

- An antenna subset selected in one fading block is likely to be chosen also in the next fading block (since channel state is not change to a large extent)

↓

- For previously selected elements, estimate precisely by using longer training sequences

Training sequence assignment with selection bias



- The channel estimate accuracy varies by antenna elements
- The optimal antennas should be chosen considering each estimate accuracy

Precise estimation Coarse estimation

- For previously selected elements, apply precise estimation with longer training sequences
- Expecting to be selected again

- For the rest of elements, apply coarse estimation with shorter training sequences

MIMO antenna selection considering channel estimate error

- Problem : From the elements with different estimate error, how can we select the best antenna subset ?
- The antenna selection methods proposed so far are not directly available since they do not consider difference of estimate error
- We want to enhance capacity averagely by as easy criteria as possible

↓

- Select antennas to maximize "Lower bound of the capacity with presence of channel estimate error"

Lower bound of channel capacity with presence of channel estimate error

- Ting (2001)

MIMO channel model : $y = Hx + n$

In synchronized detection,

the component which behaves as noise : Effective noise

$$\begin{aligned} y &= \widehat{H}x + \left(H - \widehat{H}\right)x + n \\ &= \widehat{H}x + \widehat{n} \end{aligned}$$

Effective noise $\left(\widehat{n} = \left[H - \widehat{H}\right]x + n \right)$

$\widehat{H}$: Estimated channel

Lower bound of capacity :

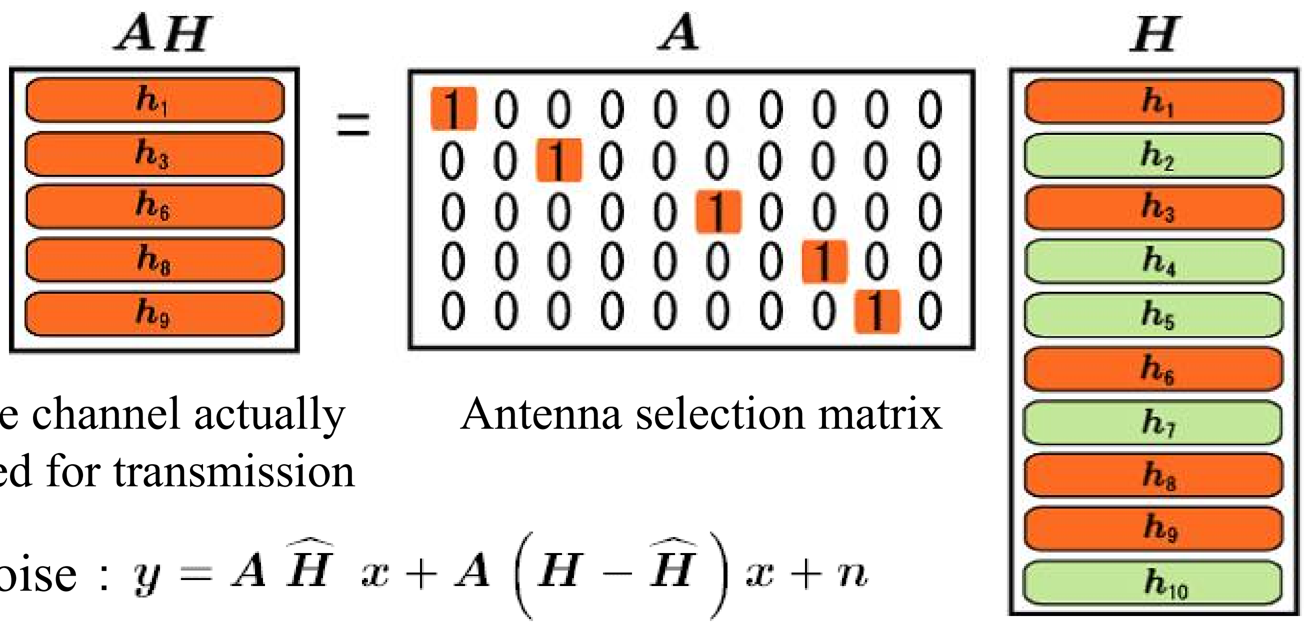
$$C \geq \log_2 \det\left(I + \widehat{H}\widehat{H}^{\mathrm{H}}\Phi^{-1}\right)$$

Φ : Covariance of effective noise

$\Phi \triangleq \mathrm{E}_{H}\, \widehat{n}\, \widehat{n}^{\mathrm{H}}$

Lower bound of capacity for antenna selection systems

- Antenna selection matrix extracts the specified row-vectors



The channel actually used for transmission

Antenna selection matrix

Effective noise : $\boldsymbol{y} = \boldsymbol{A}\,\widehat{\boldsymbol{H}}\,\boldsymbol{x} + \boldsymbol{A}\left(\boldsymbol{H} - \widehat{\boldsymbol{H}}\right)\boldsymbol{x} + \boldsymbol{n}$

$$= \boldsymbol{A}\,\widehat{\boldsymbol{H}}\,\boldsymbol{x} + \boldsymbol{A}\,\hat{\boldsymbol{n}}$$

Here, we want to obtain A, which maximizes lower bound of capacity

$$C \geq \log_2 \det\left(\boldsymbol{I} + \boldsymbol{A}\,\widehat{\boldsymbol{H}}\,\widehat{\boldsymbol{H}}^{\mathcal{H}}\boldsymbol{A}^{\mathcal{H}}\underline{\left[\boldsymbol{A}\,\boldsymbol{\Phi}\,\boldsymbol{A}^{\mathcal{H}}\right]^{-1}}\right)$$ → Generally difficult

A method which maximizes normal channel capacity is available

(Fast Antenna Subset Selection)

$$C = \log_2 \det\left(\boldsymbol{I} + \boldsymbol{A}\,\widehat{\boldsymbol{H}}\,\widehat{\boldsymbol{H}}^{\mathcal{H}}\boldsymbol{A}^{\mathcal{H}}\right)$$

Fast antenna selection in ML channel estimation

$$\log_2 \det\left(\boldsymbol{I} + \boldsymbol{A}\,\widehat{\boldsymbol{H}}\,\widehat{\boldsymbol{H}}^{\mathcal{H}}\boldsymbol{A}^{\mathcal{H}}\underline{\left[\boldsymbol{A}\,\boldsymbol{\Phi}\,\boldsymbol{A}^{\mathcal{H}}\right]^{-1}}\right) \rightarrow \max$$

If the effective noise matrix Φ becomes diagonal form,
(ML estimation → Since estimation error is uncorrelated, effective noise matrix become diagonal form)

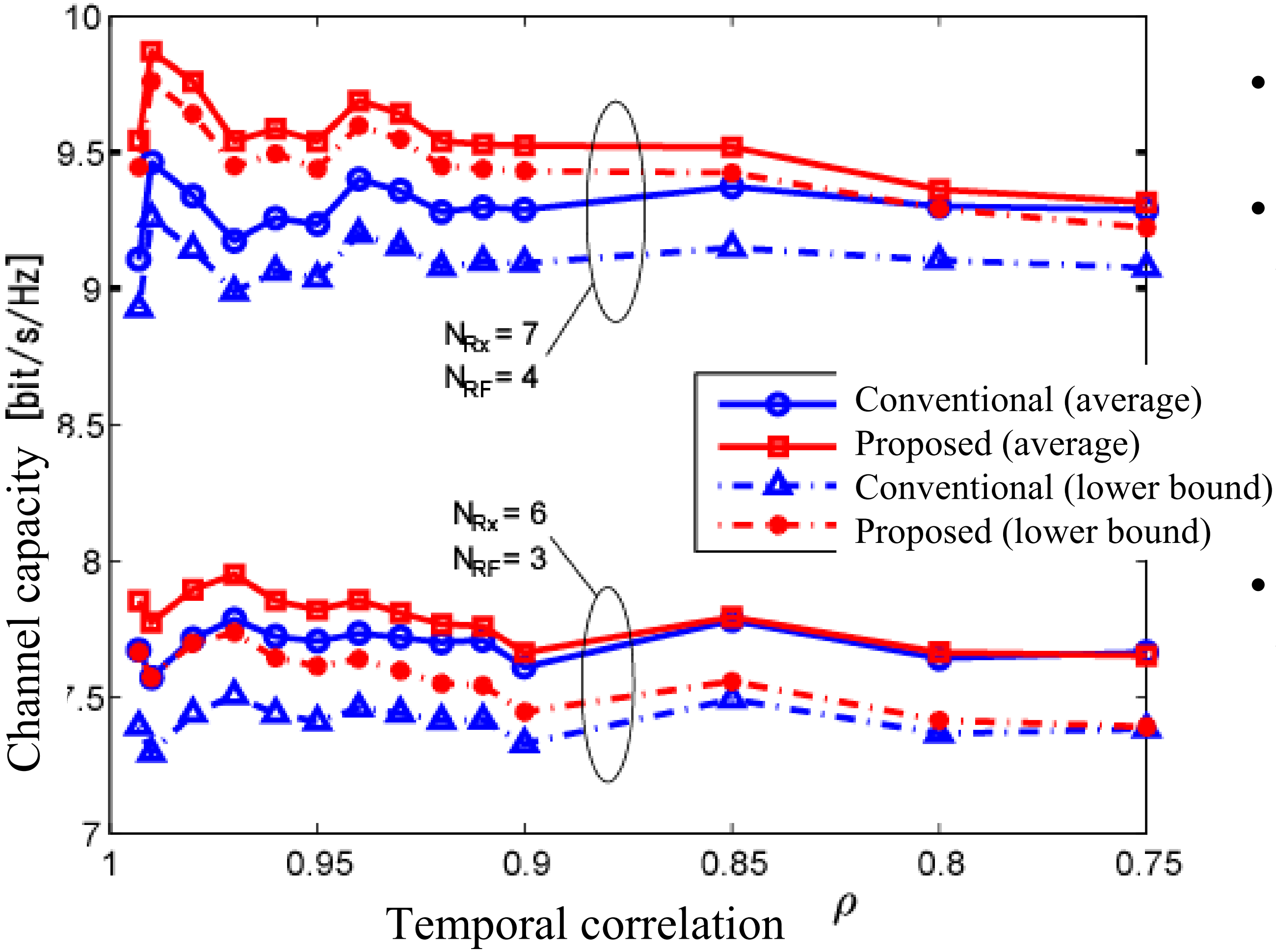
$$\log_2 \det\left(\boldsymbol{I} + \boldsymbol{A}\,\widetilde{\boldsymbol{H}}\,\widetilde{\boldsymbol{H}}^{\mathcal{H}}\boldsymbol{A}^{\mathcal{H}}\right) \rightarrow \max$$

$$\boldsymbol{\Phi} = \mathrm{diag}[r_1\ r_2\ \cdots\ r_{N_{\mathrm{Rx}}}]$$

$$\widetilde{\boldsymbol{H}} \triangleq \begin{bmatrix} [\widehat{\boldsymbol{H}}\ ]_{1,:}/\sqrt{r_1} \\ [\widehat{\boldsymbol{H}}\ ]_{2,:}/\sqrt{r_2} \\ \vdots \\ [\widehat{\boldsymbol{H}}\ ]_{N_{\mathrm{Rx}},:}/\sqrt{r_{N_{\mathrm{RF}}}} \end{bmatrix}$$

- Equivalent to the conventional antenna selection method except that each row-vector of the channel matrix was divided by corresponding effective noise
- The fast antenna selection methods proposed so far are available without modification
- The element whose estimate accuracy is low automatically becomes unlikely to be chosen

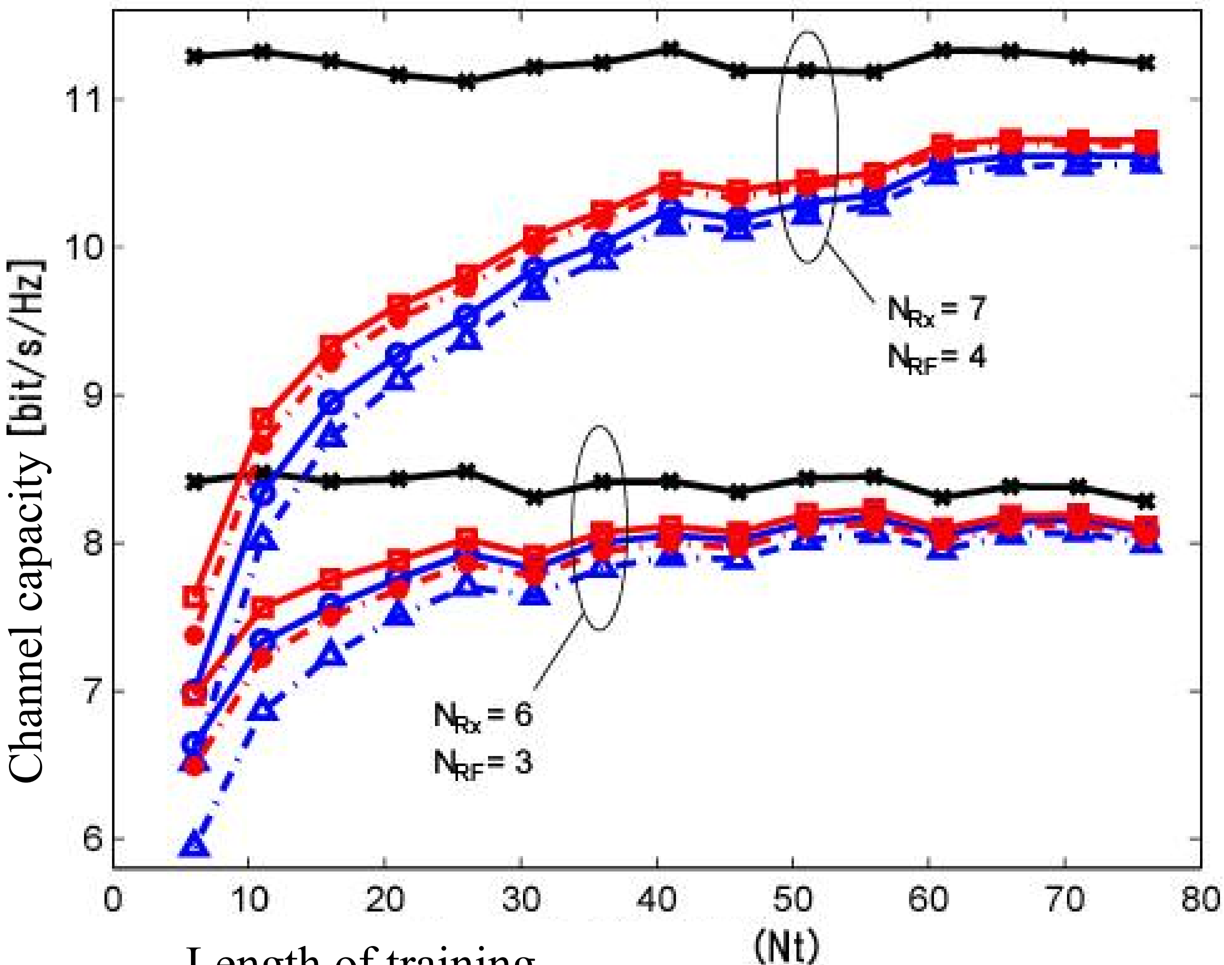
Temporal correlation and capacity improvement

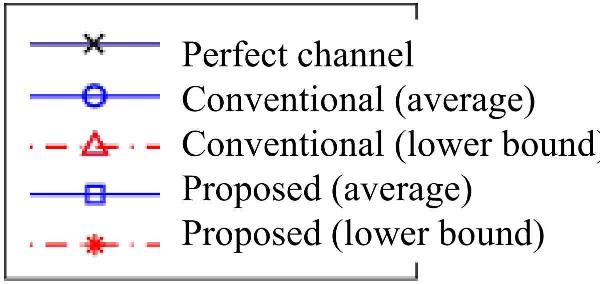


- SNR = 8dB
- Precise estimation training length = 16
- Coarse estimation training length = 4
- Conventional method training length = 10 * 2

- 3～5% improvement of capacity and its lower bound
- Efficient for strong temporal correlation
- More efficient for smaller average SNR

Length of training and capacity improvement





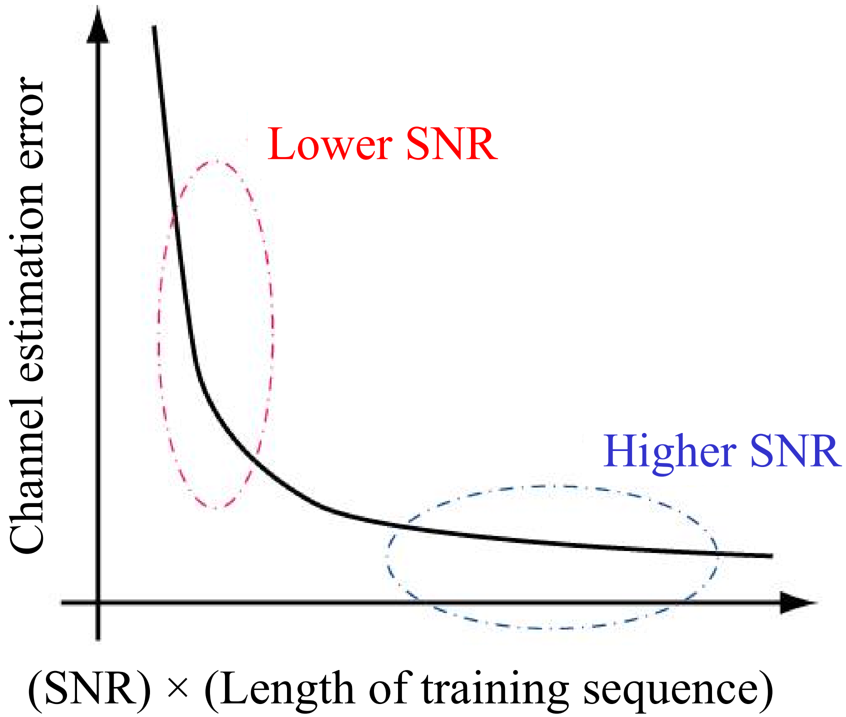
Length of training sequence

- Length of training in precise estimation is 3 times as long as that of coarse estimation
- Horizontal axis means sum length of both precise and coarse estimation
- average SNR = 8dB
- temporal correlation = 0.95

- As the training sequence becomes shorter, capacity improvement becomes larger

Reason for inefficiency in higher SNR

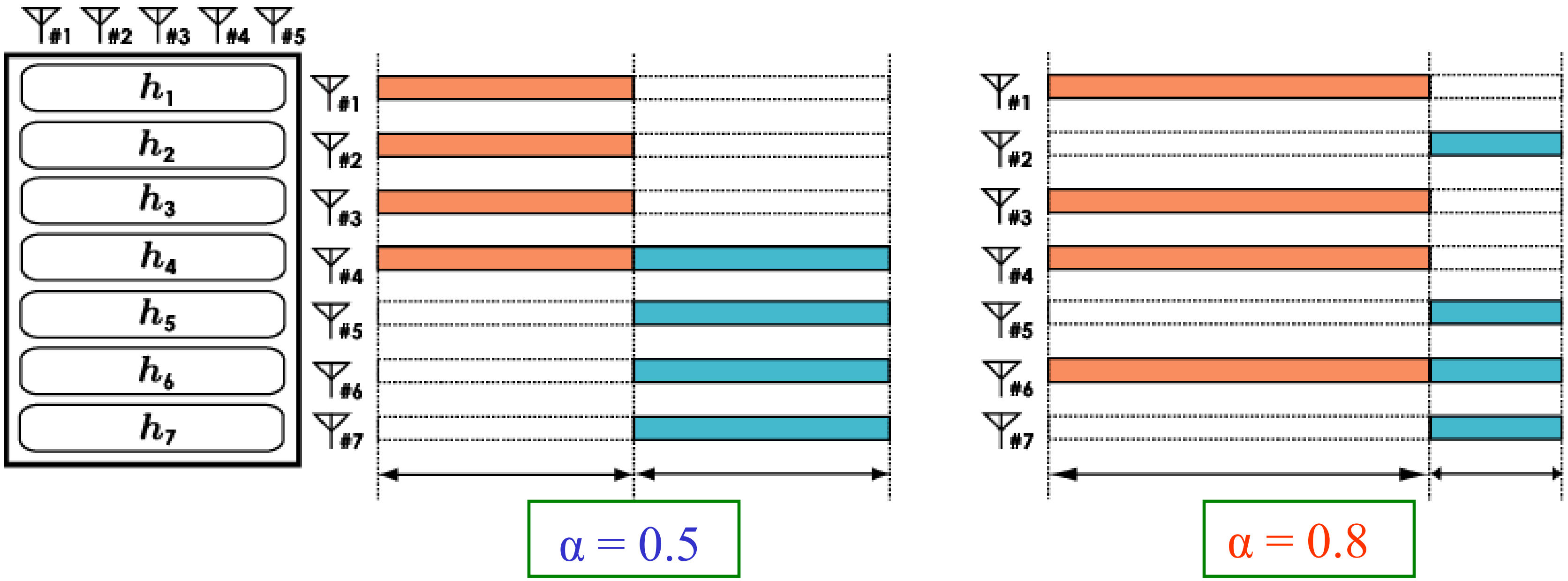
- Proposed approach is "to assign training sequence as many as possible"
- In ML channel estimation, estimate error and total power of training sequence have a reciprocal relationship



- In higher SNR environment, since channel estimation error is not vary to a large extent, proposed method becomes less efficient

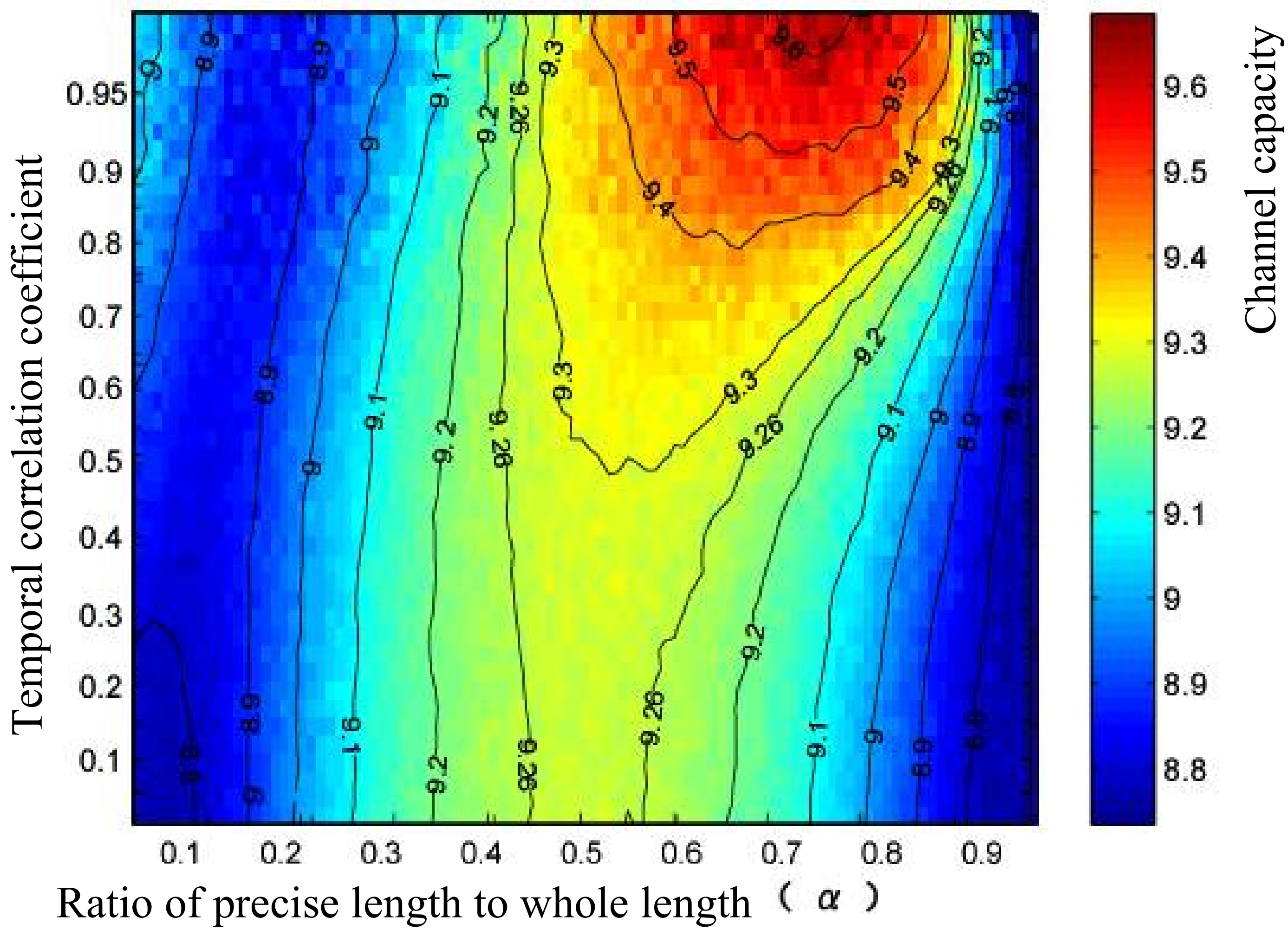
Optimal training length assignment for precise and coarse estimation

- Ratio α = (Training length in precise estimation) / (whole length)
- If temporal correlation is large, precisely estimated elements are more likely to be selected → larger α is suited ?



- Strong temporal correlation→Optimal α is near to 1 ?
- Weak temporal correlation→ Optimal α is near to 0.5 ?

Temporal correlation and optimal assignment ratio



- If temporal correlation is strong, larger ratio of precise estimation is suited (upper limit is α=0.75）
- Especially effective where temporal correlation is more than 0.9
- For temporal correlation less than 0.6, α=0.5 is optimal

Summary

- Proposed "two-stage(precise and coarse) channel estimation scheme" for MIMO antenna selection systems
- 3~5% capacity improvement in lower SNR and shorter training sequences
- The fast antenna subset selection algorithm is directly available if ML channel estimation is employed

Future work

- Simple method to measure temporal correlation
- More realistic estimation of capacity improvement