移動通信研究グループ合同輪講

アレー信号処理におけるSpatial Signature推定と多重散乱波環境におけるアレー最適信号合成への応用

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荒木研究室　　鄭　重　植

Contents

1. DCMP : Directionally Constrained Minimization of Power
2. ZF : Zero Forcing

Motivation

Demands on Mobile Communications Systems

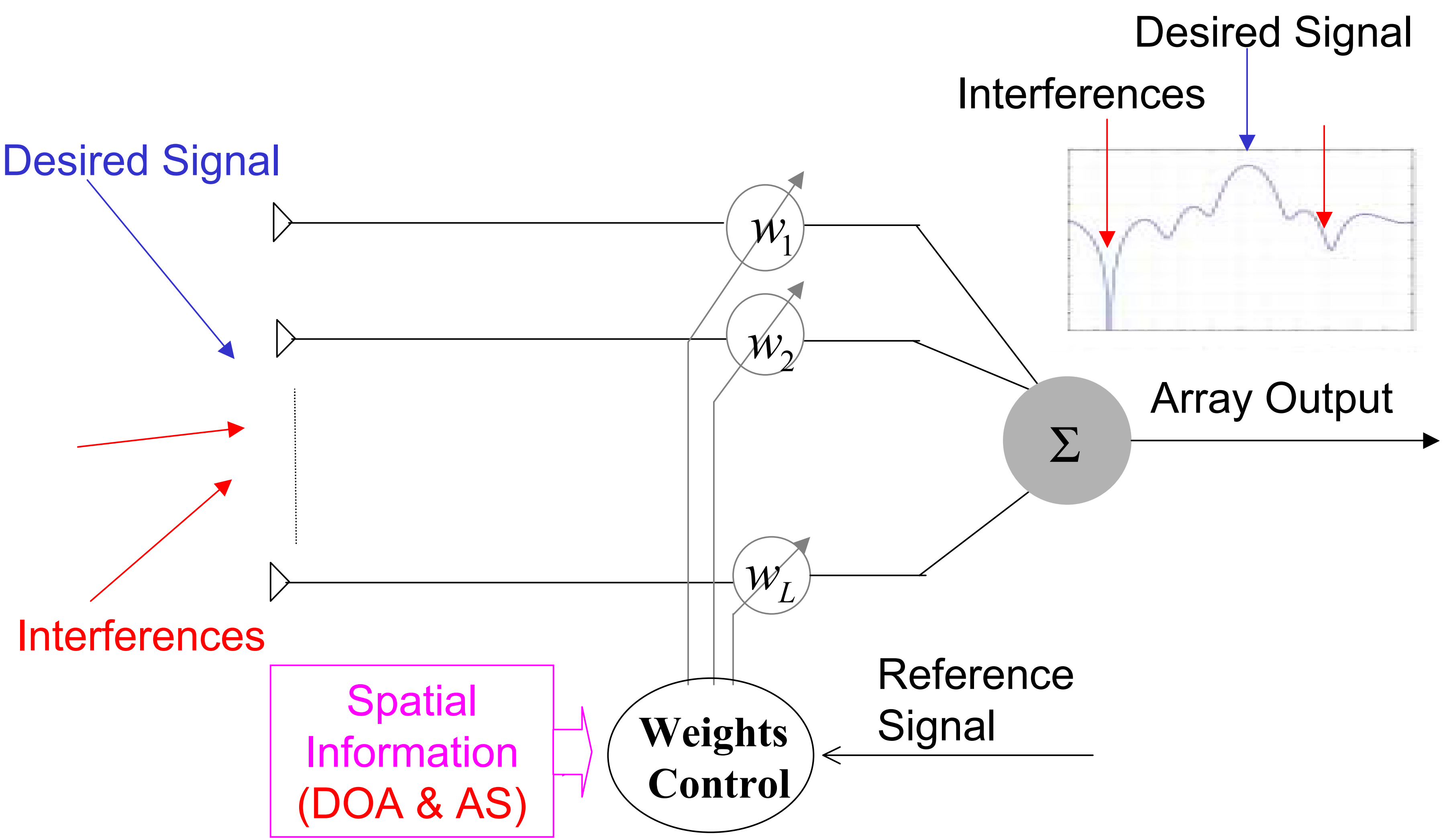
- **Expectation to Spatial Signal Processing**
  - Maximization in SINR
  - Decrease in BER
  - Optimal Design of Communication Systems

- **Technologies**

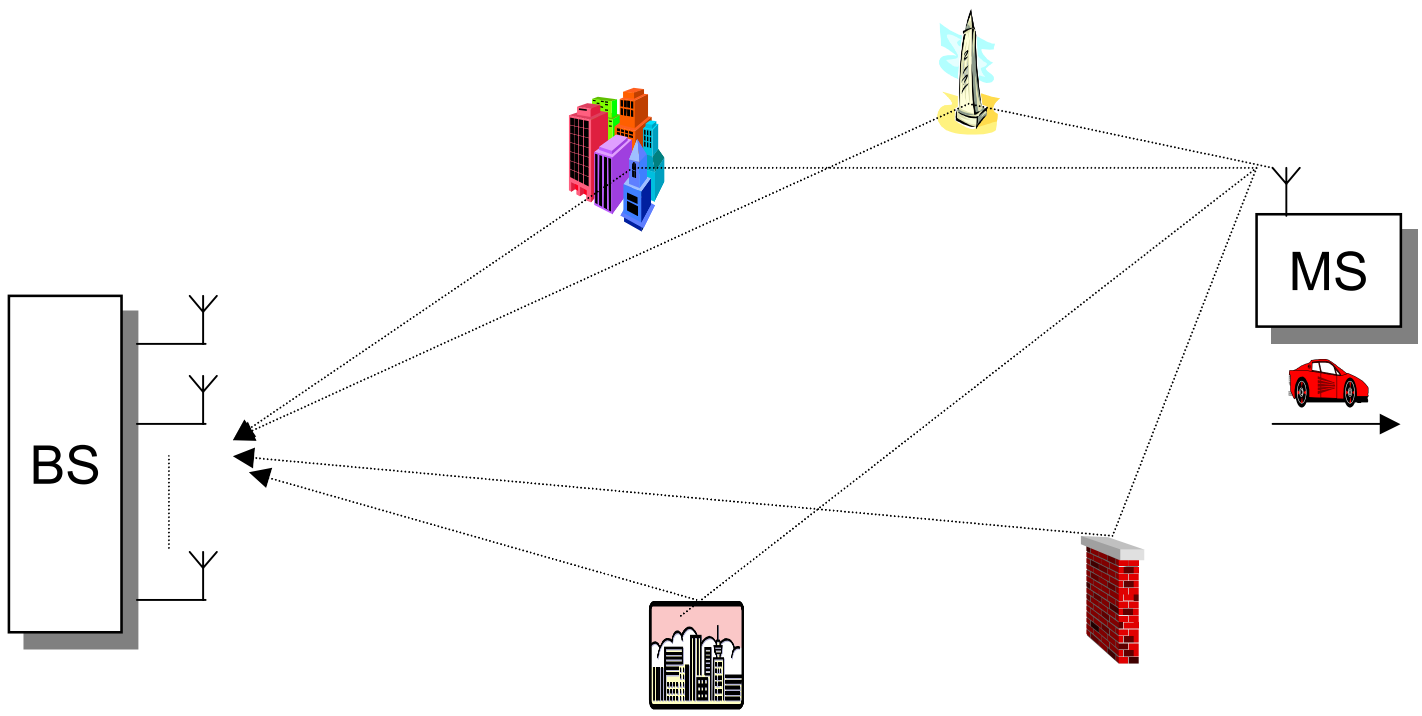
  → Estimation of Spatial Signature for Mobile Channel

  → Signal Combining Techniques

Background (1)

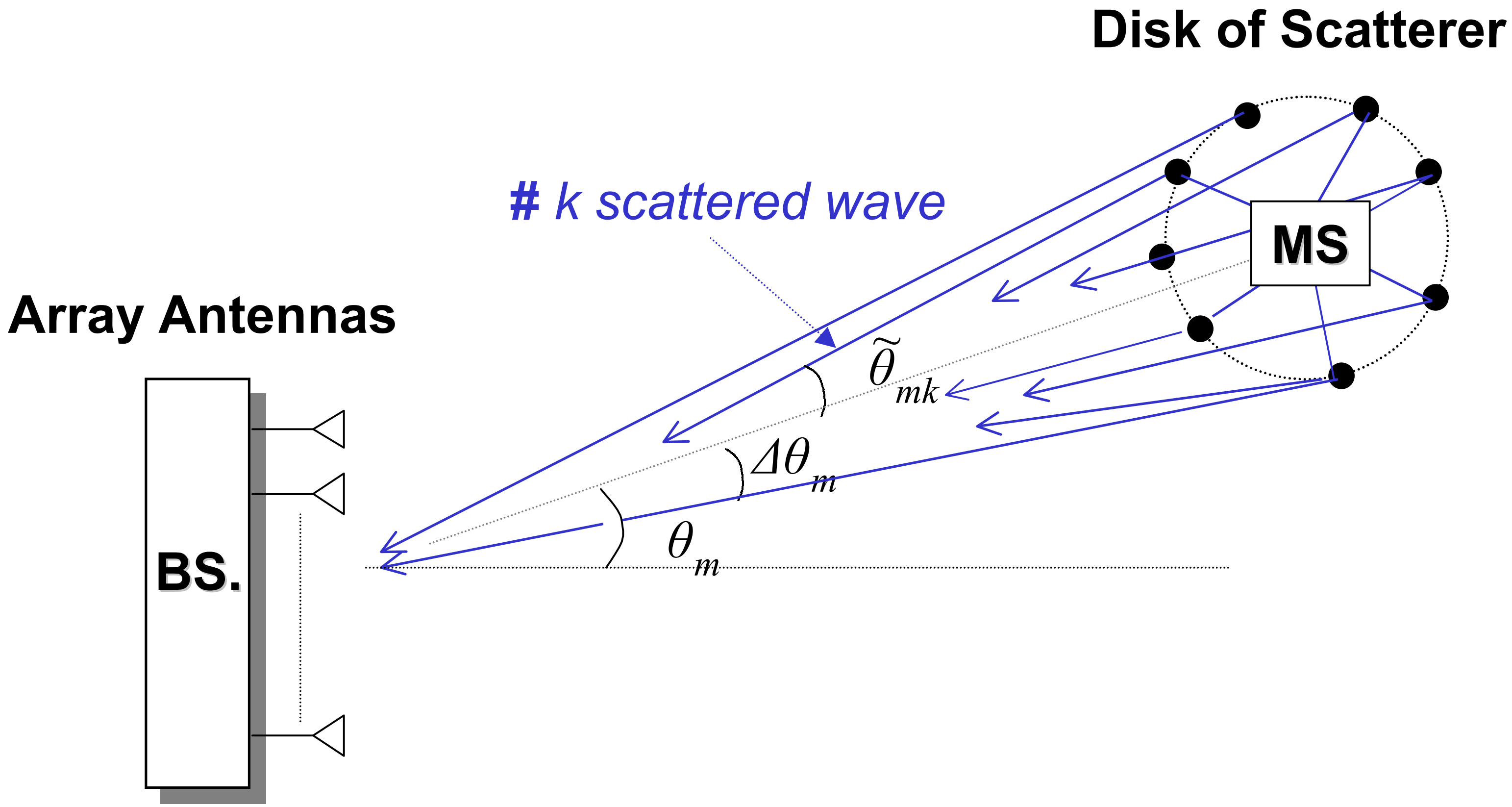


Mobile Communication Environments



Background (2)

Mobile Communication Environments



Background (3)

- DOA Estimation based on Plane Waves Model
  - Causing Modeling Errors in Angular Spread Environment
- Degradation of Estimation Performance of Spatial Signature
  - Obstracles to Signal Waveforms Recovery & SINR Maximization
- Requiring Robust DOA & AS Estimators against Realistic Environments

Related Research (1)

Problem of Estimating AS

- **Effects of Multipath-Induced AS on DOA estimators**

  → T. Sorelius et.al., (Proc. IEEE/IEE Int. Workshop, 1995

- **Estimation of Nominal DOA and AS**

  → T. Trump & B. Ottersten (Signal Processing, 1996)

- **Low Complexity Estimators**

  → Bengtsson & B.Ottersten (IEEE Trans. SP, 2001)

- **Effects of Local Scattering DOA estimation with MUSIC & ESPRIT**

  → D.Asztely & B.Ottersten (ICASSP, 1998)

- **Effects of Local Scattering on DOA estimation with MUSIC**

  → D.Asztely & B.Ottersten (IEEE, 1999)

Related Research (2)

Problem of combining Signals in AS environments

- **An Adaptive Array for Mobile Communication Systems**

  → S. Anderson et.al., (IEEE Trans. VT, 1991)

- **Modified Array Manifold for Signal Waveform Estimation**

  → D.Asztely & B.Ottersten (Proc. 30th Asilomar Conf., 1996)

- **Signal Waveform Estimation in AS Environment**

  → M. Bengtsson & B.Ottersten (Proc. 30th Asilomar Conf.,1996)

Objectives

- To cope with Modeling Errors of DOA Estimators in AS
- To obtain More Accurate Spatial Signature(SS) Estimates
- To provide Robust Signal Combining Technique in AS Environments

Solution

Proposals for Joint Estim. of DOA & AS→SS Estim.

Extended Array Mode Vector ⇨ **MUSIC & ESPRIT**

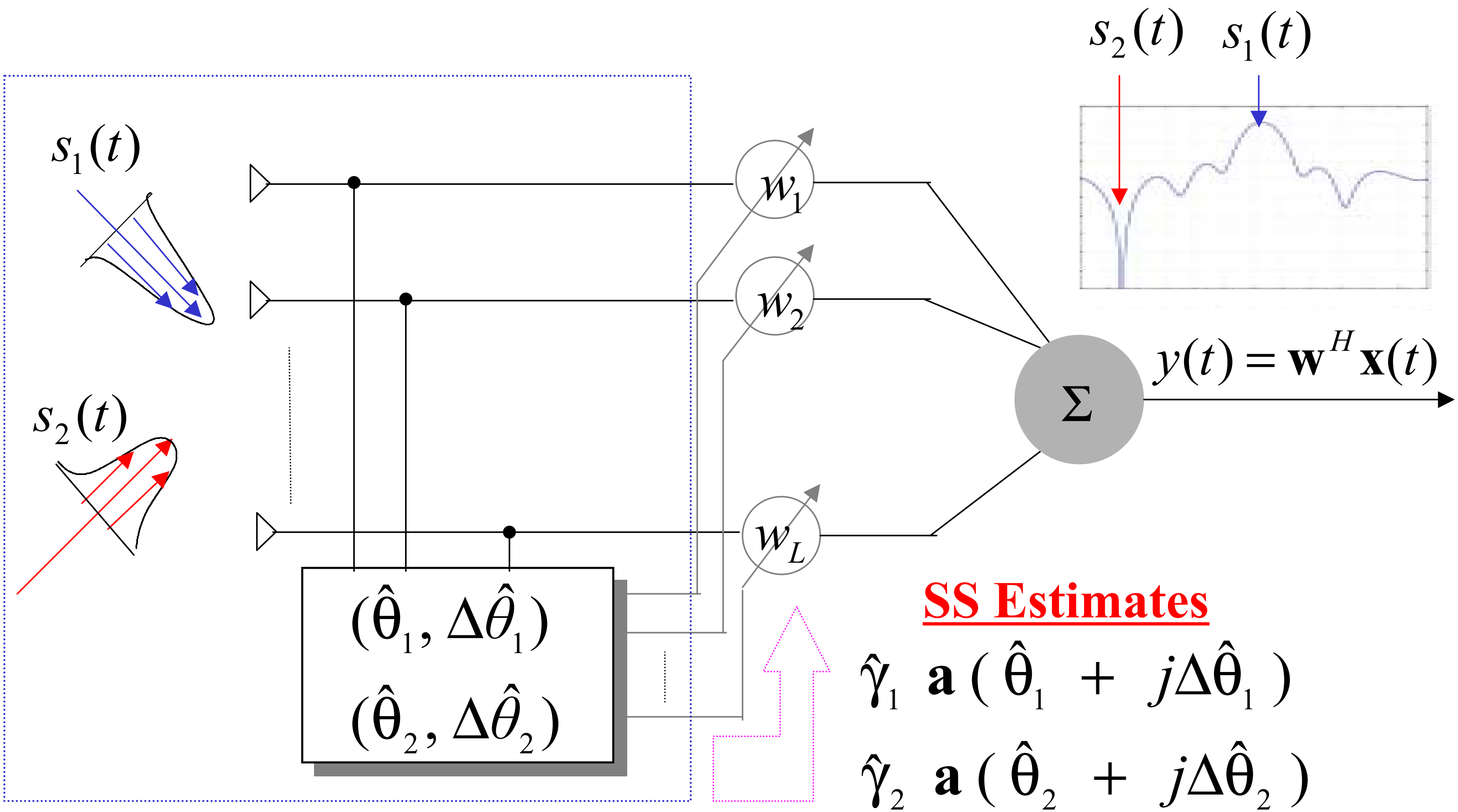
⇨

Proposal for Optimal Signal Combining using EAMV

DCMP & ZF ⇨ **SINR Evaluation**

(1) Slow Fading Environments modeled by Local Scattering.
(2) Spatial Signal Processing at BS.

Spatial Processing at Base Station



SS Estimates

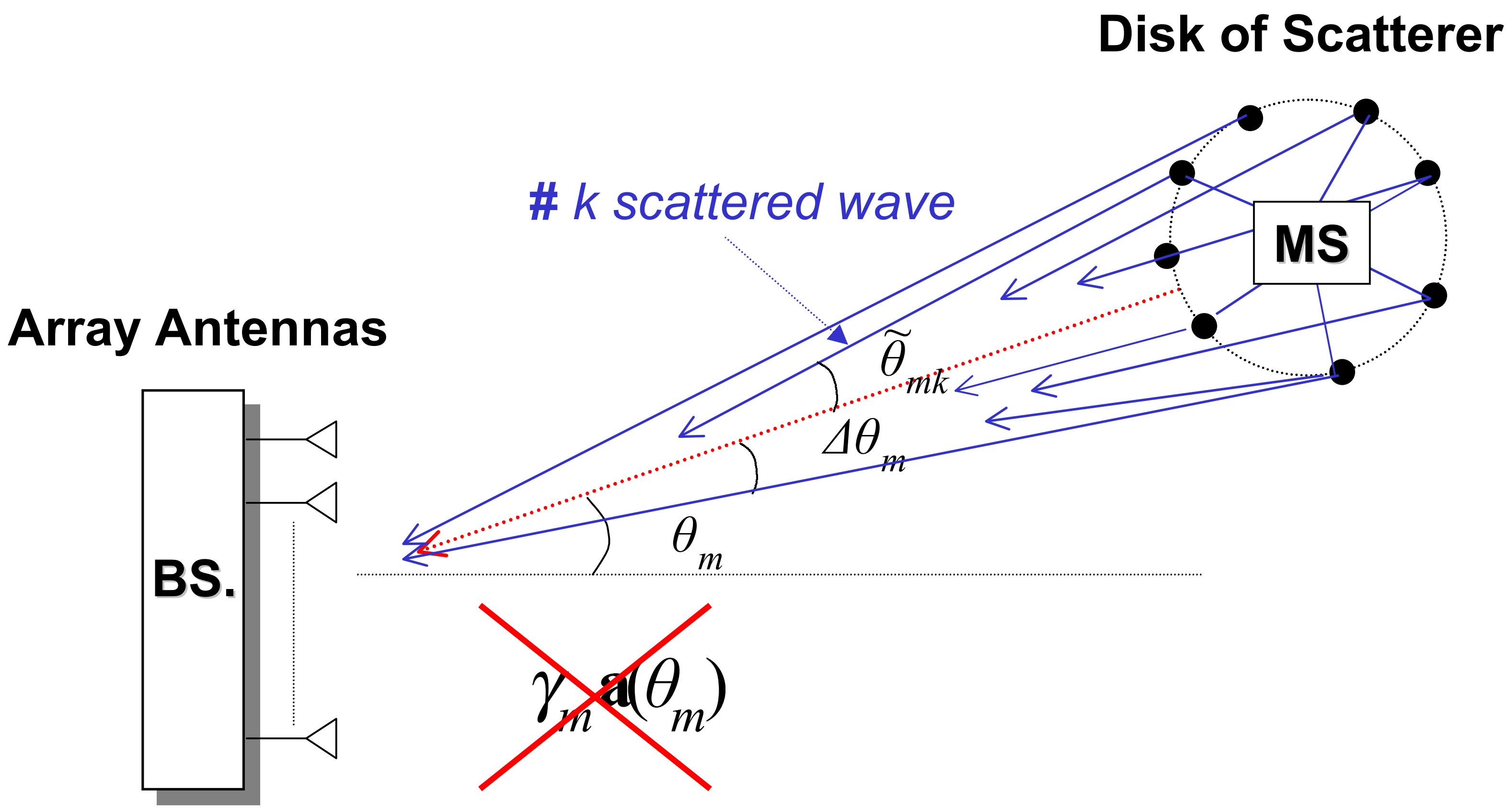
$\hat{\gamma}_1 \ \mathbf{a}(\hat{\theta}_1 + j\Delta\hat{\theta}_1)$

$\hat{\gamma}_2 \ \mathbf{a}(\hat{\theta}_2 + j\Delta\hat{\theta}_2)$

A brief description of mobile channel related to AS

<table>
<tr><th colspan="4">Frequency Flat Channel $T_s >> T_m$</th></tr>
<tr><td rowspan="2">No AS
$\sigma_\theta = 0$</td><td colspan="2">Narrow AS $\sigma_\theta << \theta_{3\text{dB}}$</td><td rowspan="2">Wide AS
$\sigma_\theta \geq \theta_{3\text{dB}}$,
$\sigma_\theta \approx \theta_{3\text{dB}}$</td></tr>
<tr><td>Slow Fading
$T_c >> T_o$</td><td>Fast Fading
$T_c \approx T_o$</td></tr>
<tr><td>Plane Wave Model</td><td>Conv. Approach (1)</td><td>Conv. Approach (2)</td><td>???</td></tr>
<tr><td colspan="4">Frequency Selective Channel $T_s \approx T_m$</td></tr>
<tr><td colspan="4">Spatial and Temporal Model</td></tr>
</table>

Local Scattering Model



Data Model in Scattering Environments

Conventional Approach

$$\mathbf{x}(t) = \sum_{k=1}^{K_m} \beta_{mk}\, \mathbf{a}(\theta_m + \tilde{\theta}_{mk})\, s_m(t) + \mathbf{n}(t)$$

Spatial Signature ← $\sum_{k=1}^{K_m} \beta_{mk}\, \mathbf{a}(\theta_m + \tilde{\theta}_{mk})$

Conventional Array Mode Vector → $\mathbf{a}(\theta_m + \tilde{\theta}_{mk})$

$$\left(\sum_{k=1}^{K_m} \beta_{mk}\right)\mathbf{a}(\theta_m + \tilde{\theta}_{mk}) \cong \left(\sum_{k=1}^{K_m} \beta_{mk}\right)\mathbf{a}(\theta_m) + \left(\sum_{m=1}^{K} \beta_{mk}\tilde{\theta}_{mk}\right)\left.\frac{\partial \mathbf{a}(\theta)}{\partial \theta}\right|_{\theta=\theta_m}$$

$$\cong \gamma_m \left(\mathbf{a}(\theta_m + \mathrm{Re}\{\zeta_m\}) + \mathrm{Im}\{\zeta_m\}\left.\frac{\partial \mathbf{a}(\theta)}{\partial \theta}\right|_{\theta=\theta_m} \right)$$

$$\gamma_m \equiv \sum_{k=1}^{K_m} \beta_{mk} \qquad \zeta_m \equiv \frac{\sum_{k=1}^{K_m} \beta_{mk}\tilde{\theta}_{mk}}{\sum_{k=1}^{K_m} \beta_{mk}}$$

Assumptions for Data Model

Frequency Flat Channel $T_s >> T_m$

Narrow AS $\sigma_\theta << \theta_{3\mathrm{dB}}$
Slow Fading $T_c >> T_o$

Assumptions for Data Model

(A 1)

1Burst $f_D \cdot T_{obs} \approx 0$

NEGLIGIBLE

Coherence Time

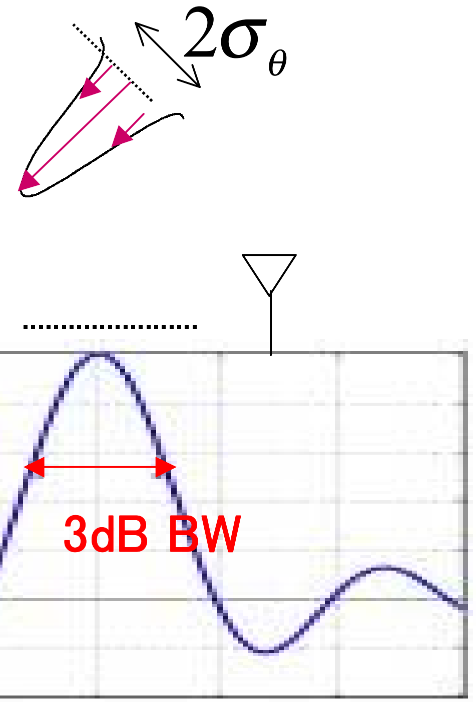
Observation Time

One Symbol Duration

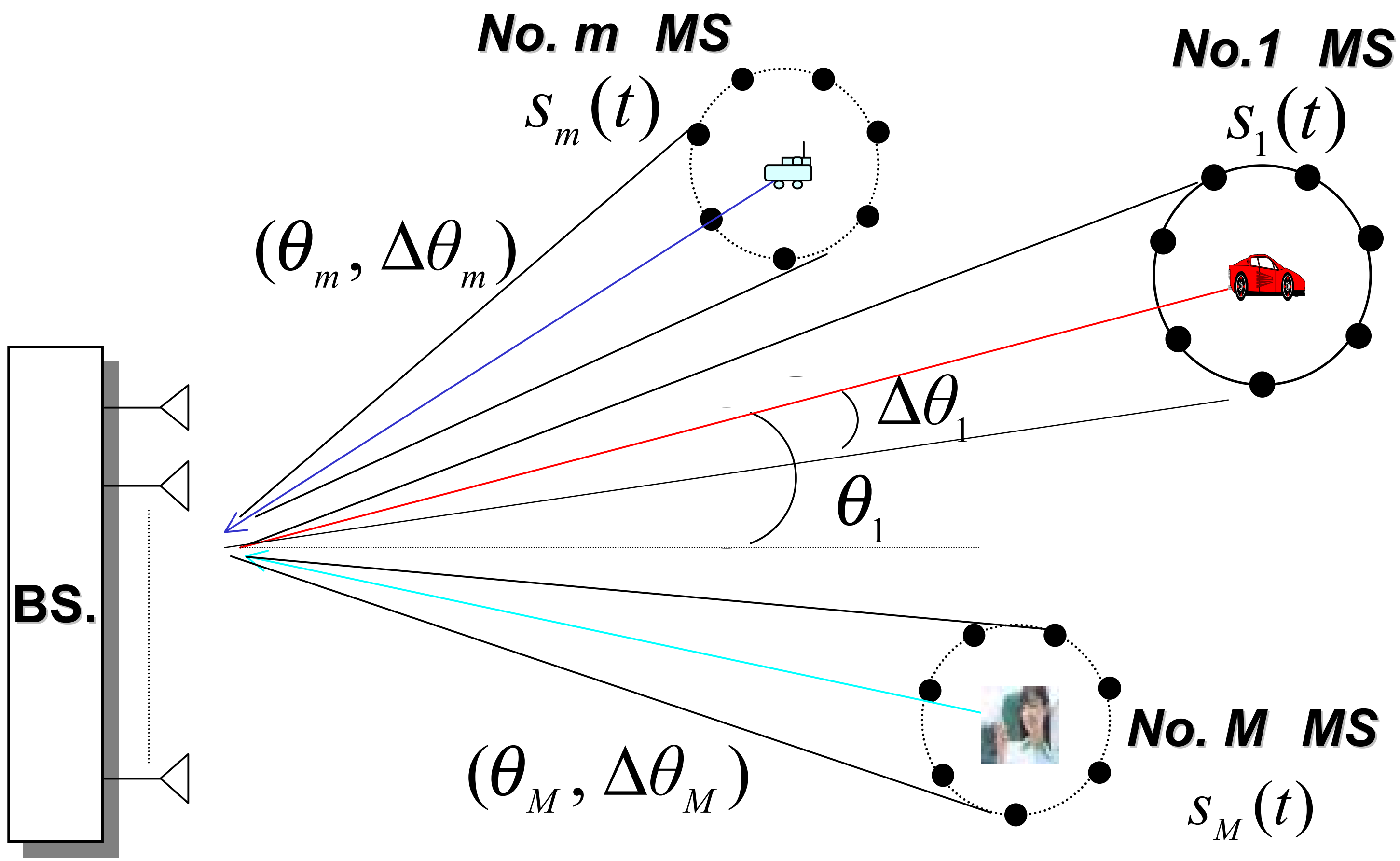
Max. Excess Delay Time

(A 2)

$$\sigma_\theta << \theta_{3dB}$$



Multiple Clusters Environments



Extended Array Mode Vector (EAMV)

$$\mathbf{x}(t) = \sum_{m=1}^{M} \sum_{k=1}^{K_m} \beta_k \mathbf{a}(\theta_m + \tilde{\theta}_{mk}) s_m(t) + \mathbf{n}(t)$$

$$\gamma_m \ \mathbf{a}\left(\theta_m + \mathrm{Re}\{\zeta_m\} + \mathrm{Im}\{\zeta_m\}\right)$$

$$\zeta_m \equiv \frac{\sum_{k=1}^{K_m} \beta_{mk} \tilde{\theta}_{mk}}{\sum_{k=1}^{K_m} \beta_{mk}}$$

Fading Coefficient

Inst. DOA

Inst. AS

Comparison (1)

First-Order Approximation of Spatial Signatures

$$\gamma_m \, \mathbf{a}\,(\theta'_m + j\Delta\theta_m)$$

$$\gamma_m \left(\mathbf{a}(\theta'_m) + \mathrm{Im}\{\zeta_m\} \left. \frac{\partial \mathbf{a}(\theta)}{\partial \theta} \right|_{\theta=\theta_m} \right)$$

Comparison (2)

How the AS can be obtained ?

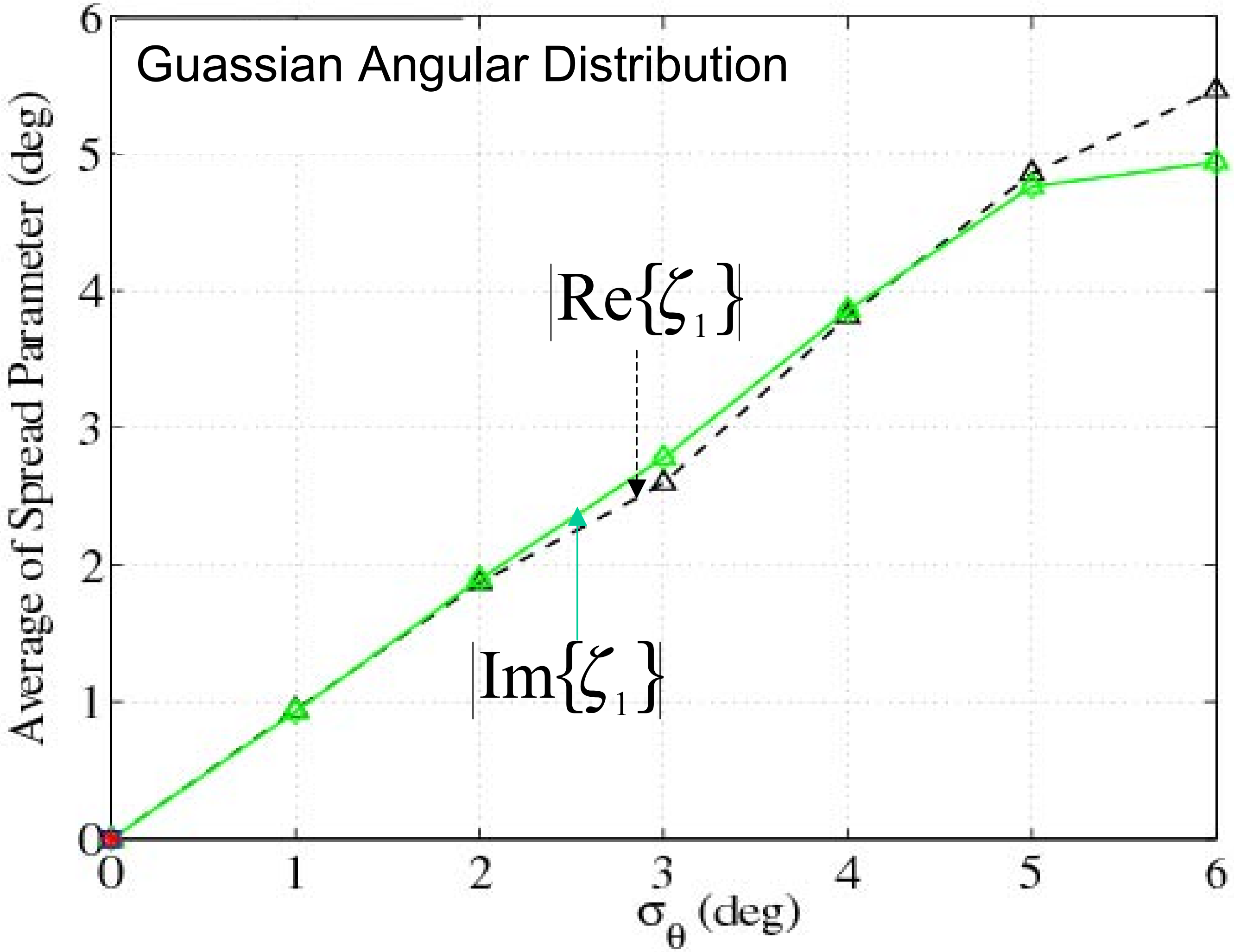
Frequency Flat Channel $T_s >> T_m$

Narrow AS $\sigma_\theta << \theta_{3dB}$
Slow Fading $T_c >> T_o$

Conventional Approach (1) → Standard Deviation of DOA Estimates

Proposed Approach → Instantaneous DOA & Instantaneous AS

Statistical Property in Spread Parameter



Summary

- Proposal of EAMV representing Inst. DOA & Inst. AS
- The EAMV incorporates $\mathrm{Im}\{\zeta_1\}$ into AS.
- Range of the first-order approx. → limited to the small AS
- The EAMV is applicable to many DOA estimation algorithms.
- It is expected to be effective parameters in the slow fading environments

: **Signal Waveform Estimation in AS Environment**

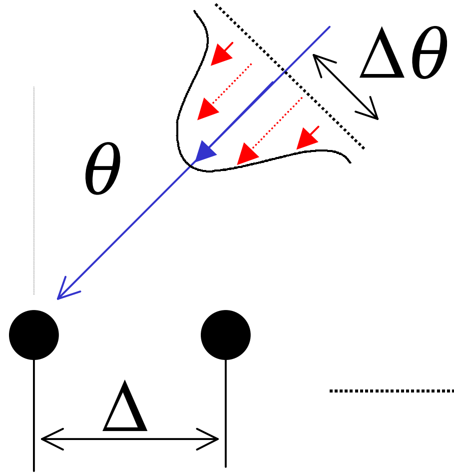
→ M. Bengtsson & B.Ottersten (Proc. 30th Asilomar Conf.,1996)

Review for Parameter Estimation Algorithms

Spectral-based Methods — **Parametric Methods**

- Spectral-based Methods
  - Beamforming Methods
    - Conventional Beamformer
    - Capons's Beamformer
  - Subspace Methods
    - **MUSIC**,
    - Min-Norm
- Parametric Methods
  - Root-MUSIC,
  - **ESPRIT**
  - MD-MUSIC
  - ML, WSF

EAMV

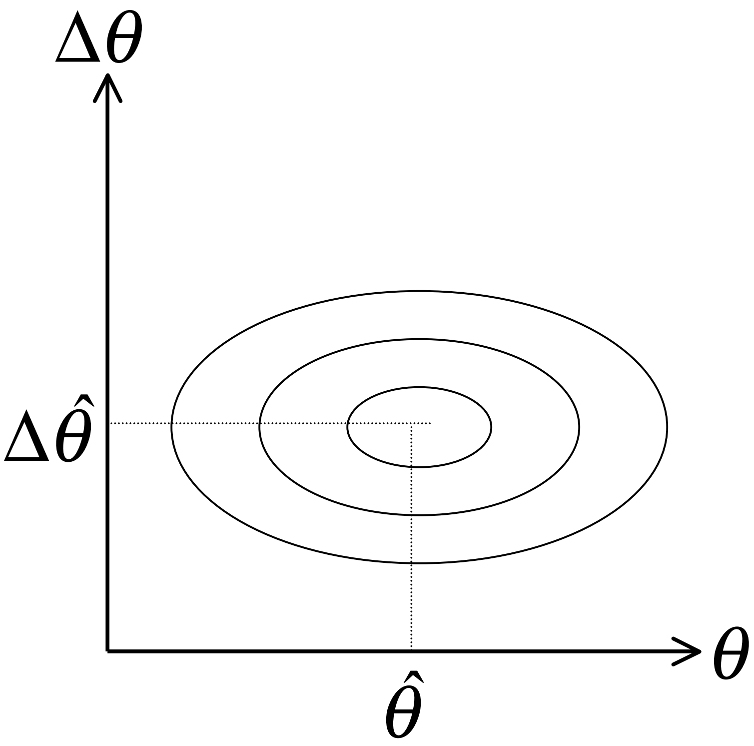


$$\mathbf{a}(\theta + j\Delta\theta) \cong \left[1 \;\; e^{j\frac{2\pi}{\lambda}\Delta\sin(\theta + j\Delta\theta)} \;\; \cdots e^{j(L-1)\frac{2\pi}{\lambda}\Delta\sin(\theta + j\Delta\theta)} \right]^T$$

MUSIC for Joint Estimation of DOA & AS

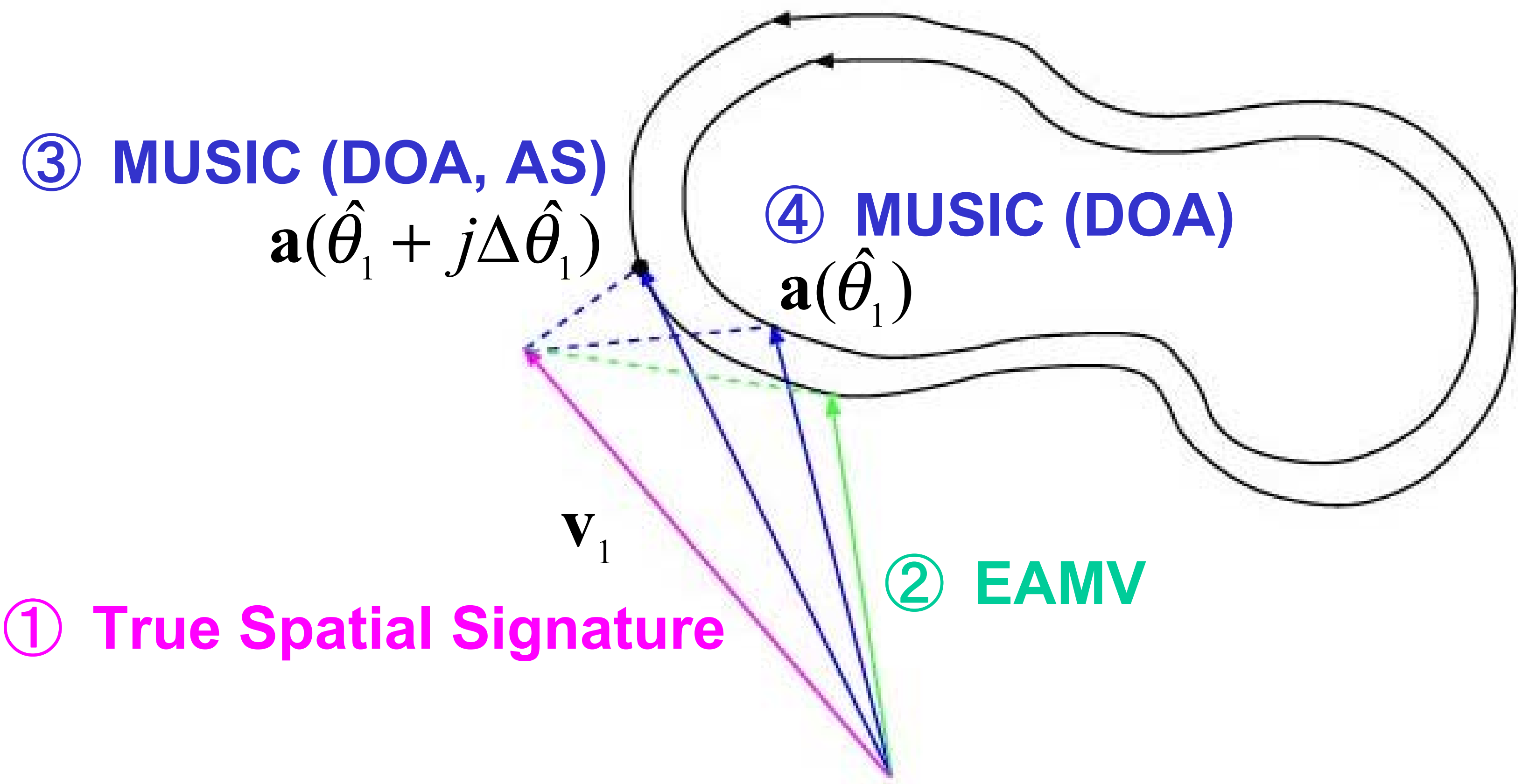
Min. of MUSIC Cost Function

$$\min_{\hat{\theta}_m, \Delta\hat{\theta}_m} \frac{\left\| \mathbf{E}_N^H \mathbf{a}(\theta + j\Delta\theta) \right\|^2}{\left\| \mathbf{a}(\theta + j\Delta\theta) \right\|^2}$$

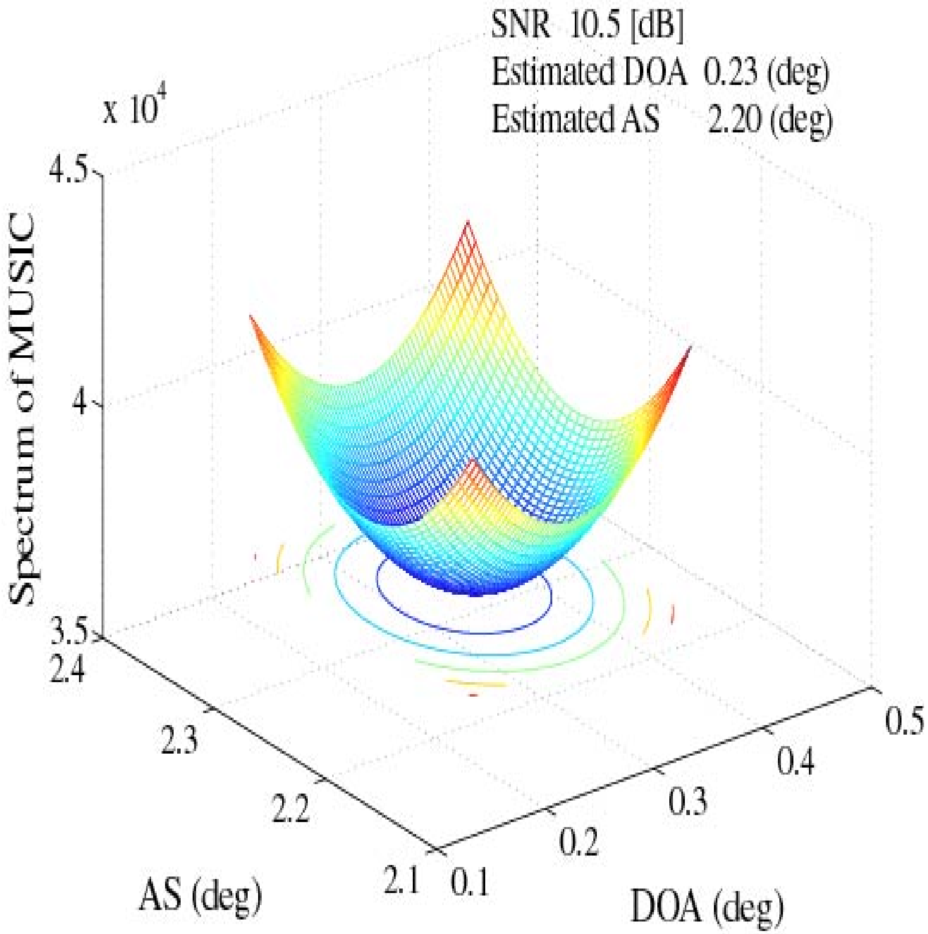


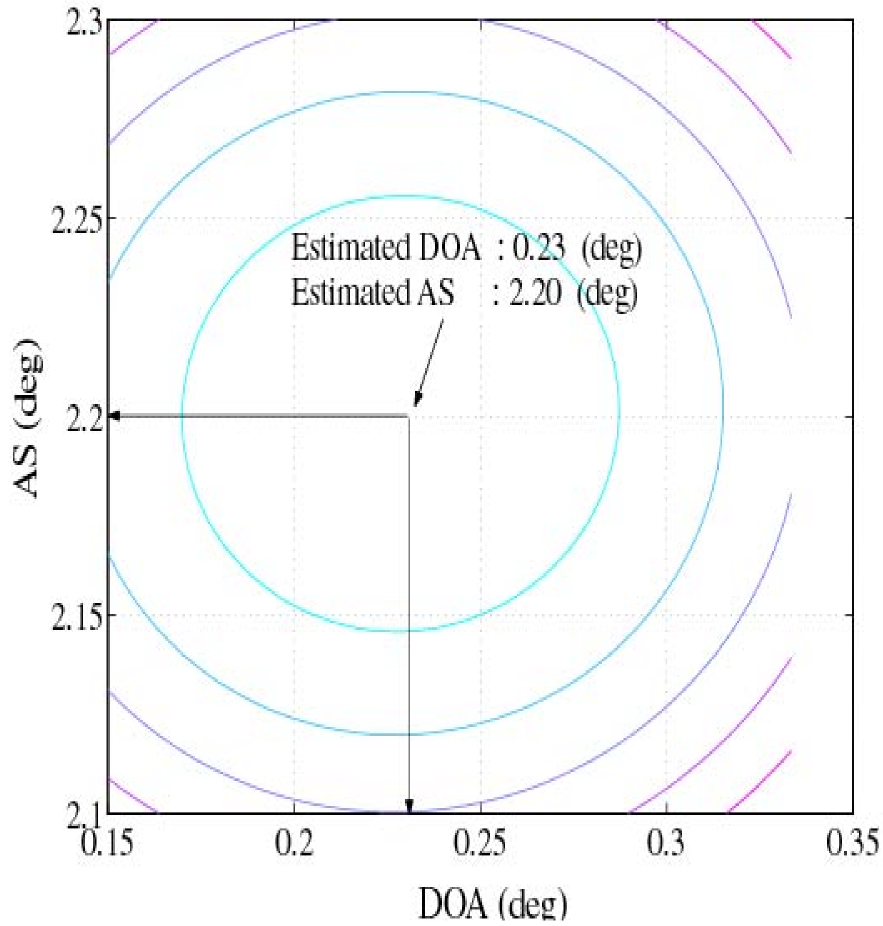
if $\Delta\theta = 0 \rightarrow$ Conventional MUSIC.

Array Manifold over Complex Angle Planes
-- Trace of EAMV --



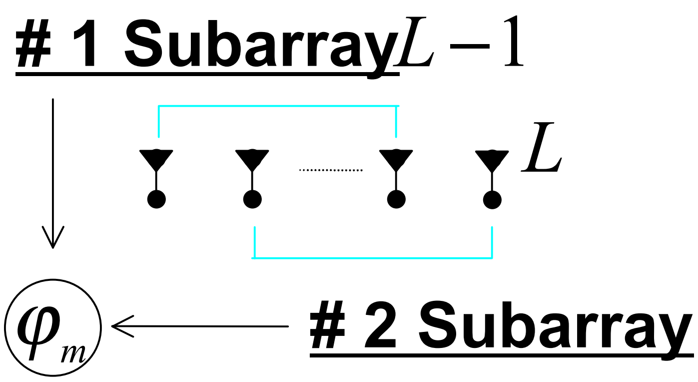
Example of Estimates (Inst. DOA & Inst. AS)





ESPRIT for Joint Estimation of DOA & AS

- **Two Identical Subarray**
- **Translational Invariance Principle**



$$\hat{\varphi}_m = \exp\left(j \frac{2\pi}{\lambda} \Delta \sin\left(\hat{\theta}_m + j \Delta\hat{\theta}_m \right) \right)$$

Estimation Performance

- Instantaneous DOA and AS Estimates
- Proximity of True Spatial Signature
  - One Signal Case
  - Multiple Signals Case

① Proximity Evaluation to Spatial Signature

Data Fitting Error

② APPROX. : EAMV

$$\gamma_m \, \mathbf{a}(\theta_m + j\Delta\theta_m)$$

③ Reconstruction of EAMV by DOA & AS Estimate

$$\hat{\gamma}_m \, \mathbf{a}(\hat{\theta}_m + j\Delta\hat{\theta}_m)$$

④ Reconstruction of AMV by only DOA Estimate

$$\hat{\gamma}_m \, \mathbf{a}(\hat{\theta}_m)$$

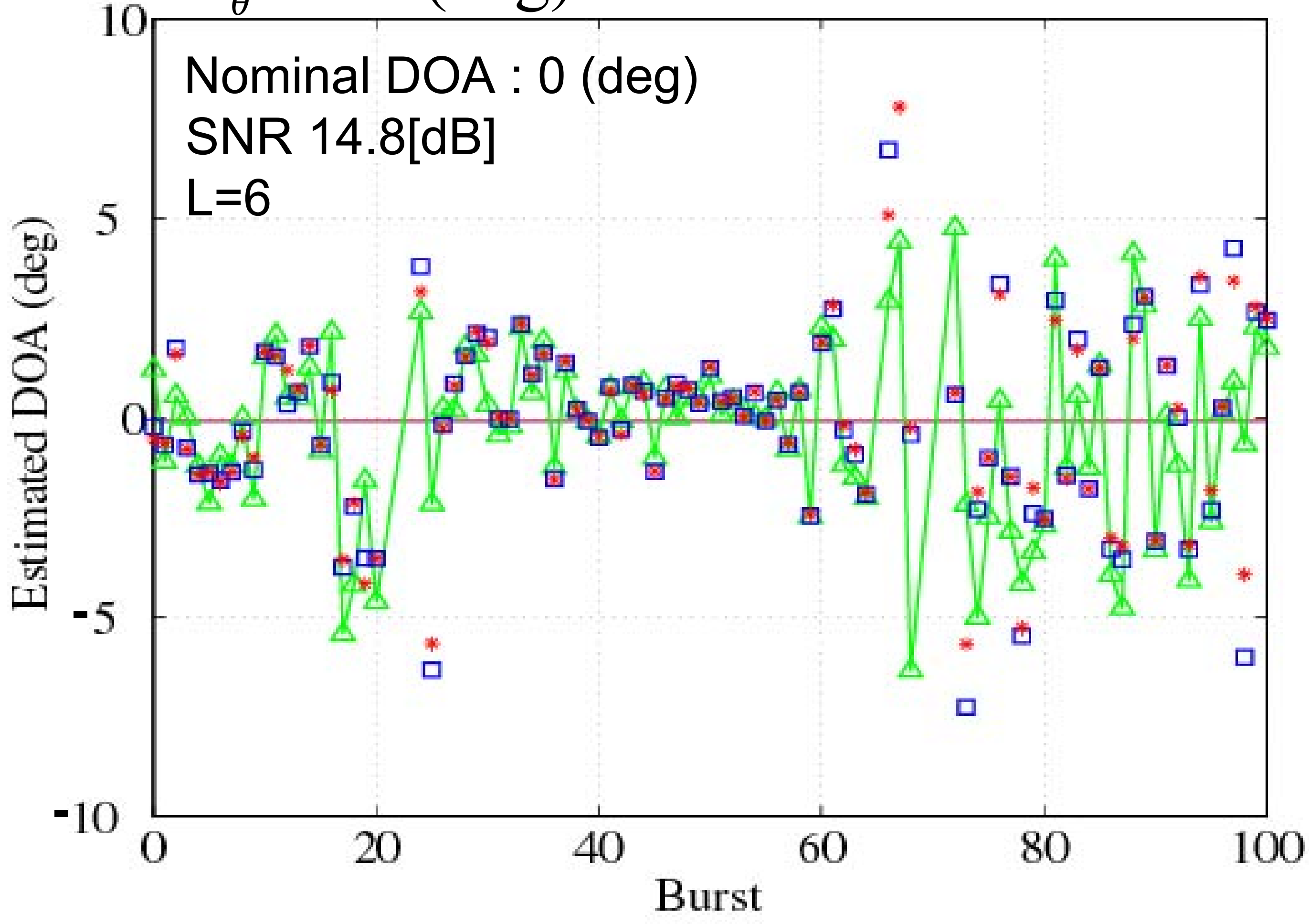
⑤ Error due to Finite Samples collected to obtain Sample Covariance Matrix

Simulation Conditions (1)

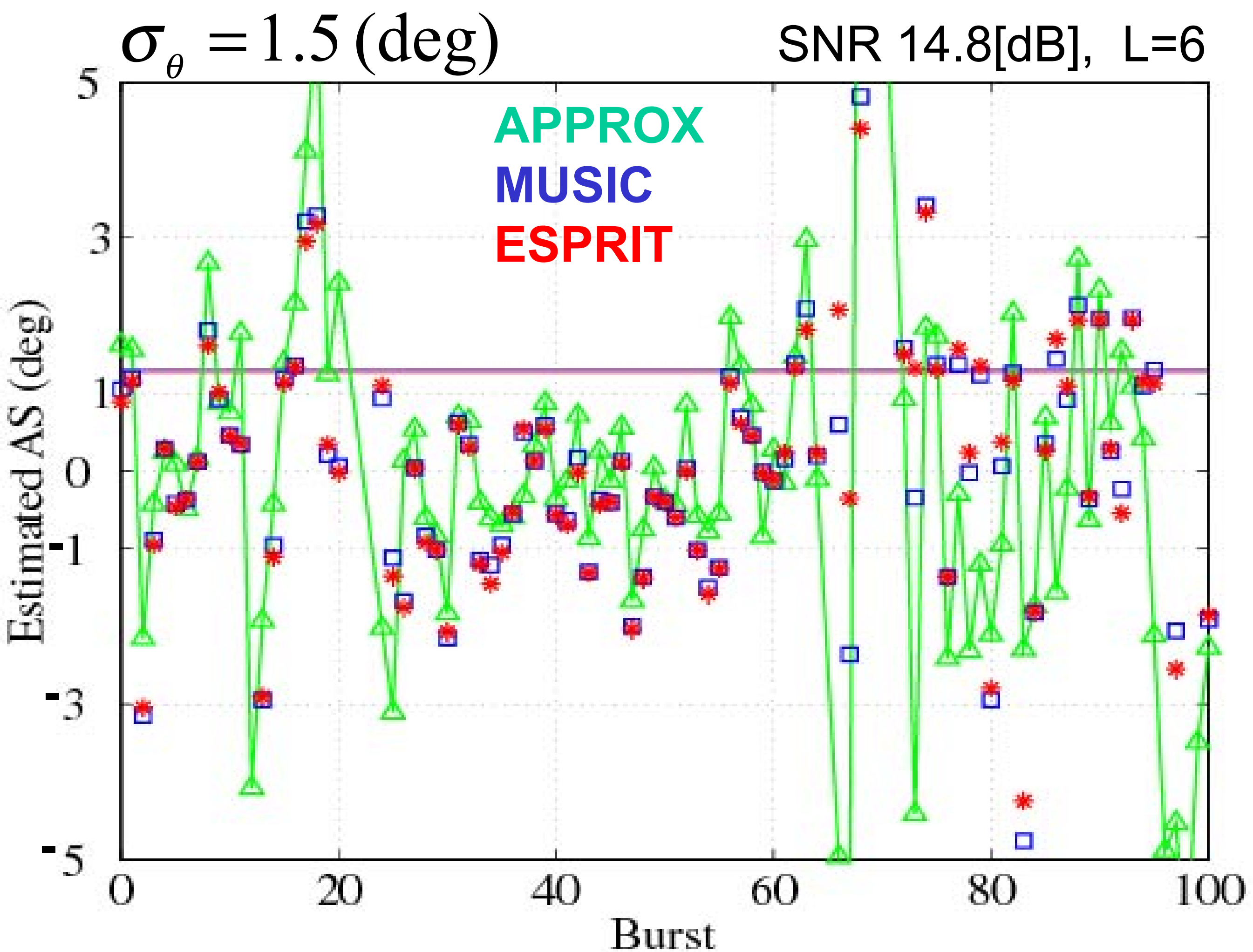
Type of Antenna	Uniform Linear Array Antenna
Number of Elements	Variable
Interelement Spacing	A Half of Wavelength
DOAs	0 (deg) / −10, 10 (deg)
Number of Scattered Waves	32
Angular Distribution	Gaussian Distributed at BS
Angular Spread (AS) : σ_θ	Variable
Snapshots / burst	127, Variable (BPSK)

Instantaneous DOA Estimates

$$\sigma_\theta = 1.5\,(\text{deg})$$

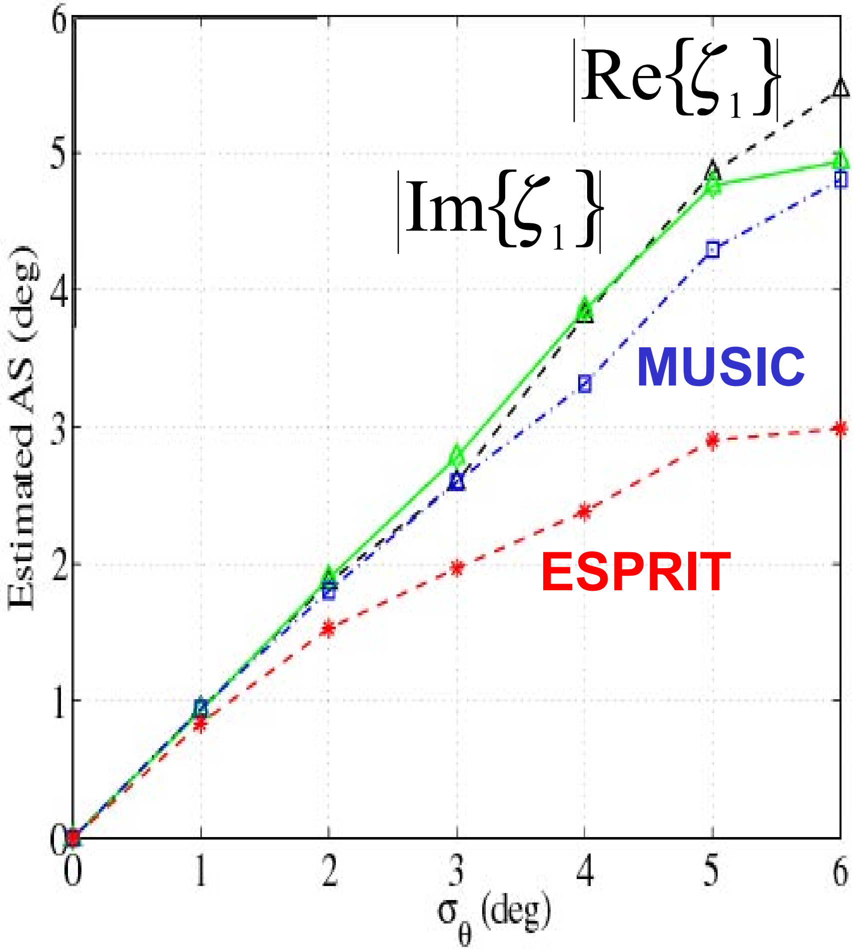


Instantaneous AS Estimates

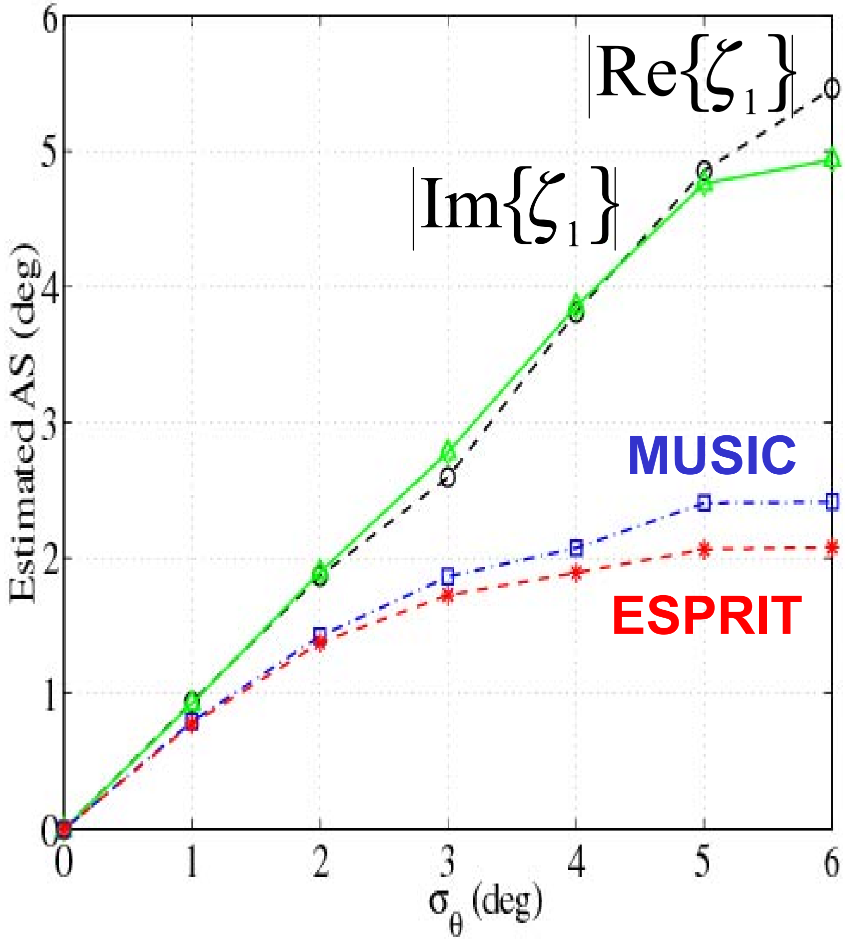


Evaluation of First-Order Moment $E\left[\left|\hat{\theta}_m - \theta_m\right|\right]$

Conv. MUSIC



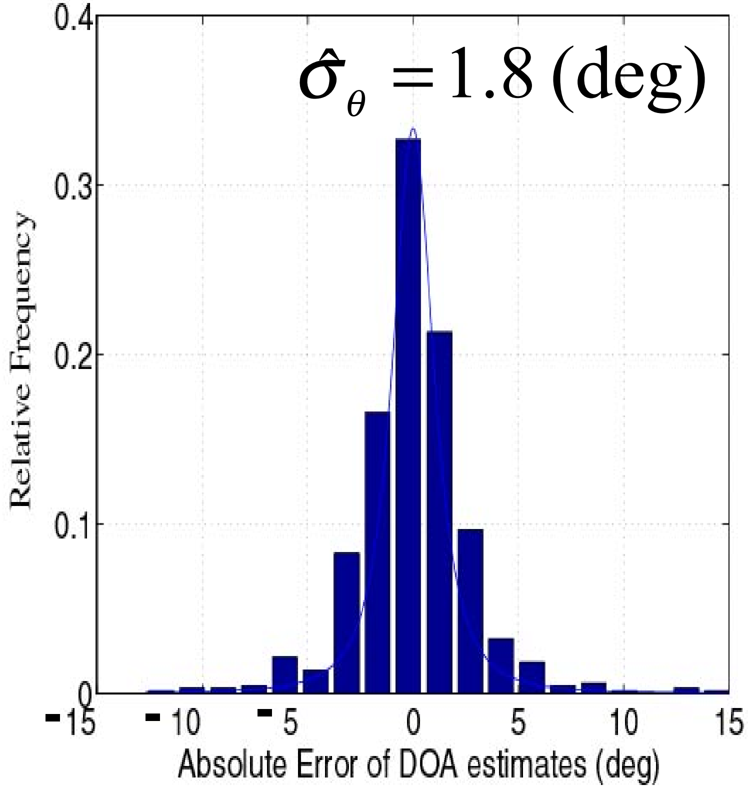
Proposed



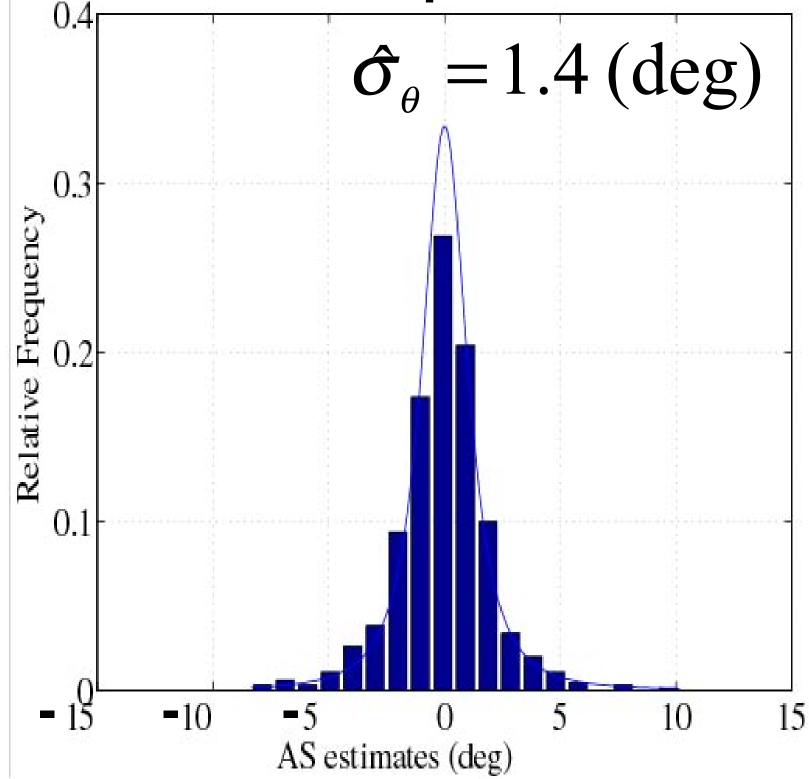
Evaluation of First-Order Moment

$$\sigma_\theta = 2.0 \text{ (deg)} \qquad E\left[\left|\hat{\theta}_m - \theta_m\right|\right]$$

Conv. MUSIC



Proposed



① Proximity Evaluation to Spatial Signature

Data Fitting Error

② APPROX. : EAMV

$$\gamma_m \, \mathbf{a}(\theta_m + j\Delta\theta_m)$$

③ Reconstruction of EAMV by DOA & AS Estimate

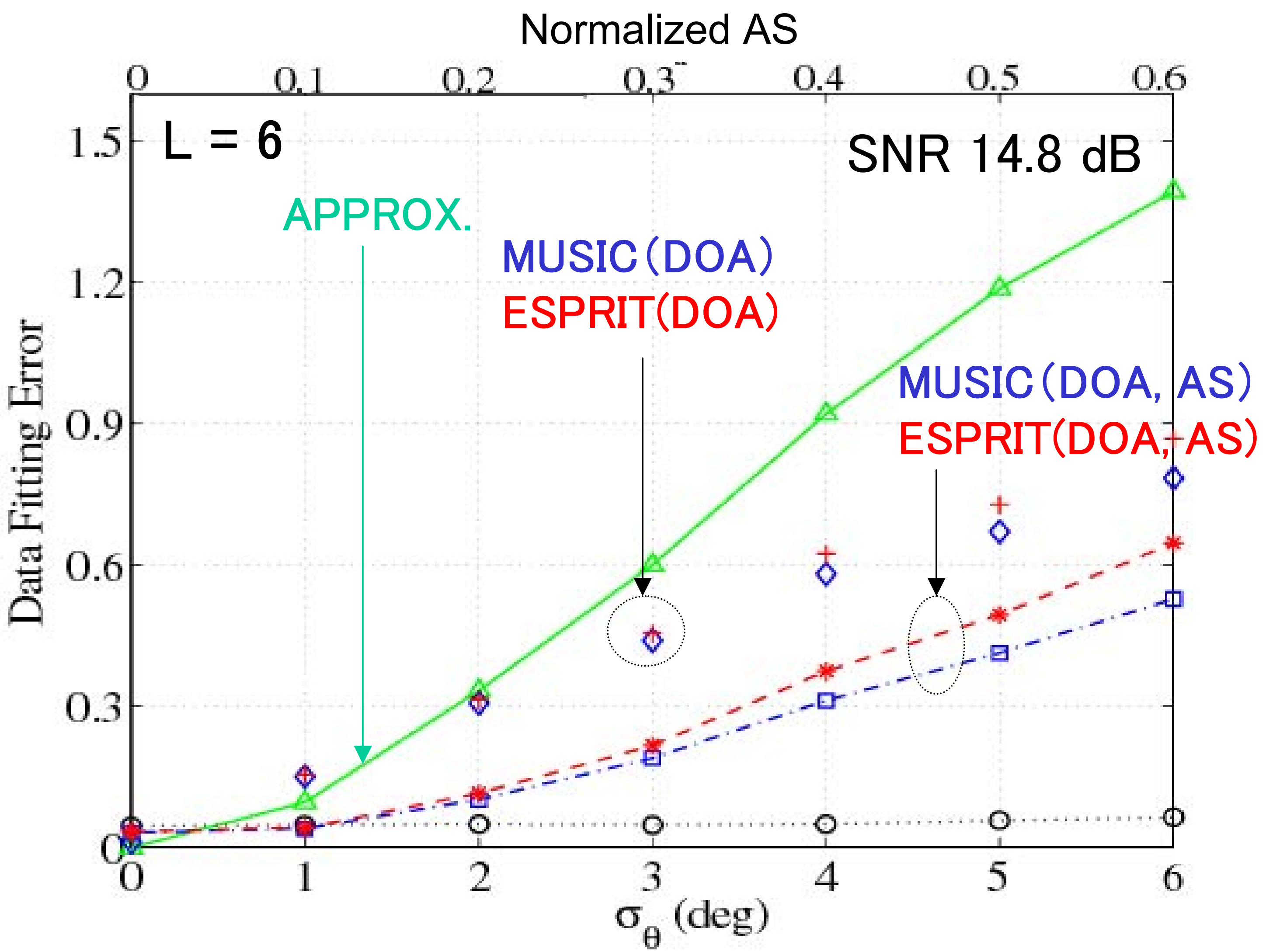
$$\hat{\gamma}_m \, \mathbf{a}(\hat{\theta}_m + j\Delta\hat{\theta}_m)$$

④ Reconstruction of AMV by only DOA Estimate

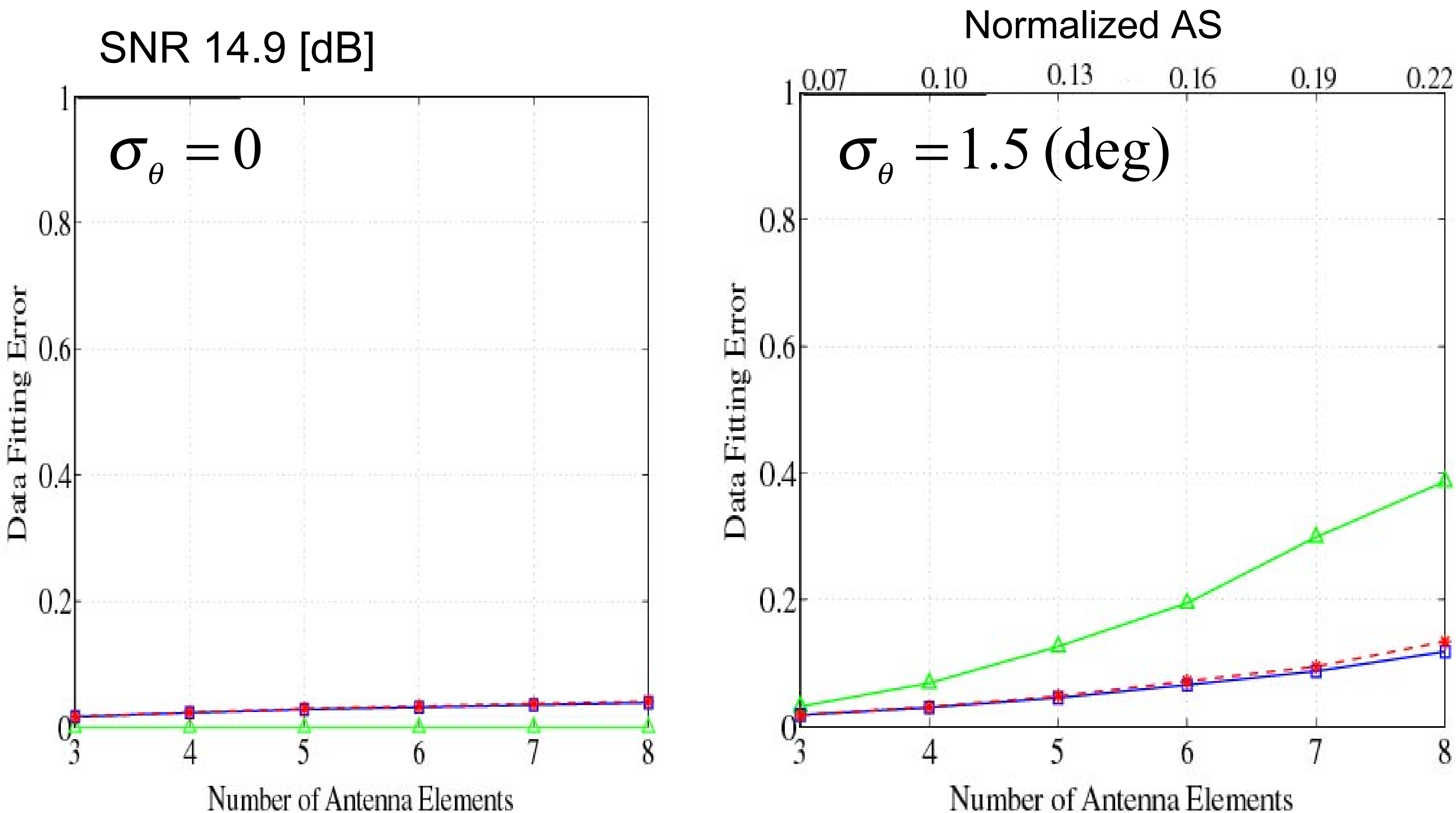
$$\hat{\gamma}_m \, \mathbf{a}(\hat{\theta}_m)$$

⑤ Error due to Finite Samples collected to obtain Sample Covariance Matrix

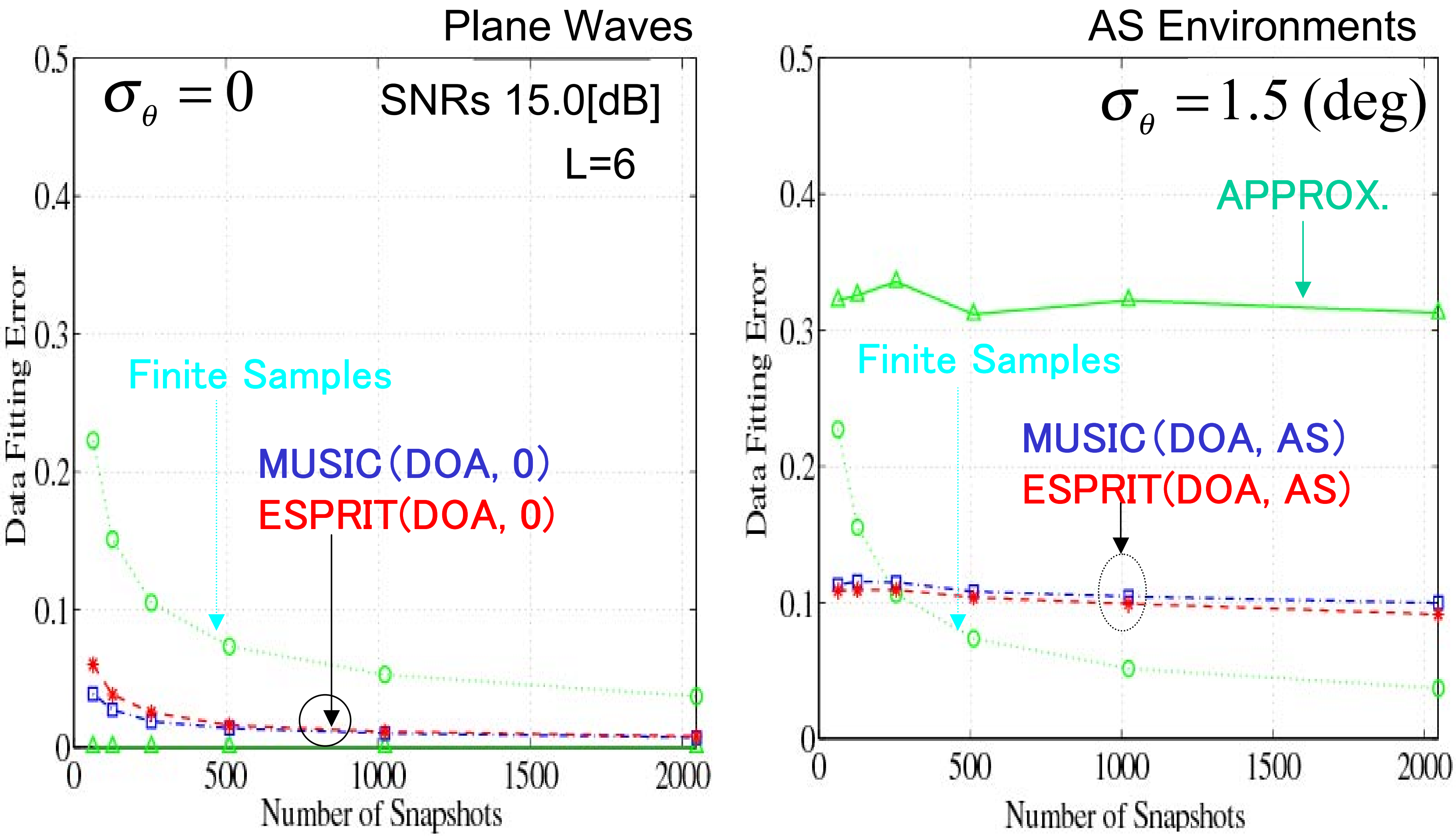
Proximity Evaluation (1)



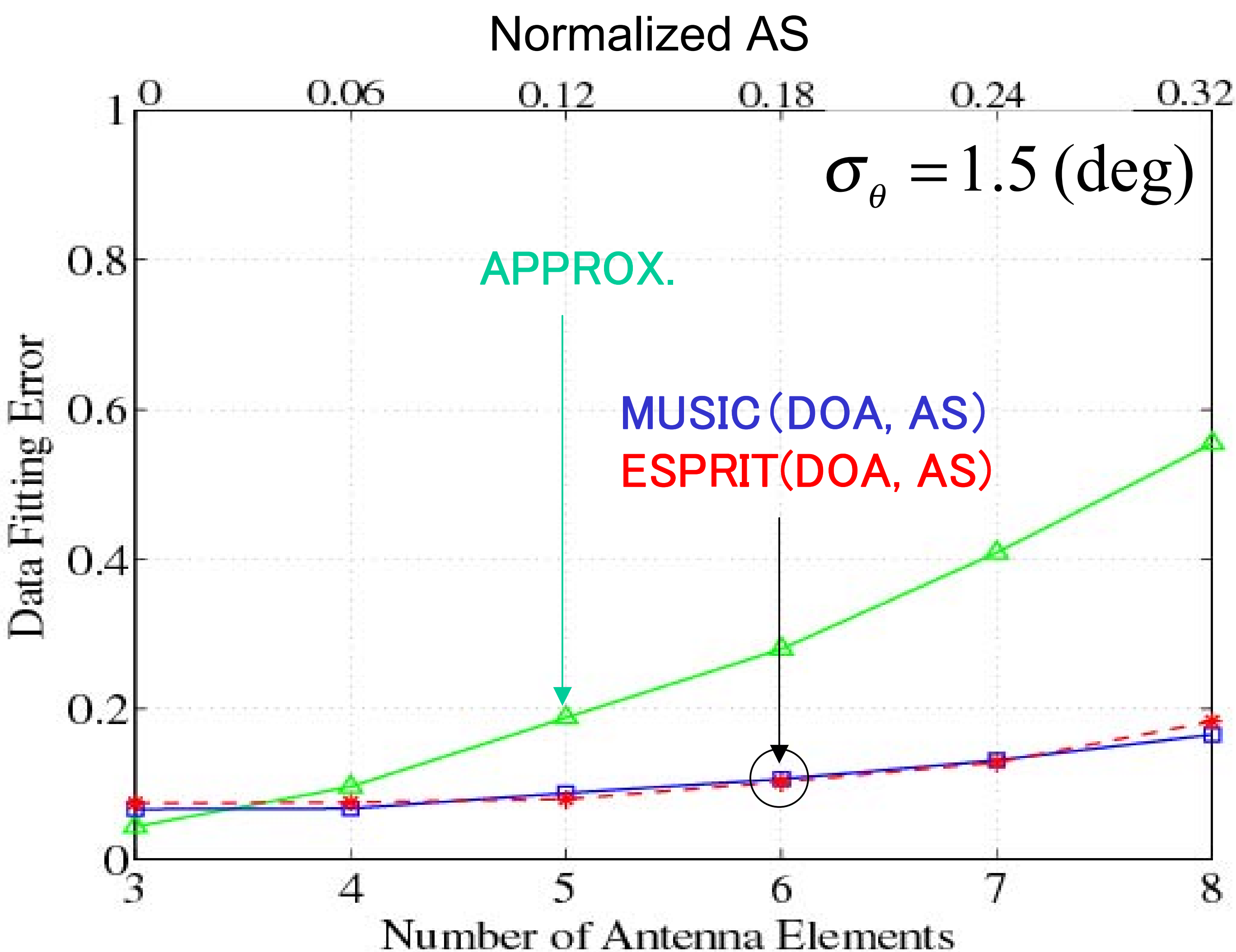
Proximity Evaluation (2)



Error due to Finite Samples



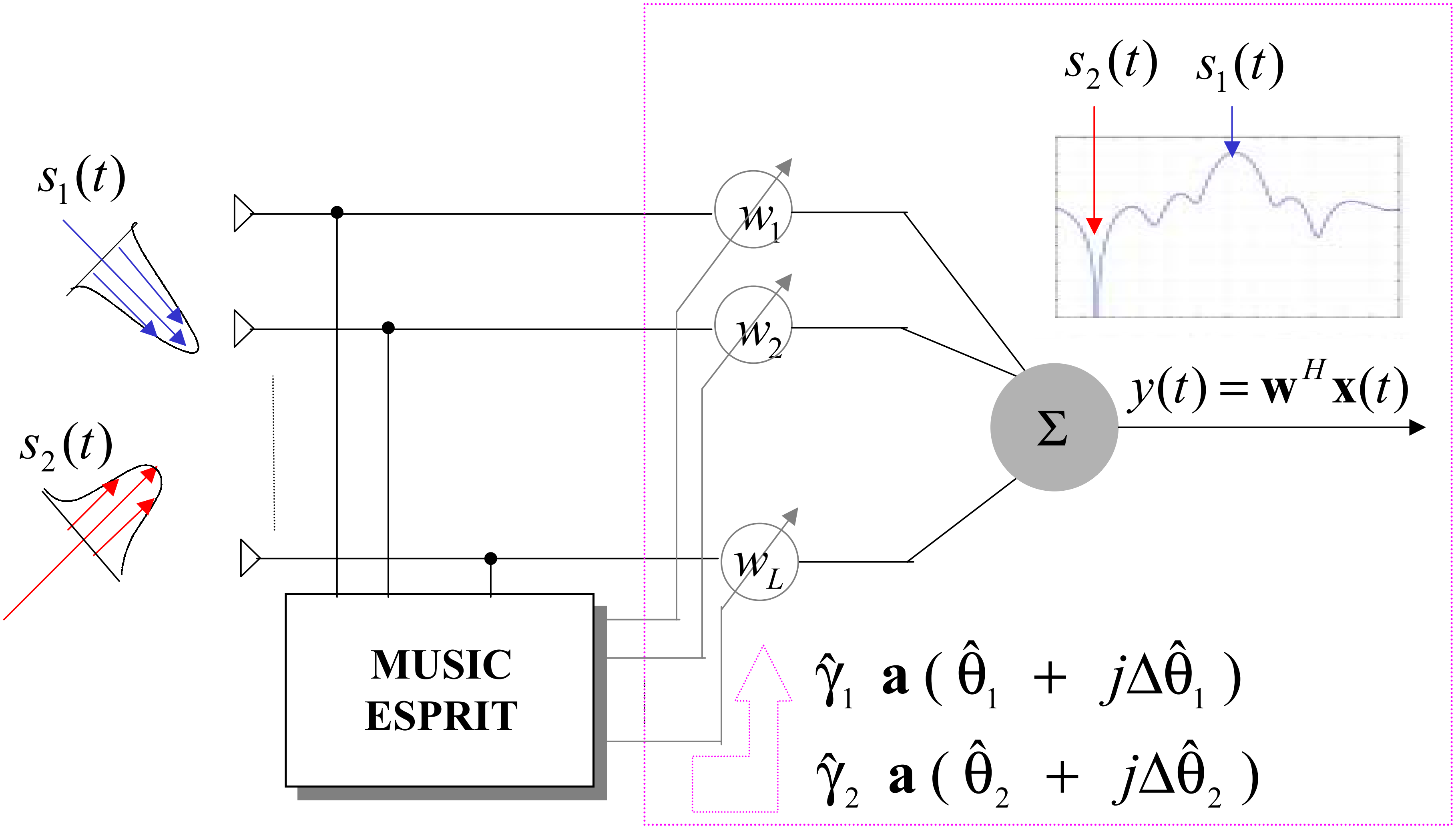
Effect on Increase of Antenna Elements



Summary

- Proposal of MUSIC & ESPRIT for Joint Estimation (DOA & AS)
- Proximity Evaluation from Spatial Signature Estimates
  - Estimation Performance of MUSIC & ESPRIT
- It showed that the large-size antenna itself in the AS environment does not always improve the estimation performance.
- The data fitting errors in both MUSIC & ESPRIT are less than the error due to first-order approximation.
- In the AS, the error due to finite samples is not dominant.
- The statistical analysis for the estimator is required.

Spatial Processing at Base Station



Robust Optimal Signal Combining Technique Based on EAMV

(1) Review for Signal Combining Techniques

(2) Directionally Constrained Minimization of Power (DCMP)

(3) Zero-Forcing (ZF)

(4) Performance Evaluation

(5) Summary

Review for Signal Combining Techniques

Methods based on Reference Signal

↓

- MMSE

Methods based on DOA Information

↓

- Conventional Beamforming
- Null Steering Beamforming (ZF)
- LCMV[1] (MVDR or DCMP)

LCMV[1] : Linearly Constrained Minimum Variance Beamforming

Related Research (2)

Problem of combining Signals in AS environments

- **An Adaptive Array for Mobile Communication Systems**

  → S. Anderson et.al., (IEEE Trans. VT, 1991)

- **Modified Array Manifold for Signal Waveform Estimation**

  → D.Asztely & B.Ottersten (Proc. 30th Asilomar Conf., 1996)

- **Signal Waveform Estimation in AS Environment**

  → M. Bengtsson & B.Ottersten (Proc. 30th Asilomar Conf.,1996)

Directionally Constrained Minimization of Power (DCMP)

$$\arg \min_{\mathbf{w}} \mathbf{w}^H \mathbf{R} \mathbf{w} \quad \text{subj. to} \quad \mathbf{w}^{\mathbf{H}} \mathbf{v}_1 = \text{const.}$$

$$\mathbf{w}_{\text{dcmp}} = \mathbf{R}^{-1} \mathbf{v}_1 \longrightarrow \textbf{Spatial Signature}$$

$$\textbf{Max. SINR} = \frac{\text{Output Desired Signal Power}}{\text{Output Interference Signal Power} + \text{Output Noise Power}}$$

Zero Forcing (ZF)

$$\hat{\mathbf{s}}(t) = \arg\min_{\mathbf{s}(t)} \left\| \mathbf{x}(t) - \mathbf{V}\mathbf{s}(t) \right\|^2$$

$$\hat{\mathbf{s}}(t) = (\mathbf{V}^H \mathbf{V})^{-1} \mathbf{V}^H \mathbf{x}(t) \qquad \mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2]$$

$$\hat{\mathbf{w}}_{\mathrm{zf}} = \left[\mathbf{V}(\mathbf{V}^H \mathbf{V})^{-1}\right]_{\text{1st column}}$$

$$\hat{\mathbf{w}}_{\mathrm{zf}} = \arg\max_{\mathbf{w}} \text{Output SNR} \ \text{ subj. to } \ \mathbf{w}^{\mathrm{H}} \mathbf{v}_2 = 0$$

Max. SINRs (Theoretical Values)

For DCMP

$$\text{Max. SINR}_{\text{dcmp}} = \text{Input SNR}\left(1 - \frac{|\rho|^2}{1 + \text{Input INR}}\right)$$

DCMP $\begin{smallmatrix} > \\ \text{or} \\ \approx \end{smallmatrix}$ **ZF**

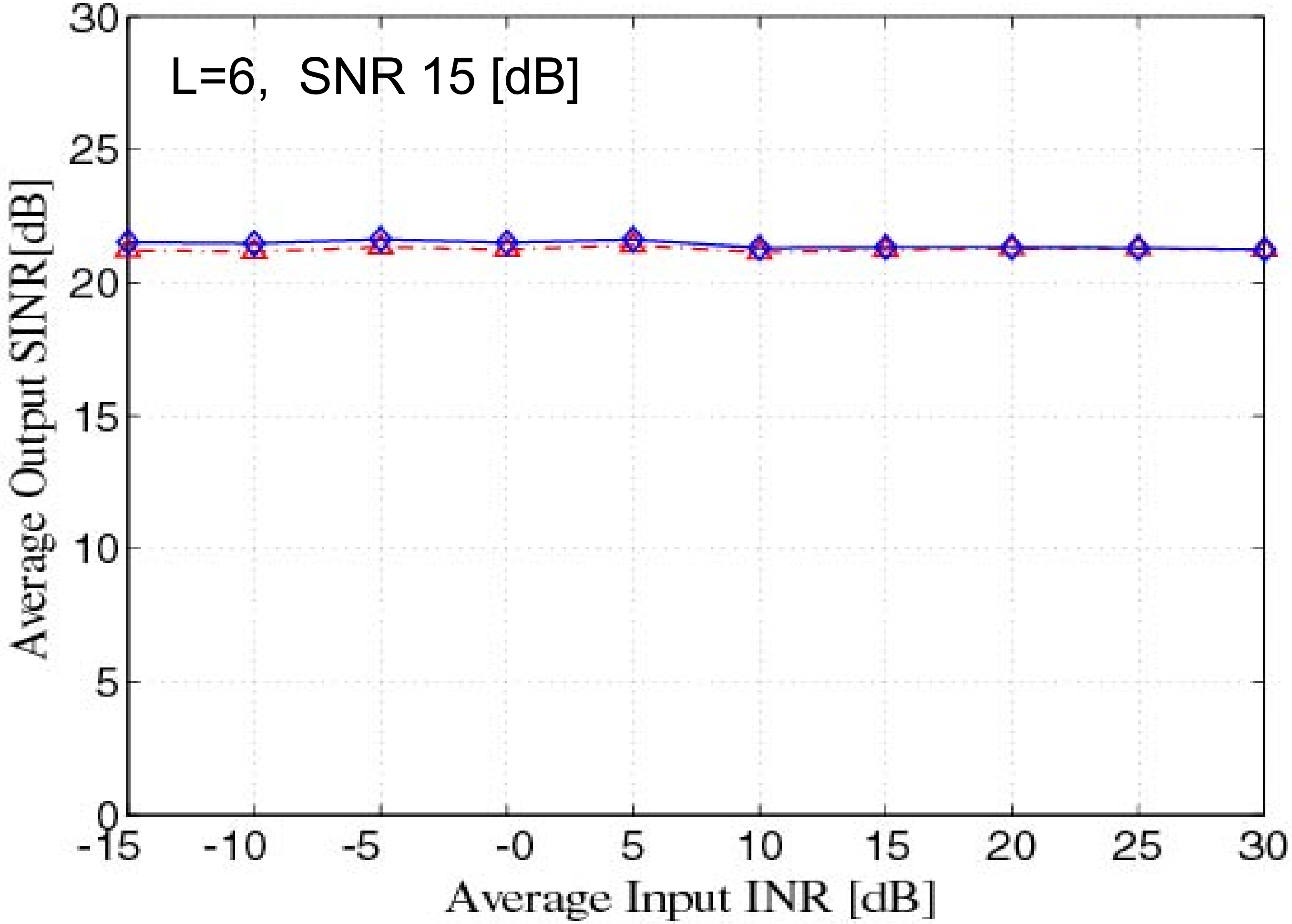
Spatial Corr. Coeff.

$$\rho = \frac{\mathbf{v}_1^H \mathbf{v}_2}{\|\mathbf{v}_1\| \|\mathbf{v}_2\|}$$

For ZF

$$\text{Max. SINR}_{\text{zf}} = \text{Input SNR}\left(1 - |\rho|^2\right)$$

Max. SINRs (Theoretical Values)



Simulation Conditions (2)

- **DOA and AS Estimates : from MUSIC**
- **DOAs : -10, 10 (deg)**
- **<u>Evaluation for Four Spatial Signature</u>**

(1). True SS (Spatial Signature) $\mathbf{v}$

(2). EAMV Estimates $\mathbf{a}(\hat{\theta}_m + j\Delta\hat{\theta}_m)$

(3). AMV with only DOA Estimates $\mathbf{a}(\hat{\theta}_m)$

(4). AMV with Nominal DOA $\mathbf{a}(\theta_m)$

(0) Ideal Case that Covariance & Spatial Signature are perfectly known

(3). AMV with only DOA Estimates

- **An Adaptive Array for Mobile Communication Systems**
  → S. Anderson et.al., (IEEE Trans. VT, 1991)
- **Modified Array Manifold for Signal Waveform Estimation**
  → D.Asztely & B.Ottersten (Proc. 30th Asilomar Conf., 1996)
- **Signal Waveform Estimation in AS Environment**
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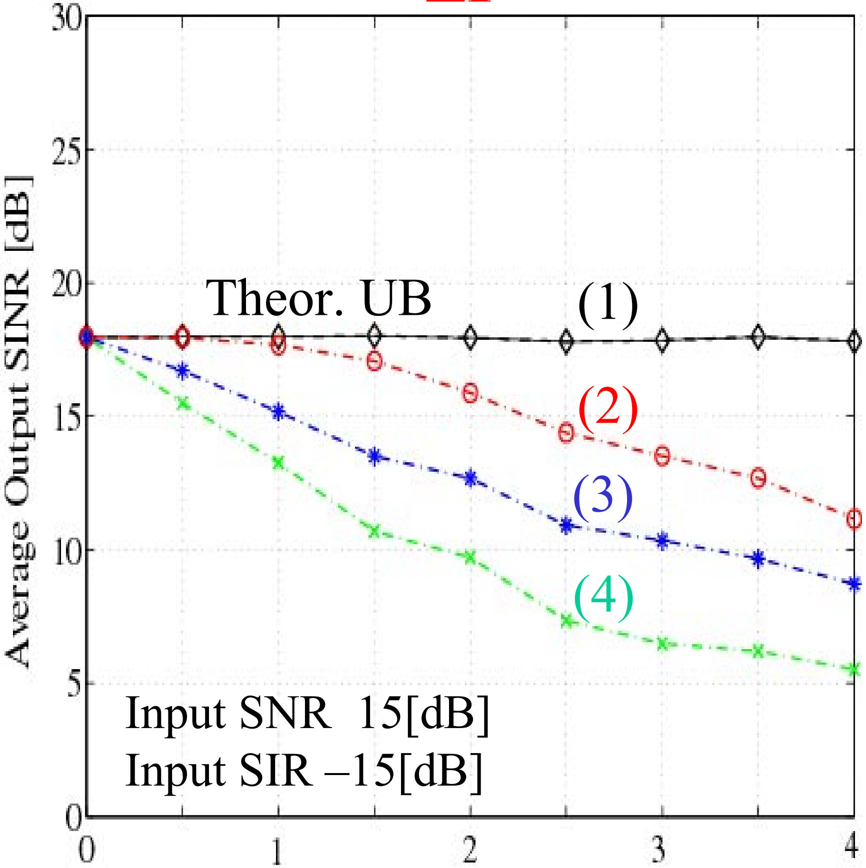
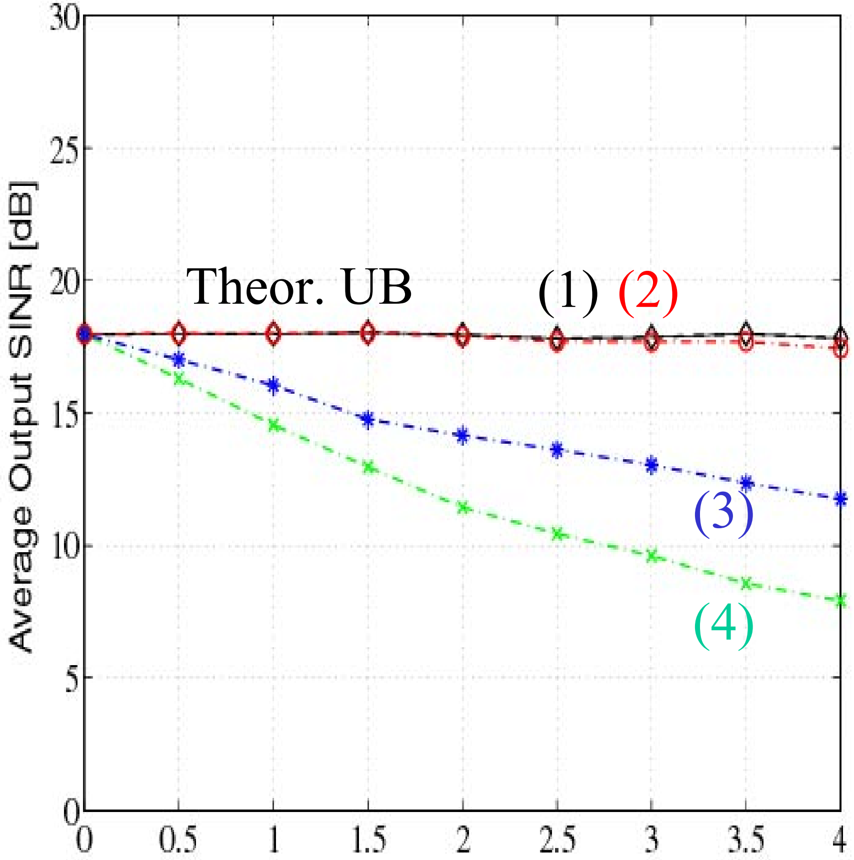
Performance Evaluation in AS Environment (1)
– Infinite Samples, L=3

ZF



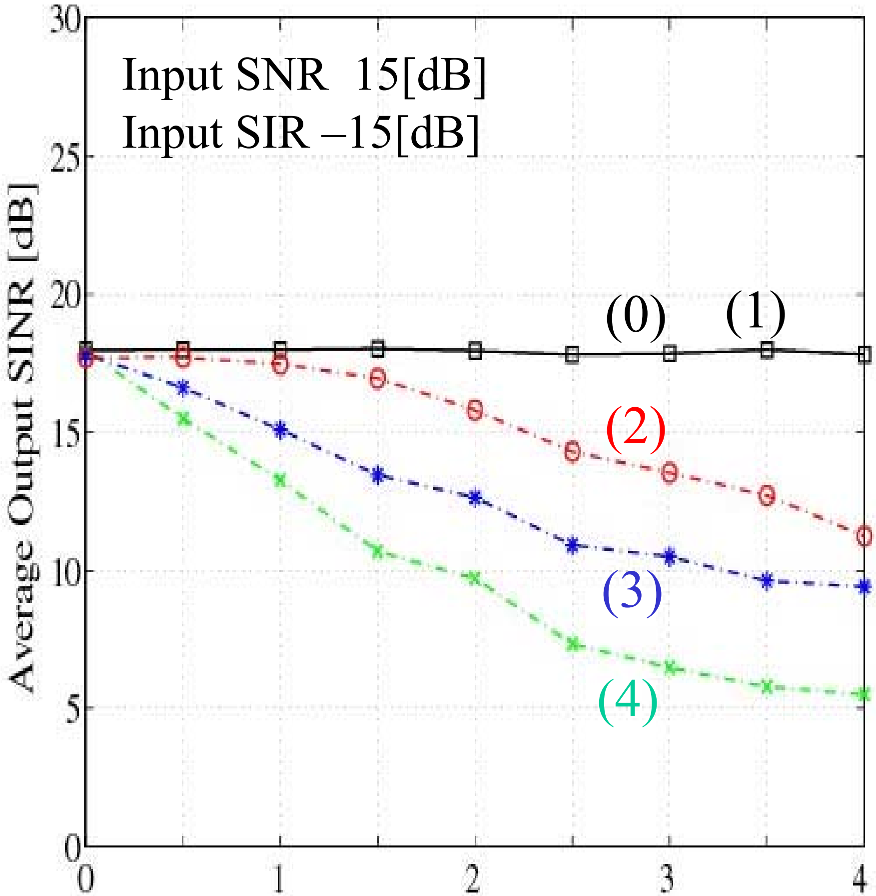
DCMP



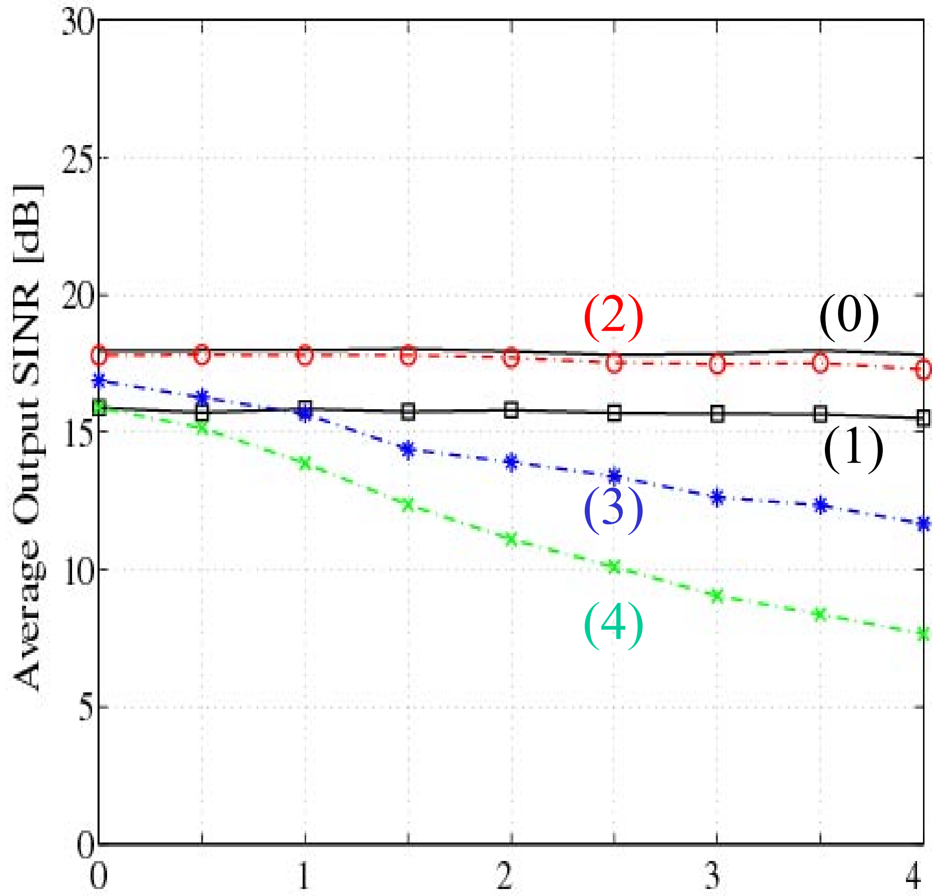
Performance in AS Environment (2)

127 Samples, L=3

ZF

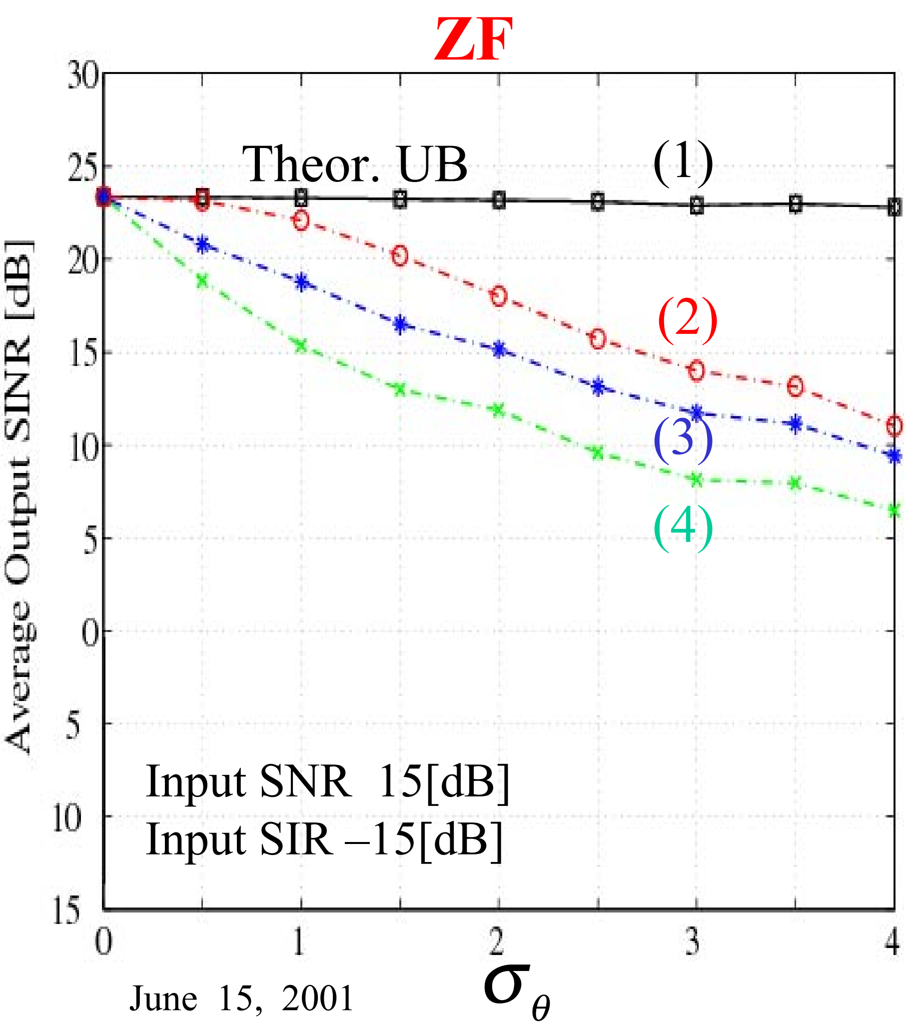


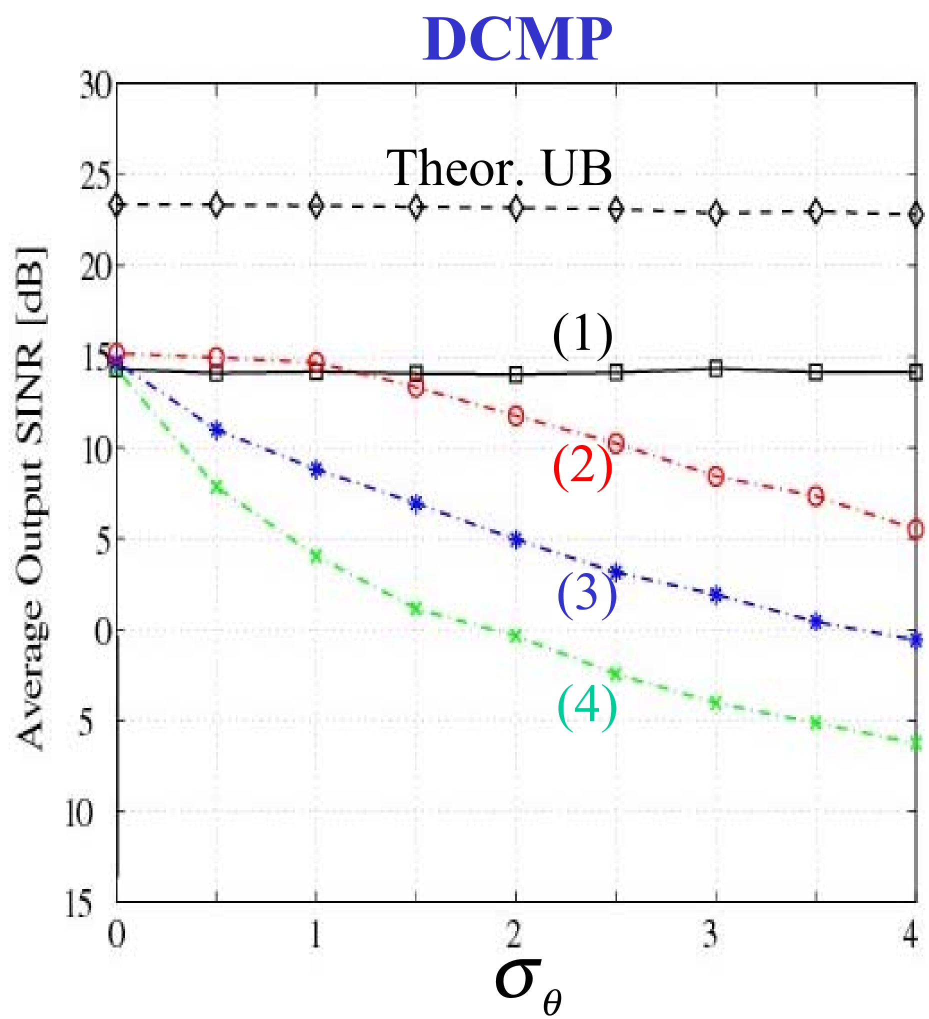
DCMP



Performance in AS Environment (3)

127 Samples, L=6





Sensitivity Evaluation of Algorithms

Definition of Corr. Coeff. between Weight Vectors

$$\rho_{\mathbf{w}} = \frac{\left\| \mathbf{w}_{(0)}^{H} \mathbf{w}_{(i)} \right\|}{\left\| \mathbf{w}_{(0)} \right\| \left\| \mathbf{w}_{(i)} \right\|}$$

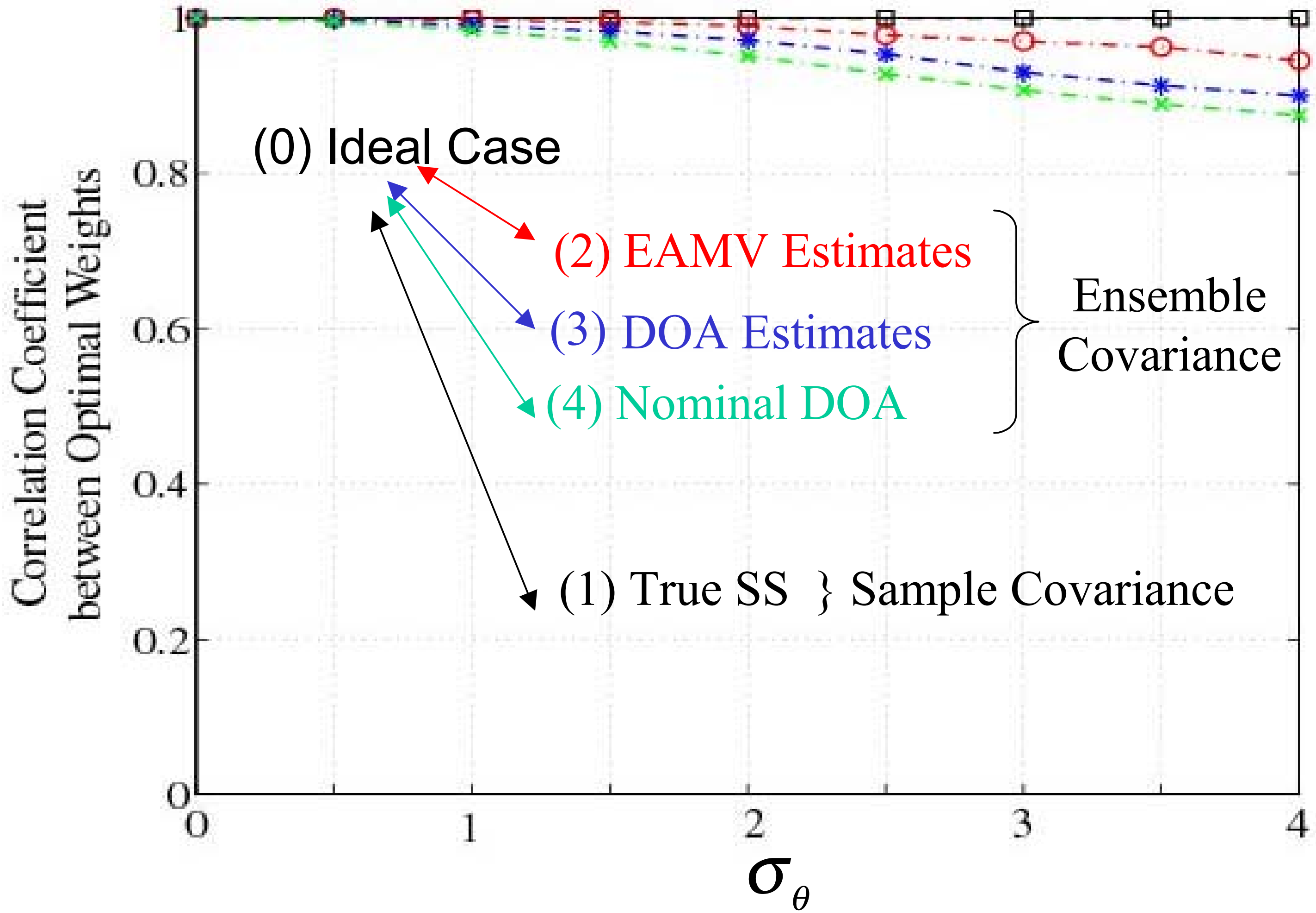
(i)=(1), (2), (3), (4)

(0) Ideal Case

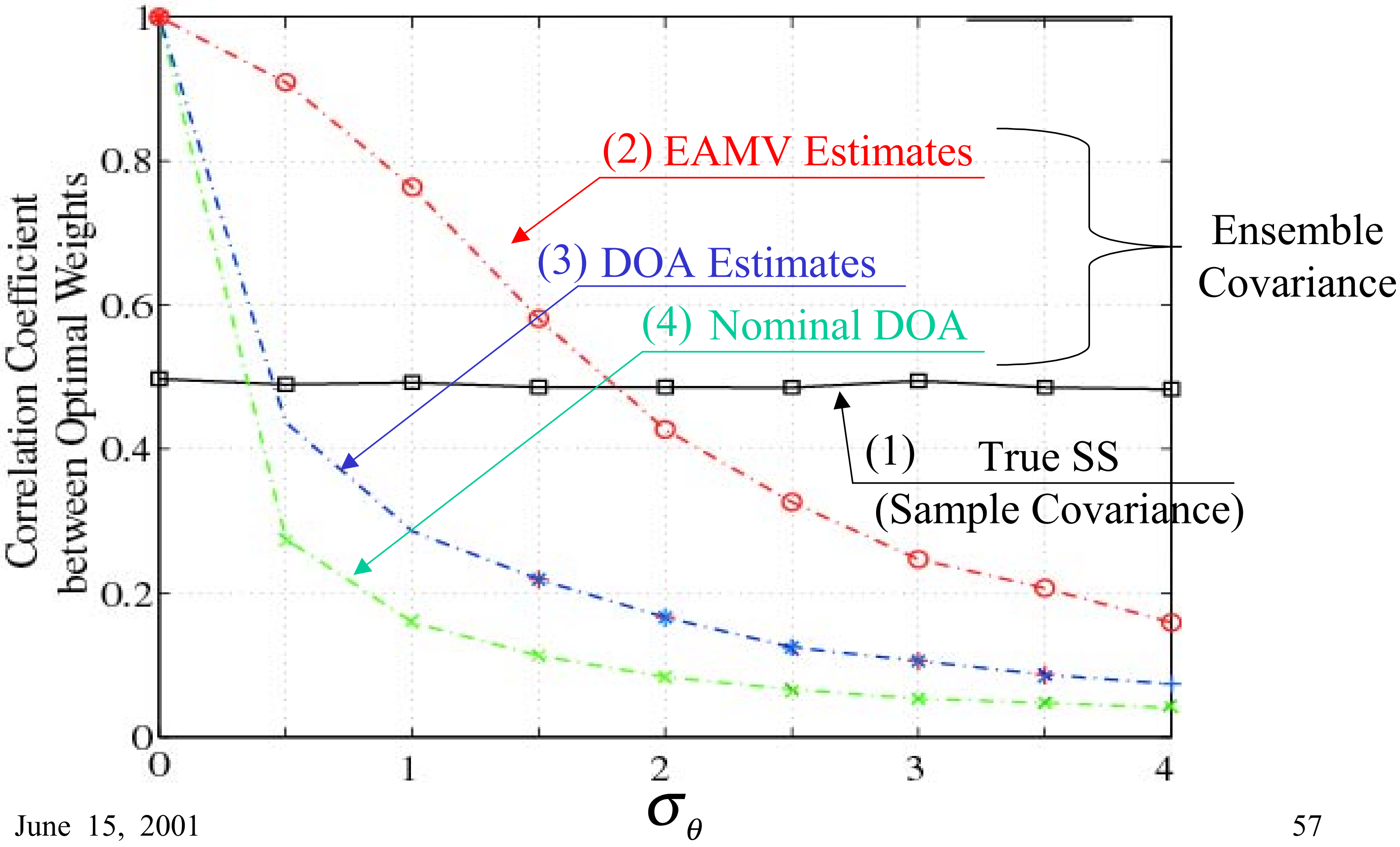
(2) EAMV Estimates
(3) DOA Estimates
(4) Nominal DOA
} Ensemble Covariance

(1) True SS } Sample Covariance

Sensitivity of ZF in AS Environment (1)



Sensitivity of DCMP in AS Environment (2)

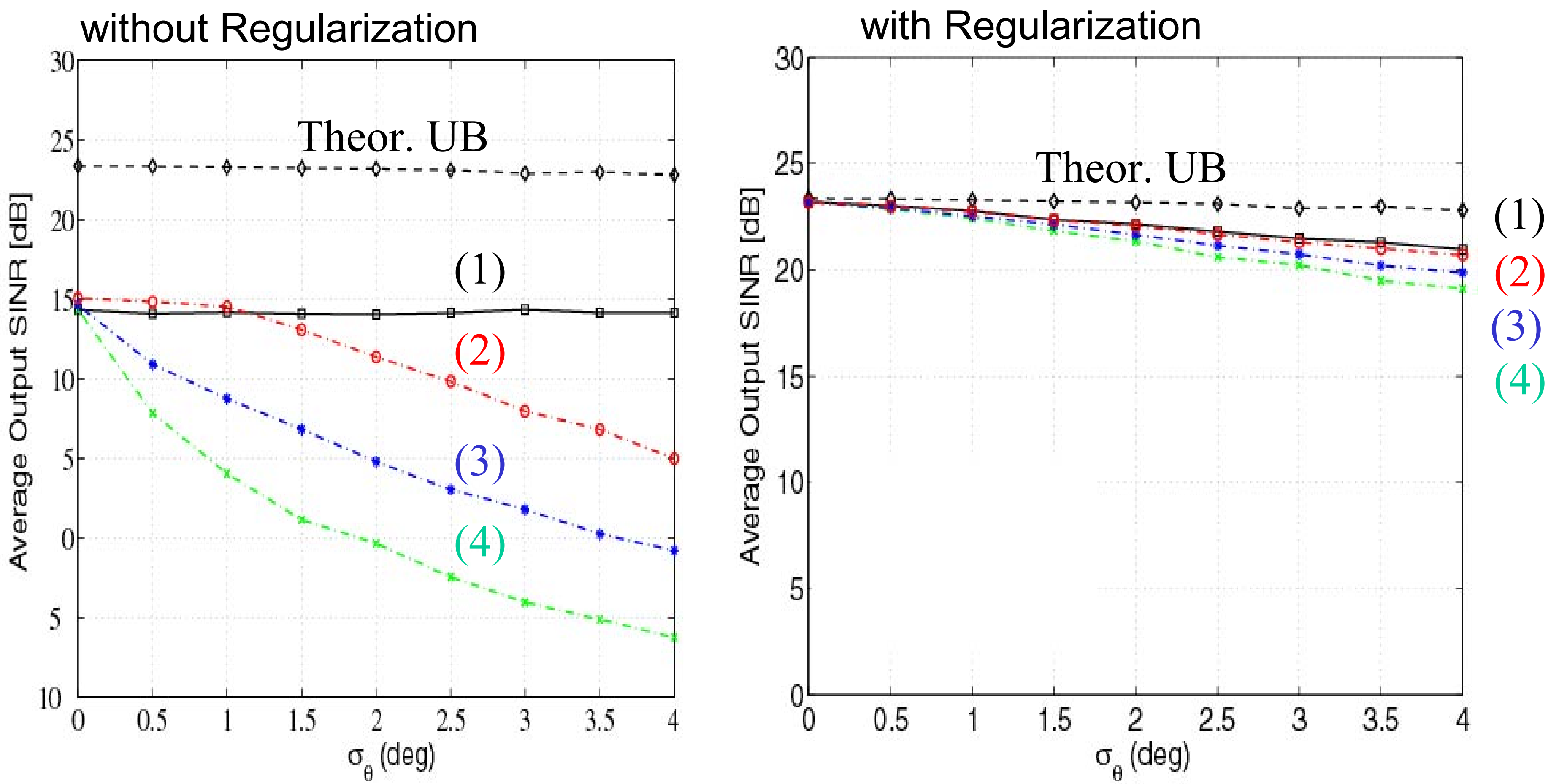


Regularization of Covariance Matrix : DCMP (Diagonal Loading)

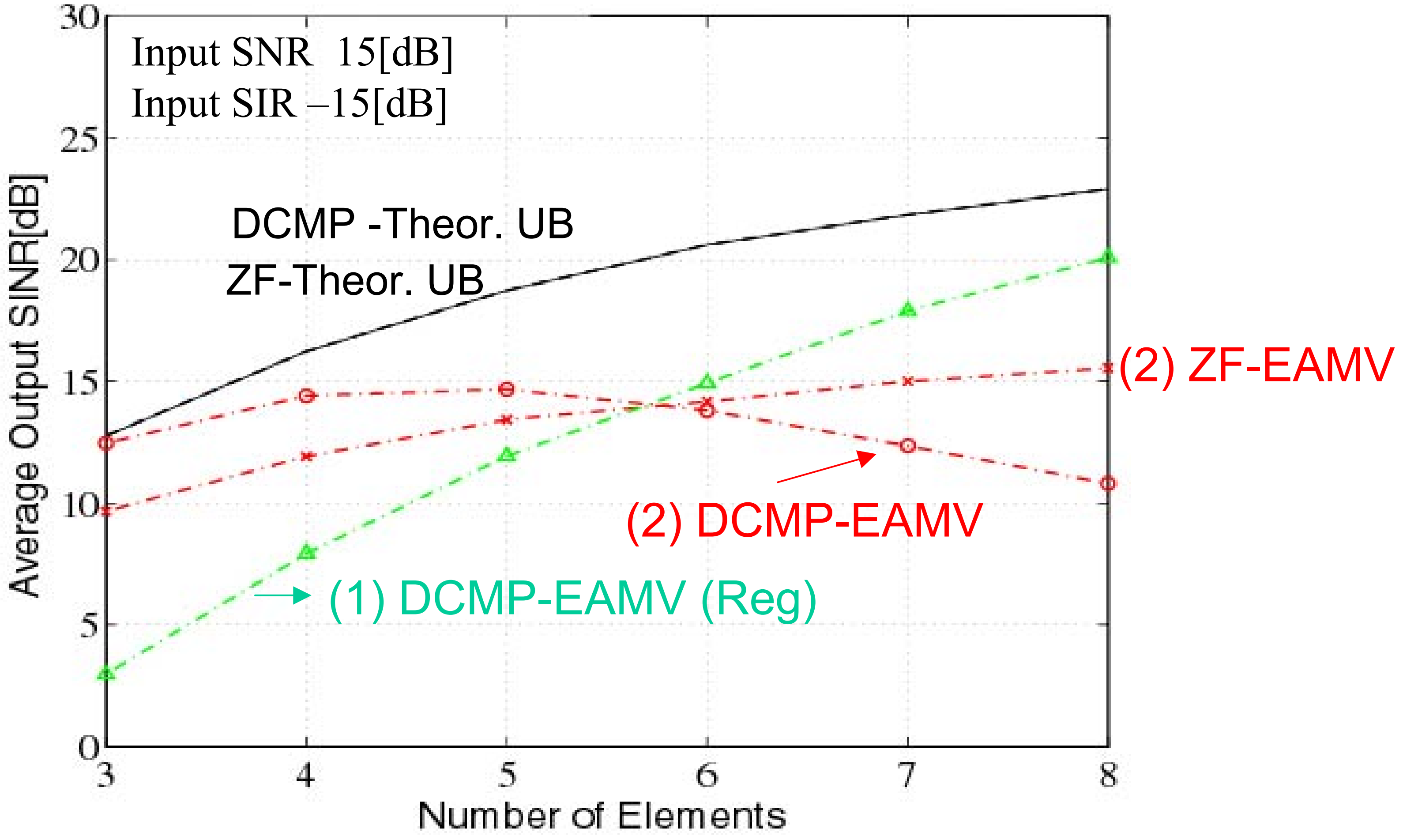
$$\overline{\mathbf{R}} = \hat{\mathbf{R}} + \alpha_n \mathbf{I}$$

Regularization of Covariance Matrix : DCMP

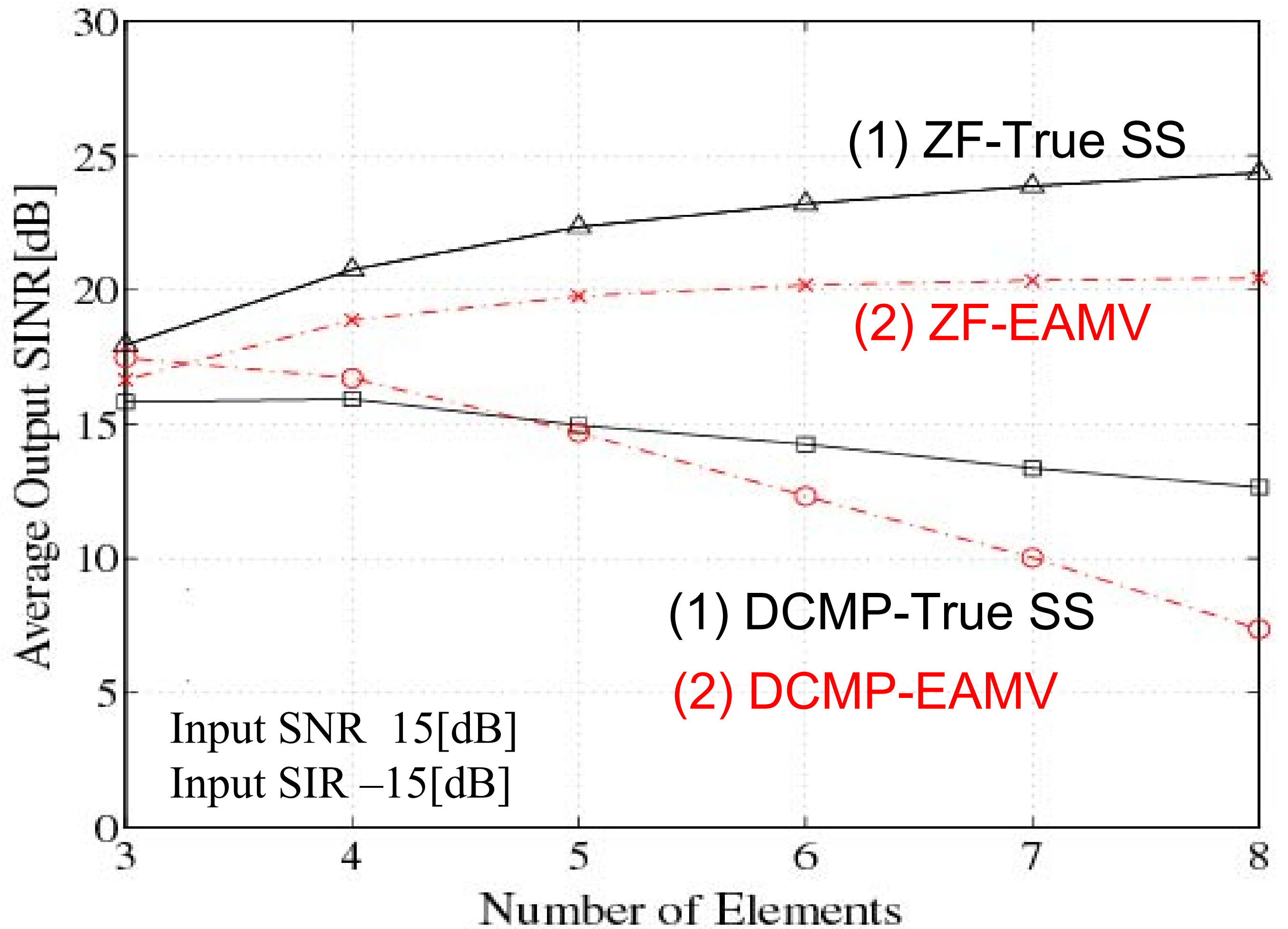
127 Samples, L=6



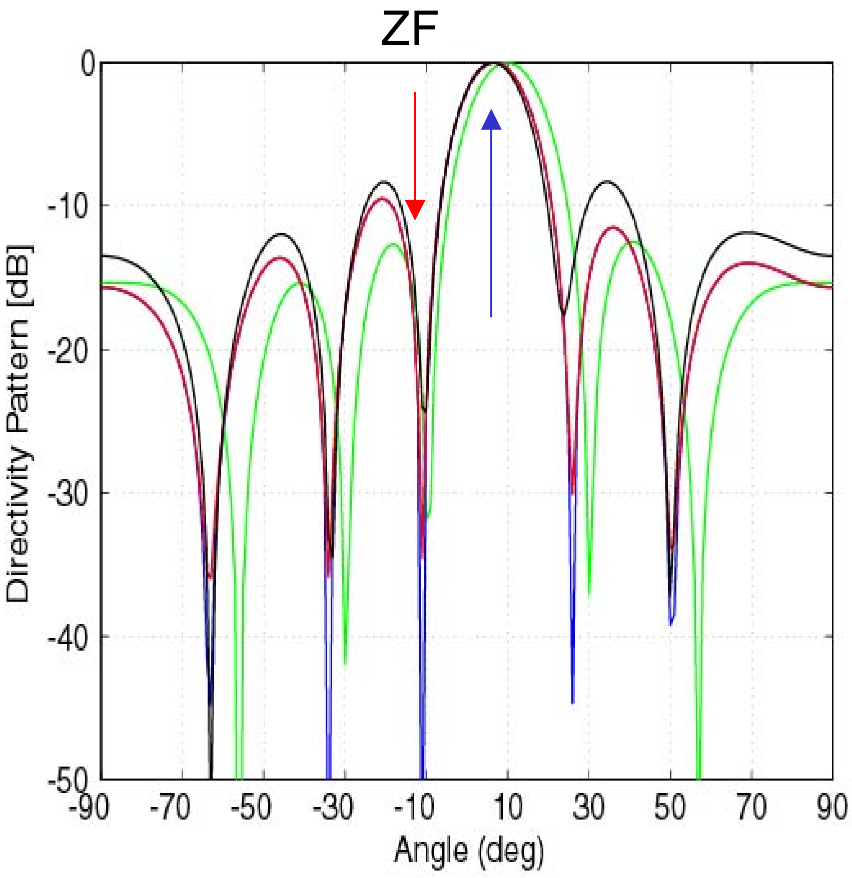
Effect of Number of Antenna Elements

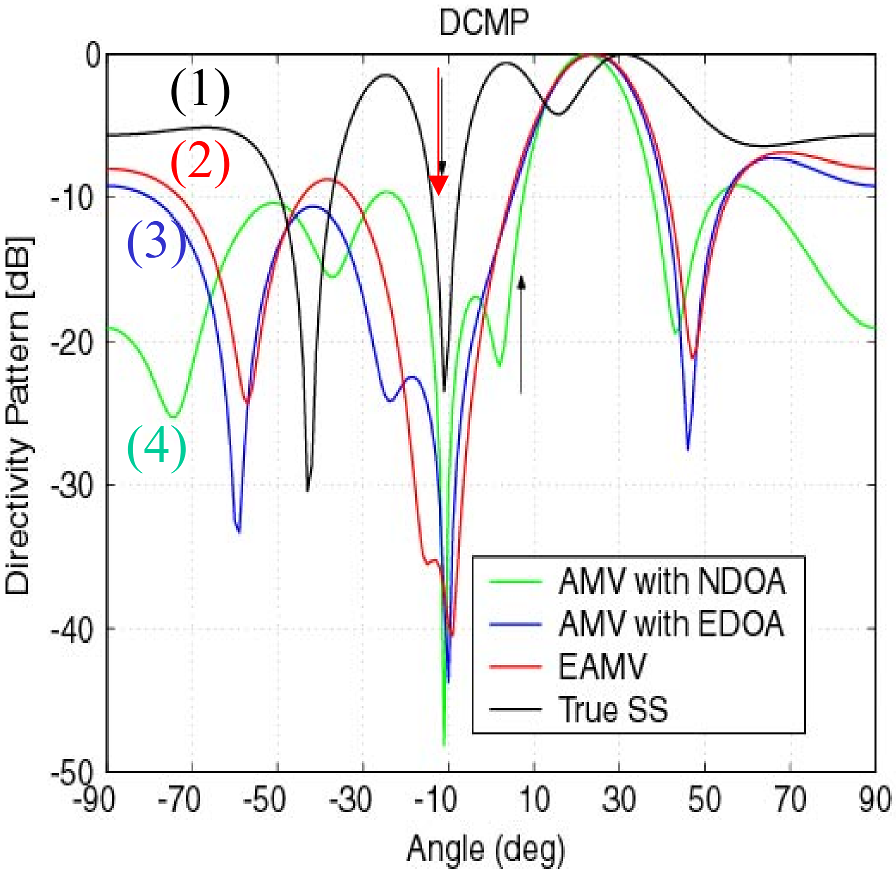


Effect of Number of Antenna Elements



Beam Pattern of Array Antenna

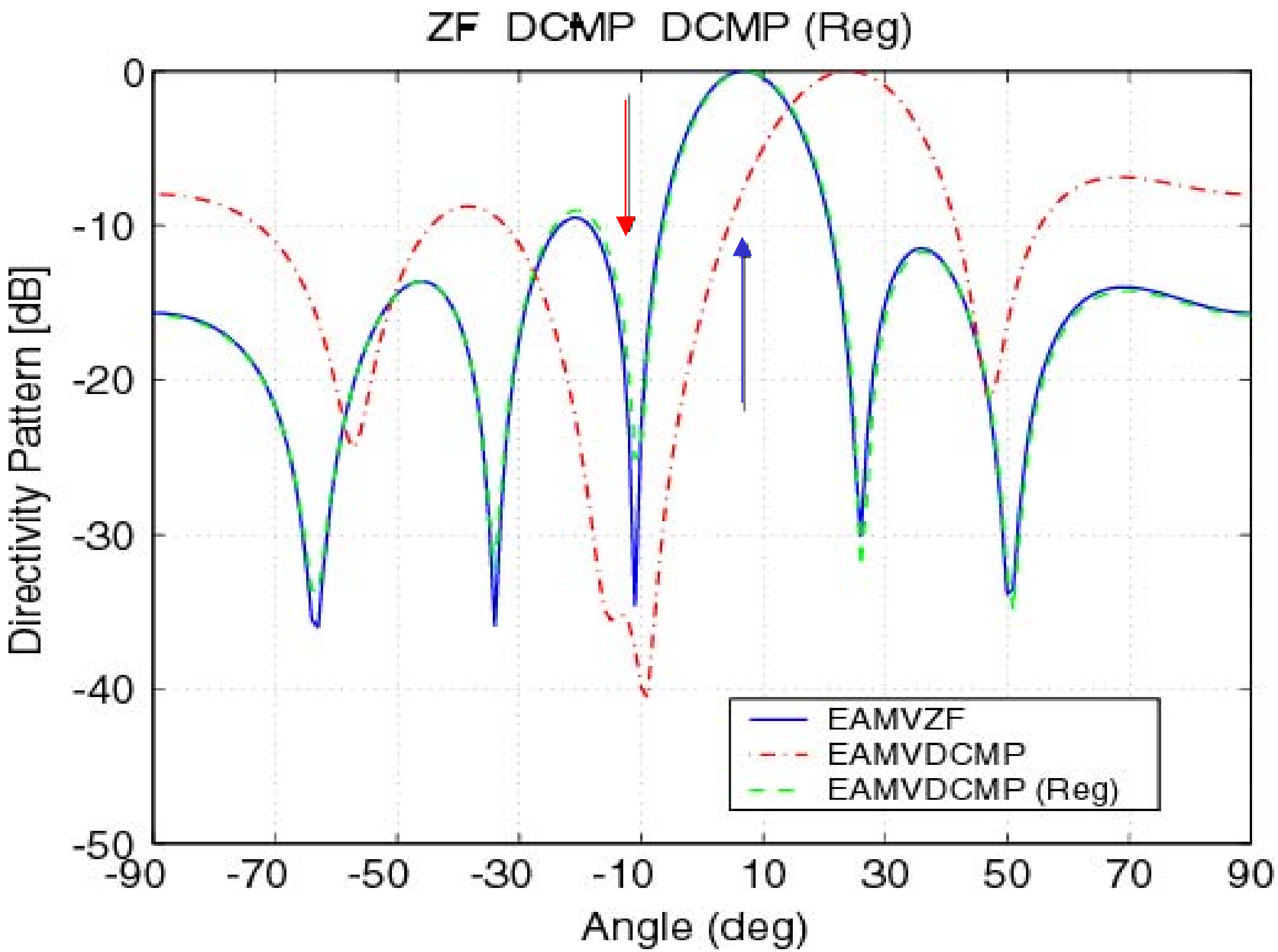




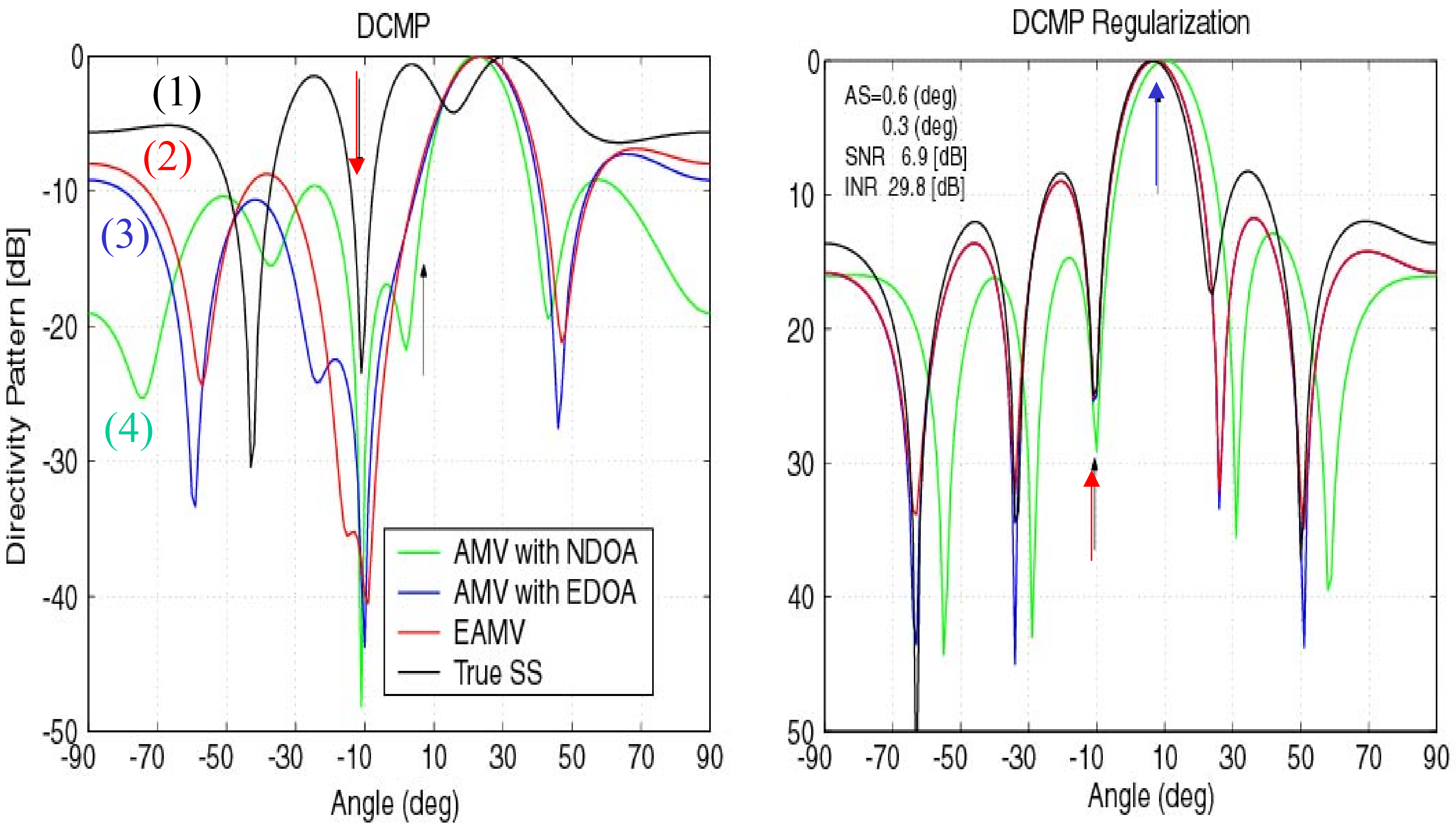
Input SINR : -22.9[dB]

Input SNR : 6.9, Input INR : 29.8

Beam Pattern of Array Antenna



Variation of Beam Pattern by Regularization



Input SINR : -22.9[dB]

Input SNR : 6.9, Input INR : 29.8

Input SINR : -22.9, Input SNR : 6.9, Input INR : 29.8

Output SINR

ZF (NDOA) : 1.2, ZF(EDOA) : 1.3,

***ZF (EAMV) : 3.3*, ZF (True SS) : 14.6**

DCMP(NDOA) : -10.9, DCMP (EDOA) : -2.0

DCMP (EAMV) : -1.03, DCMP (True SS) : 10.7

DCMP Reg

(NDOA) : 13.2, (EDOA) : 13.4

***(EAMV) : 13.6,* (True SS) : 13.8**

Conclusions

- It is expected to reduce considerably model errors in algorithms based on the plane wave data model.
- The applicability to other superresolution algorithms is also expected..
- Proximity Evaluation from Spatial Signature Estimates
- It follows that the proposed method can obtain more accurate SS estimates than the case using only the DOA.
- Proposal of Optimal Signal Combining Techniques using EAMV Estimates.

  → Reduction of the effect due to weight perturbations

  → Enhanced SINR Performance.