Noise and Interference

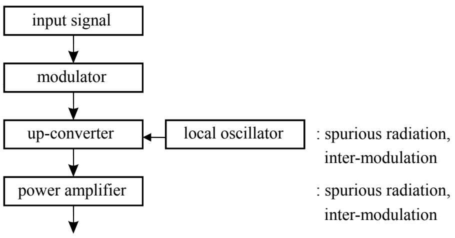
[Contents]

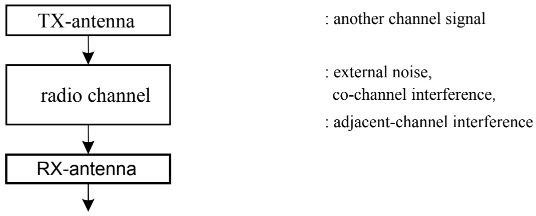
- Noise
- Interference
- Array Signal Processing for Interference Canceling
- RF Front-end Signal Processing
- Spatial Fading Emulator

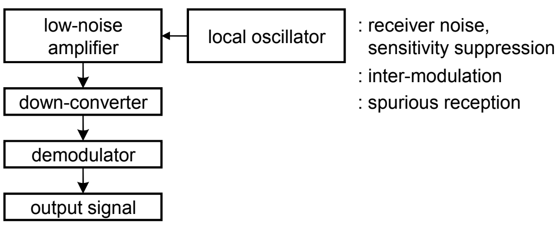
- Noise and Interference in Wireless Communication Systems

Noise and Interference determine a quality of communication system and an achievable bit rate.

Schematic diagram of wireless communication systems







Noise and Interference in TX

- Transmitter noise
  (Continuous spectrum noise below 60dB)
  ← Spectrum Impurity (Phase Noise) in Local Oscillator
  High S / N Oscillators are required.
- Spurious radiation (Line spectrum noise)
  ← Non-linearity in power-amplifiers and/or frequency converter
  Sharp Band pass Filters are required.
- Inter-modulation in TX
  ← Strong another signal entering through TX antenna
  High-Q Filters and Isolators are required.

Noise and Interference in Radio Wave Channel

- External noise
  ← Lightning, Solar noise, Thermal noise, Artificial noise, …, impulsive and continuous spectrum noise
- Co-channel interference
  → Sensitivity suppression
- Adjacent-channel interference
  → Side-lobe spectrum of adjacent channel signal

Noise and Interference in RX

- Receiver noise

Thermal white noise power $= kTB$

(k : Boltzmann constant $= 1.38 \times 10^{-23}$ [J/K]

T : Temperature B : Bandwidth)

$@ T = 300K \rightarrow N_0 = 1 - 174[\text{dBm/Hz}]$

Noise Figure $: (F = SN_{\text{in}} / SN_{\text{out}})$

Noise Measure $: (M = (F-1)/(1-1/G))$

- Sensitivity suppression
  Low gain before IF-stage, Sharp Band-pass Filter in RF-stage and IF-stage, and Low noise in LO are required.
- Spurious reception
  Image frequency
- Inter-modulation in RX
  3rd order and 5th order IM are dominant.

Noise

- Thermal noise
  The equivalent noise power spectrum density in W/Hz generated in any ideal coherent amplifier of electromagnetic wave

$$N_0 = hf \Big/ \left[e^{hf/kT} - 1 \right]$$

When frequency f is small enough $(< 10^{10}\,\text{Hz})$

$$N_0 \cong hf / (1 + hf/kT - 1) = kT$$

where h : Planck constant $\approx 6.6252 \times 10^{-34} [J \cdot s]$

k : Boltzman constant

- Shot noise: Poisson Process

$$N_0 \propto I_0 \text{ (DC current)}$$

- Switching noise of Capacitance

kT/C

Poisson Distribution

$$P_n = e^{-\lambda} \frac{\lambda^n}{n!} \quad (n = 0, 1, 2, \cdots)$$

$$\bar{n} = \sum_{n=0}^{\infty} n P_n = \lambda$$

$$\overline{(n - \bar{n})^2} = \lambda$$

∴Shot Noise Power ∝ DC Currant

Ex.) A number of electrons passing through junction
A number of access events to network

Equivalent Resistance of Switch Capacitance

$$\text{Req} = \frac{1}{c f_s}$$

f_s : switching frequency

Equivalent Noise Temperature of Noise Sources

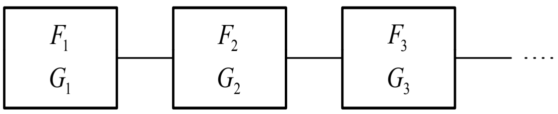
$$T_{\text{equiv}} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots$$

Since the noise temperature and noise figure F_e referenced to Temperature T_0 are related by

$$F_e = \frac{T_e}{T_0} + 1$$

Cascade Connection of LNA

with Noise Figure F and Gain G



Noise Figure and Internal Noise

$$F = \frac{(S/N)_i}{(S/N)_o} = \frac{N_{\text{int}} + G N_i}{G}$$

$$S_o = G S_i$$

$$N_o = N_{\text{int}} + G N_i$$

$$\therefore N_{\text{int}} = (F-1) G N_i$$

N_i : Reference Noise Level

The corresponding overall noise figure is then given by the Friis noise formula,

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$$

$$G_{\text{total}} = G_1 \, G_2 \, G_3 \cdots$$

F_1 should be minimum.

2-Stage Case → Noise Measure

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1} \qquad F_{12} \gtrless F_{21}$$

$$\updownarrow$$

$$F_{21} = F_2 + \frac{F_1 - 1}{G_2} \qquad M_1 = \frac{F_1 - 1}{1 - \frac{1}{G_1}} \gtrless \frac{F_2 - 1}{1 - \frac{1}{G_2}} = M_2$$

Power-limited System & Interference-limited System

- Propagation-limited systems
  Thermal and man-made noise play the most important roles in large-scale systems.
  (i.e. **satellite systems**)
- Interference-limited systems
  Unwanted interfering signals from nearby cells in which the same frequency is reused, play the most critical role in **cellar and micro cellar systems**.

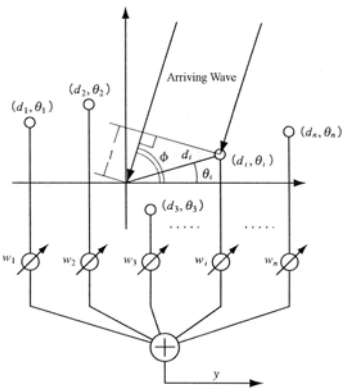
- Propagation delay
  Severe inter-symbol interference is possible if the differential delay between two signals is too great and the received power levels are nearly equal.
- Simulcast transmitting frequency offsets
  In digital paging applications, frequencies are often offset from each other to mitigate the effects of standing wave interference patterns, which could otherwise cause localized areas of poor coverage.
  The offset frequency increments for digital messaging systems having symbol rates up to 3,200 symbols per second are 100-450Hz. The maximum offset of the carrier frequency is chosen to never exceed ± 600Hz.

Interference in Mobile Communication Systems

- Personal Radio
  (Simplex: Signal channel, non-simultaneous transmission)
  Maximum Interference Effect
- MCA
  (Dusimplex: Two channels, non-simultaneous transmission)
  Medium Interference Effect
- Automotive Telephone
  (Duplex: Two channels, simultaneous transmission)
  Low Interference Effect

Interference Cancel by Array Signal Processing

Spatial Signal Processing
- SINR Criteria
- MSE Criteria



$\mathbf{x}(t) = \mathbf{a}_s s(t) + \mathbf{a}_i i(t) + \mathbf{n}(t)$: received signal model

$\mathbf{a}_s = \mathbf{a}(\theta_s)$: spatial signature for desired signal $s(t)$
$\mathbf{a}_i = \mathbf{a}(\theta_i)$: spatial signature for undesired signal $i(t)$
$\mathbf{n}(t)$: additive noise

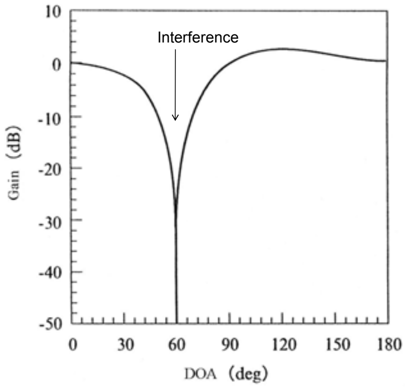
- Linear Signal Processing

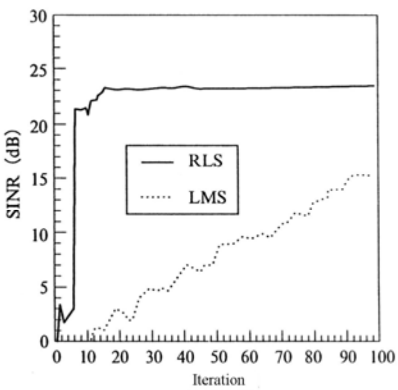
$y(t) = \mathbf{w}^{+}\mathbf{x}(t)$: output signal

$\mathbf{w}$: weight vector for linear processing

$$y(t) = y_s(t) + y_i(t) + y_n(t)$$
$$= \mathbf{w}^{+}\mathbf{a}_s s(t) + \mathbf{w}^{+}\mathbf{a}_i i(t) + \mathbf{w}^{+}\mathbf{n}(t)$$

$$\text{SINR} = \frac{E\left[\left|y_s(t)\right|^2\right]}{E\left[\left|y_i(t)\right|^2\right] + E\left[\left|y_n(t)\right|^2\right]}$$





$\mathbf{a}(\theta)$: array mode vector with DOA, θ

e.g. ULA (Uniform Linear Array)

$\mathbf{a}(\theta) = \left(1, Z, Z^2, \cdots\right)^t$

$Z = e^{i\frac{2\pi}{\lambda}\Delta\sin\theta}$

Δ : inter element spacing

λ : wave length $(= c/f)$

- Interference Canceling principle → ZF (Zero Forcing) Optimum Weight Vector

$$\mathbf{w} = c\left[\mathbf{e}_s - \theta\mathbf{e}_i\right]$$
$$\mathbf{w}^{+}\mathbf{e}_i = \mathbf{e}_s^{+} \cdot \mathbf{e}_i - \theta^* = \theta^* - \theta^* = 0$$
$$\therefore \quad \mathbf{w} \perp \mathbf{e}_i$$

c : some constant

where

$\mathbf{e}_s = \mathbf{a}_s / \left|\mathbf{a}_s\right|,\ \mathbf{e}_i = \mathbf{a}_i / \left|\mathbf{a}_i\right|$

$\theta = \mathbf{a}_i^{+} \cdot \mathbf{a}_s / \left|\mathbf{a}_i\right|\left|\mathbf{a}_s\right| = \mathbf{e}_i^{+}\mathbf{e}_s$: spatial correlation $\left(0 \le |\theta| \le 1\right)$

$$y_s(t) = \mathbf{w}^{+} \cdot \mathbf{a}_s s(t) = \left(\mathbf{e}_s^{+} - \theta^*\mathbf{e}_i^{+}\right)\mathbf{a}_s s(t)$$
$$= \left|\mathbf{a}_s\right|\left(1 - |\theta|^2\right)\mathbf{a}_s s(t)$$
$$S = E\left[\left|y_s(t)\right|^2\right] = \left|\mathbf{a}_s\right|^2\left(1 - |\theta|^2\right)^2 E\left[\left|s(t)\right|^2\right]$$
$$y_i(t) = \mathbf{w}^{+} \cdot \mathbf{a}_i i(t) = 0$$
$$I = E\left[\left|y_i(t)\right|^2\right] = 0$$

$$y_n(t) = \mathbf{w}^+\mathbf{n}(t)$$
$$= \left(\mathbf{e}_s^{\ +} - \theta^*\mathbf{e}_i^{\ +}\right)\cdot\mathbf{n}(t)$$

$$N = E\left[\left|y_n(t)\right|^2\right] = \left(\mathbf{e}_s^{\ +} - \theta^*\mathbf{e}_i^{\ +}\right)E\left[\mathbf{n}(t)\mathbf{n}(t)^+\right]\left(\mathbf{e}_s - \theta\,\mathbf{e}_i\right)$$
$$= \left(\mathbf{e}_s^{\ +} - \theta^*\mathbf{e}_i^{\ +}\right)\sigma_n^{\ 2} I\left(\mathbf{e}_s - \theta\,\mathbf{e}_i\right)$$
$$= \sigma_n^{\ 2}\left(1 - \theta^*\theta - \theta^*\theta + \theta^*\theta\right)$$
$$= \sigma_n^{\ 2}\left(1 - |\theta|^2\right)$$

$$\therefore \quad \Gamma = S/(I+N) = \frac{P_s|\mathbf{a}_s|^2}{\sigma_n^{\ 2}}\left[1 - |\theta|^2\right]$$
$P_s = E\left[|s(t)|^2\right]$: average signal power

$\sigma_n^{\ 2} I = E\left[\mathbf{n}(t)\mathbf{n}(t)^+\right]$: average noise power

- Maximizing SINR principle →
  DCMP (Directional Constraint Minimization of Power)

Directional Constraint $\mathbf{w}^+\mathbf{a}_s$ = constant

$$\mathbf{w} = c\left[\mathbf{e}_s - \frac{\theta}{1 + \frac{\sigma_n^{\ 2}}{P_i|\mathbf{a}_i|^2}}\mathbf{e}_i\right]$$

If $\sigma_n^{\ 2} << P_i(\mathbf{a}_i)^2$, DCMP → ZF

$$\text{SINR} : \Gamma = \frac{P_s|\mathbf{a}_s|^2}{\sigma_n^{\ 2}}\left[1 - \frac{|\theta|^2}{1 + \frac{\sigma_n^{\ 2}}{P_i|\mathbf{a}_i|^2}}\right]$$

$P_i = E\left[|i(t)|^2\right]$: average interference power

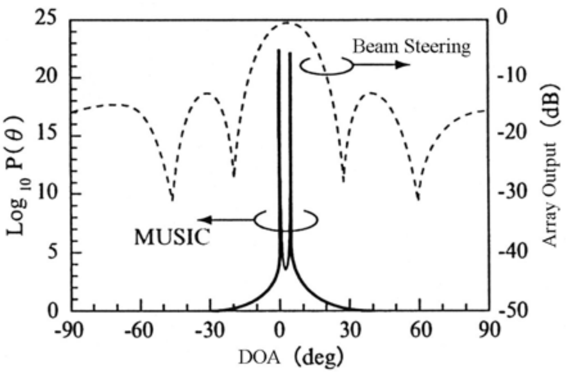
When $\mathbf{a}_s \perp \mathbf{a}_i$ (spatially orthogonal)

$\mathbf{w}_{\text{ZF}}, \mathbf{w}_{\text{DCMP}} \to \mathbf{e}_s$ Beam Forming Principle,
MRC (Maximum Ratio Combining)

$\Gamma \to \frac{P_s|\mathbf{a}_s|^2}{\sigma_n^{\ 2}}$: SNR

- Direction Finding Technique ⇒
  Estimate of SS, $\mathbf{a}(\theta)$
- MUSIC (Multiple Signal Classification)
- ESPRIT
  - SUB-SPACE METHOD
  - A PRIORI KNOWLEDGE OF SIGNAL IS NOT REQUIRED

→ Blind Estimation DOA θ: unknown parameter



Super resolution techniques

- Model-based parameter estimation
- Fine resolution than Sampling Theorem
- MUSIC, ESPRIT : Powerful DOA techniques especially in radar application.

Subspace Method

$$\mathbf{x}(t) = [\mathbf{a}(\theta_1), \cdots, \mathbf{a}(\theta_n)] \begin{bmatrix} S_1(t) \\ \vdots \\ S_n(t) \end{bmatrix} + \mathbf{n}(t)$$

Covariance Matrix

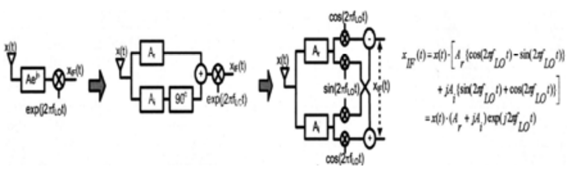
$$R_{XX} = A\,S\,A^{+} + \sigma^2 I$$
$$A = [\mathbf{a}(\theta_1), \cdots, \mathbf{a}(\theta_n)]$$

Noise Sub-space E_N
Signal Sub-space E_S

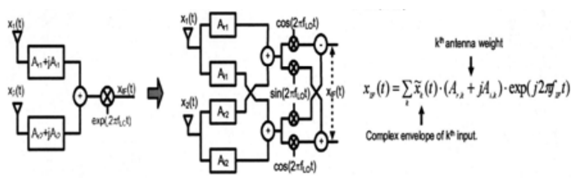
$$\underset{\theta}{\text{Minum}} \frac{|a(\theta)|^2}{a(\theta) E_N a(\theta)} = \theta_i \ (\text{unknown DOA})$$

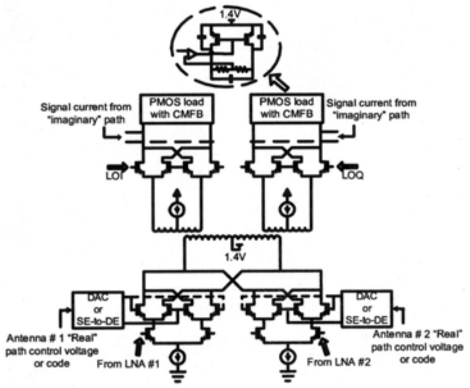
RF FRONT-END FOR SPATIAL PROCESSING

FREQUENCY CONVERSION FROM RF TO IF

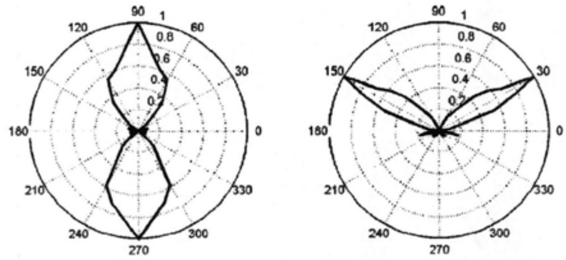


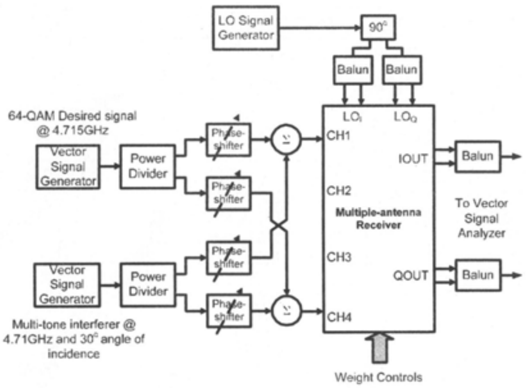
ARRAY PROCESSING by Gilbert Cell and Transformer



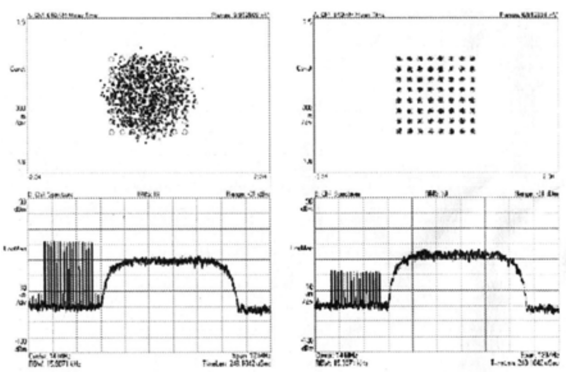


DESIRED UNDESIRED





MEASURED RESULTS BEFORE AND AFTER SIGNAL PROCESSING for Interference Canceling



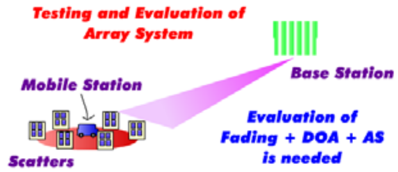
Spatial Fading Emulator

- The field testing of radio transmission techniques is often time-consuming.
- The evaluation of cellular base station antenna arrays in an anechoic chamber is needed.
- With the use of an ESPAR antenna, the superposition of scattered waves can be made easily.

Agenda

- Background
- Spatial Fading Emulator
- Deterministic Estimation
- Complex Angle
- Experimental Results
- Conclusion & Future works

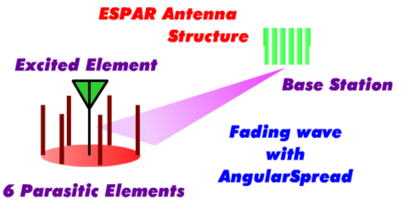
Propagation of mobile communication



Fading wave caused by the superposition of scattered waves

→With the use of an ESPAR antenna, fading waves can be easily made.

Structure of Emulator



$$\begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_7 \end{bmatrix} = \boldsymbol{Y}[\boldsymbol{Y} + \boldsymbol{Y}_L]^{-1} \begin{bmatrix} I_{CW} \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

The input impedance of surrounding parasitic elements will be controlled to generate the fading properties.

$\boldsymbol{Y}_L = \mathrm{diag}[1/z_s, 1/jx_2, \cdots, 1/jx_7]$: variable

Y : Array Antenna Admittance Matrix : fixed

Control of bias voltages to varactors

⇩

Control of Y_L

⇩

Control of $[i_1, i_2, \ldots, i_r]$

⇩

Control of multiple waves

Approximated Equation of Received Signal

Received signal model ($\mathbf{a}(\theta_i)$: Array mode vector) θi:DOA

$$\boldsymbol{r}(t) = \sum_{i=1}^{N} \beta_i \boldsymbol{a}(\theta_i)\boldsymbol{s}(t) + \boldsymbol{n}(t)$$

→ Number of estimate parameters is $2 \times N$ (β_i, θ_i)

[approximated by Taylor Series Expansion]

$$\boldsymbol{r}(t) \simeq \gamma \boldsymbol{a}(\tilde{\theta} + \xi)\boldsymbol{s}(t) + \boldsymbol{n}(t)$$

γ and θ, for the case where f is minimum, become the Maximum likelihood values.

$$\gamma = \sum \beta_i, \quad \xi = \sum \beta_i \Delta\theta_i / \gamma, \quad \theta_i = \hat{\theta} + \Delta\theta_i$$

Approximated Equation of Received Signal

$$\begin{aligned} \sum_{i=1}^{N} \beta_i \boldsymbol{a}(\tilde{\theta} + \Delta\theta_i) &\simeq \sum_{i=1}^{N} \beta_i [\boldsymbol{a}(\tilde{\theta}) + \Delta\theta_i \frac{\partial \boldsymbol{a}(\tilde{\theta})}{\partial \theta}] \\ &= (\sum \beta_i)\boldsymbol{a}(\tilde{\theta}) + (\sum \beta_i \Delta\theta_i)\frac{\partial \boldsymbol{a}(\tilde{\theta})}{\partial \theta} \\ &= \gamma \boldsymbol{a}(\tilde{\theta}) + \eta \frac{\partial \boldsymbol{a}(\tilde{\theta})}{\partial \theta} \\ &= \gamma [\boldsymbol{a}(\tilde{\theta}) + \xi \frac{\partial \boldsymbol{a}(\tilde{\theta})}{\partial \theta}] \quad (6) \\ &\simeq \gamma [\boldsymbol{a}(\tilde{\theta} + \xi)] \end{aligned}$$

$$\gamma = \sum_{i=1}^{N} \beta_i, \quad \eta = \sum_{i=1}^{N} \beta_i \Delta\theta_i, \quad \xi = \frac{\eta}{\gamma}$$

$$\boldsymbol{r}(t) \simeq \gamma \boldsymbol{a}(\tilde{\theta} + \xi)\boldsymbol{s}(t) + \boldsymbol{n}(t)$$ [approximate]

θ+ξ is a complex angle, the angular spread is also expressed.

Parameter Estimation

s(t)=1 , because a Network Analyzer is used.

$$f \stackrel{\text{def}}{=} |r_1 - \gamma a_1|^2 + |r_2 - \gamma a_2|^2 + \ldots + |r_M - \gamma a_M|^2$$

→ Estimate γ and θ where f is minimum $\quad (\theta = \theta_1 + j\theta_2)$

1. Least mean square w.r.t. γ

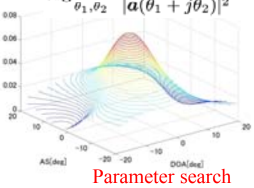
$$\hat{\gamma} = \frac{\boldsymbol{a}^\dagger \boldsymbol{r}}{|\boldsymbol{a}|^2}$$

2. The cost function is

$$f = |\boldsymbol{r} - \hat{\gamma}\boldsymbol{a}(\theta)|^2 = |\boldsymbol{r}|^2 - \frac{|\boldsymbol{a}(\theta)^\dagger \boldsymbol{r}|^2}{|\boldsymbol{a}(\theta)|^2}$$

→ Minimum

$$\arg\max_{\theta_1,\theta_2} \frac{|\boldsymbol{a}(\theta_1 + j\theta_2)^\dagger \boldsymbol{r}|^2}{|\boldsymbol{a}(\theta_1 + j\theta_2)|^2}$$



Parameter search

Distribution of a Complex Angle

- Distribution of a Complex Angle is $\sum \beta_i \Delta\theta_i / \sum \beta_i$
  → the ratio of two Gaussian distributions

$$p(\xi) = \frac{1}{2C} \frac{1}{(\xi^2/C^2 + 1)^{3/2}} \quad \text{[M-distribution]}$$

$$C = \sqrt{\theta_i^2}$$

Parameter C is the absolute first order moment of M-distribution and equal to the standard deviation of DOA of the scattering wave are in agreement.

- Random FM noise

$\theta(t)$ fluctuates randomly → FM noise

A pdf of $\dot{\theta}$, $p(\dot{\theta})$ is

$$p(\dot{\theta}) = \frac{1}{2}\sqrt{\frac{b_0}{b_2}}\left[1 + \frac{b_0}{b_2}\dot{\theta}^2\right]^{-3/2}$$

Error of parameter estimation

- Additive noise including system error is

$$|\boldsymbol{n}|^2 = |\boldsymbol{r}(t) - \gamma \boldsymbol{a}(\theta)|^2$$

Since approximation error is large when γ is small, the noise n becomes large.

$$|\gamma| < \sigma$$

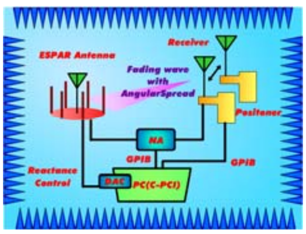
When γ is smaller than the standard deviation of noise σ, estimation is not appropriate.

Experiments in an anechoic chamber

- Measurement

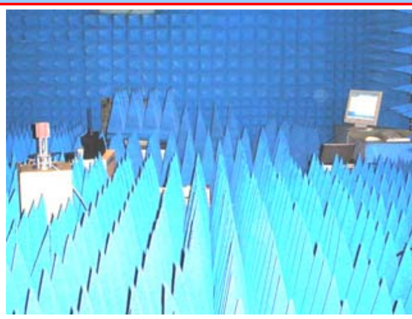
Frequency:2.484[GHz]

Distance:about 1.2[m](=10[λ])

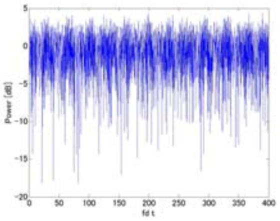


The fading wave from an ESPAR antenna is measured by a synthetic array with 6 elements.

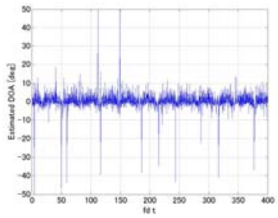
Experiments in an anechoic chamber



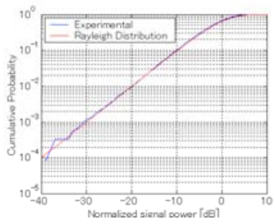
- Time property –Received power



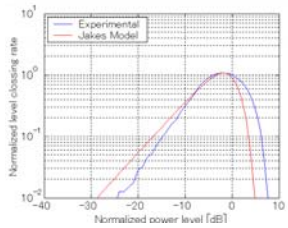
Received Signal Power



Estimated DOA

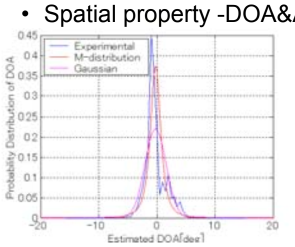


Cumulative Probability of Received Signal power

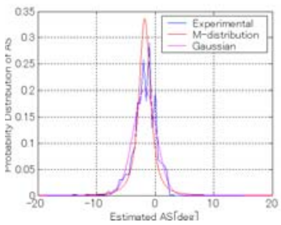


Level Crossing Rate of Received Signal Power

- Spatial property -DOA&AS



Probability Distribution of DOA



Probability Distribution of AS

- The performance of the fading emulator was verified using experimental data.

- Using the ESPAR antenna, evaluation of the array signal processing system becomes a much easier task.

Conclusion

- Emulation of Rayleigh fading in an anechoic chamber with angular spread is realized.
- It emulates cheaply and simply.
- Estimation by the Maximum Likelihood method is effective.
- It was shown that an ideal angular spread is emulated by M-distribution.

Future works

- Concurrent emulation of the multiple user
- Control of the phase distribution
- Spatial correlation