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
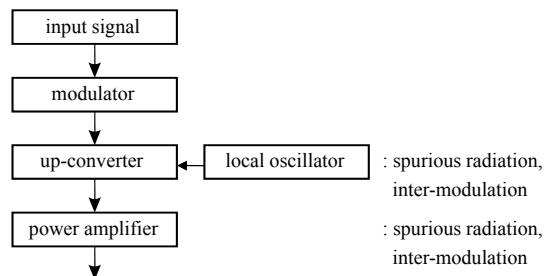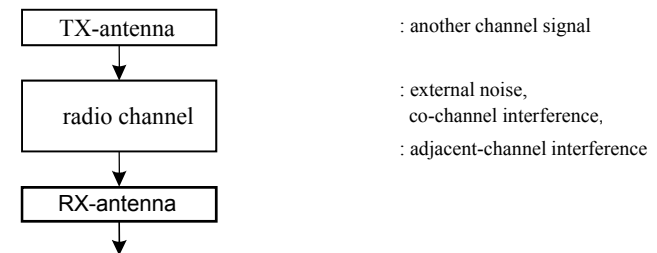
input signal → modulator → up-converter ← local oscillator : spurious radiation, inter-modulation

up-converter → power amplifier : spurious radiation, inter-modulation

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TX-antenna → radio channel → RX-antenna

: another channel signal

: external noise,
 co-channel interference,

: adjacent-channel interference

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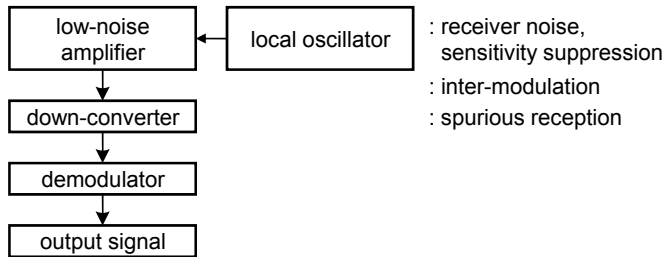
```
┌──────────────────┐      ┌──────────────────┐
│    low-noise     │◄─────│ local oscillator │   : receiver noise,
│    amplifier     │      └──────────────────┘     sensitivity suppression
└──────────────────┘
        │                                         : inter-modulation
        ▼
┌──────────────────┐                              : spurious reception
│  down-converter  │
└──────────────────┘
        │
        ▼
┌──────────────────┐
│   demodulator    │
└──────────────────┘
        │
        ▼
┌──────────────────┐
│  output signal   │
└──────────────────┘
```

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)

  $@ T = 300 K \rightarrow$ -174[dBm/Hz]

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

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

  G : $Gain$

- 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 IMD are dominant.

Noise

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

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

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

$$N_0 \Rightarrow kT$$

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

$$kT/C$$

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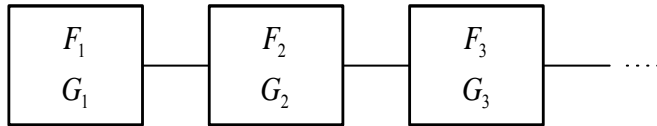
$$F_e = \frac{T_e}{T_0} + 1$$

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Cascade Connection of LNA

with Noise Figure F and Gain G

$$\boxed{\begin{array}{c} F_1 \\ G_1 \end{array}} \quad \boxed{\begin{array}{c} F_2 \\ G_2 \end{array}} \quad \boxed{\begin{array}{c} F_3 \\ G_3 \end{array}} \quad \cdots$$

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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.

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2-Stage Case $\rightarrow$ Noise Measure

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

$$\updownarrow$$

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

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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 $\pm 600\,\mathrm{Hz}$.

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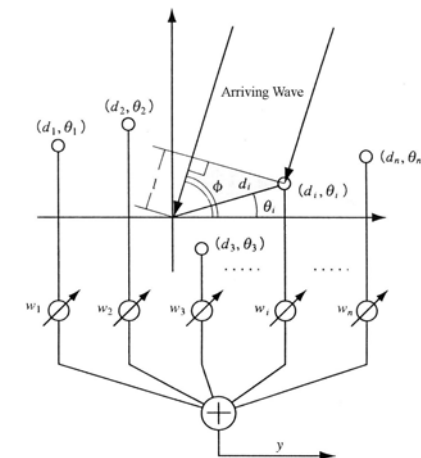
$\mathbf{x}(t) = \mathbf{a}_s s(t) + \mathbf{a}_i i(t) + \mathbf{n}(t)$: received signal model

$\mathbf{a}_s = \mathbf{a}(\theta_s)$: spatial signature for desired signal $s(t)$

θ_s : known

$\mathbf{a}_i = \mathbf{a}(\theta_i)$: spatial signature for undesired signal $i(t)$

θ_i : known

$\mathbf{n}(t)$: additive noise at the receiver

- Linear Signal Processing

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

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

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

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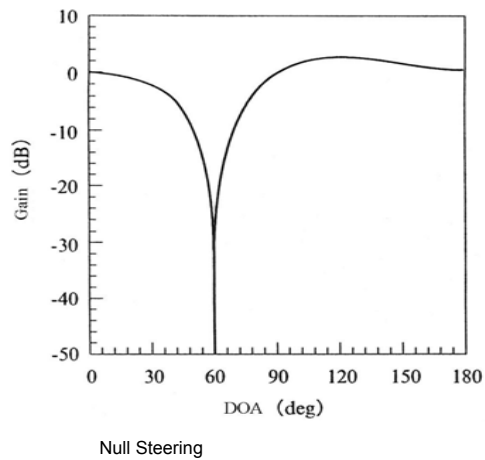
Null Steering

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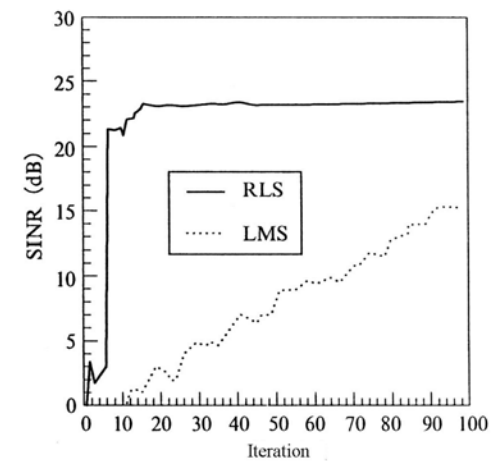
$\mathbf{a}(\theta)$: array mode vector with DOA, θ

e.g. ULA (Uniform Linear Array)

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

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

Δ : inter element spacing

λ : wave length $(= c/f)$

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

$$\mathbf{w} = c[\mathbf{e}_s - \theta\mathbf{e}_i]$$

$$\mathbf{w}^+\mathbf{e}_i = \mathbf{e}_s^+ \cdot \mathbf{e}_i - \theta^* = \theta^* - \theta^* = 0$$

$$\therefore \quad \mathbf{w} \perp \mathbf{e}_i$$

c : some constant

where

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

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

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$$y_s(t) = \mathbf{w}^+ \cdot \mathbf{a}_s s(t) = (\mathbf{e}_s^+ - \theta^*\mathbf{e}_i^+)\mathbf{a}_s s(t)$$

$$= |\mathbf{e}_s|(1 - |\theta|^2)\mathbf{a}_s s(t)$$

$$S = E\left[|y_s(t)|^2\right] = |\mathbf{a}_s|^2(1 - |\theta|^2)^2 E\left[|s(t)|^2\right]$$

$$y_i(t) = \mathbf{w}^+ \cdot \mathbf{a}_i i(t) = 0$$

$$I = E\left[|y_i(t)|^2\right] = 0$$

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$$y_n(t) = \mathbf{w}^+\mathbf{n}(t)$$

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

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

$$= (\mathbf{e}_s^+ - \theta^*\mathbf{e}_i^+)\sigma_n^2 I(\mathbf{e}_s - \theta\mathbf{e}_i)$$

$$= \sigma_n^2(1 - \theta^*\theta - \theta^*\theta + \theta^*\theta)$$

$$= \sigma_n^2(1 - |\theta|^2)$$

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SNR for ZF

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

$$P_s = E\left[|s(t)|^2\right]: \text{average signal power}$$

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

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

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

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

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

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

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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,
$\qquad\qquad$ MRC (Maximum Ratio Combining)

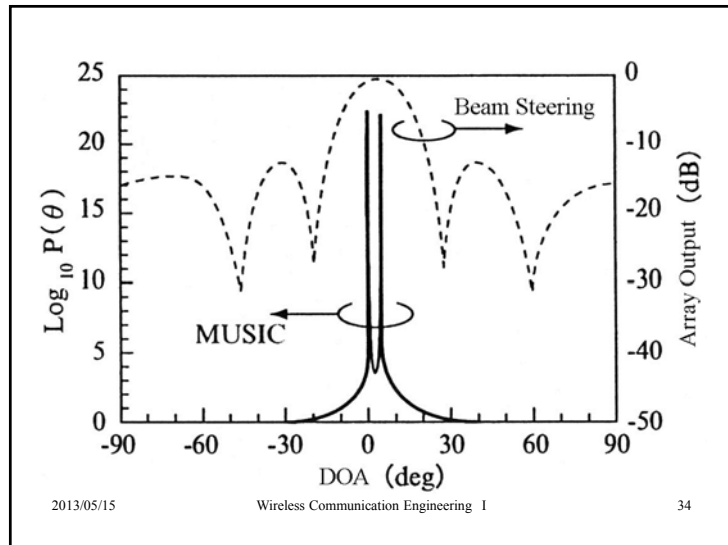$\Gamma \to \frac{P_s|\mathbf{a}_s|^2}{\sigma_n^2} : \text{SNR}$

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

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Super resolution techniques

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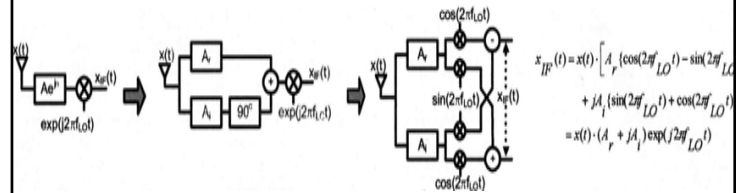- MUSIC, ESPRIT : Powerful DOA techniques especially in radar application.

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RF FRONT-END FOR SPATIAL PROCESSING

FREQUENCY CONVERSION
FROM RF TO IF

ARRAY PROCESSING by Gilbert
Cell and Transformer
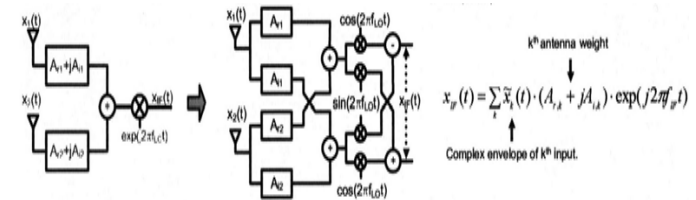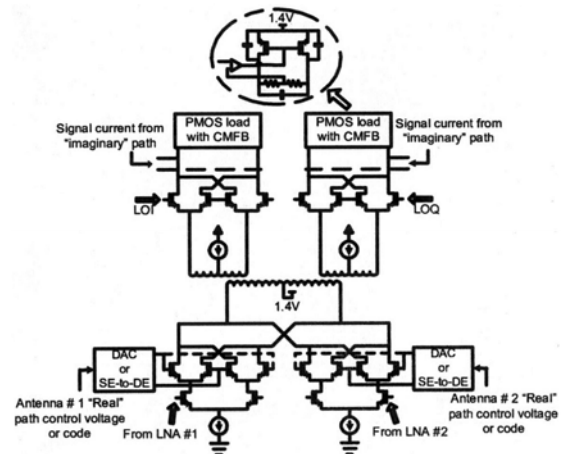
DESIRED   UNDESIRED
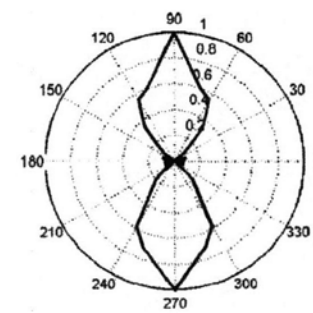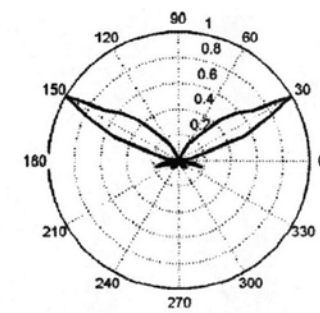
10
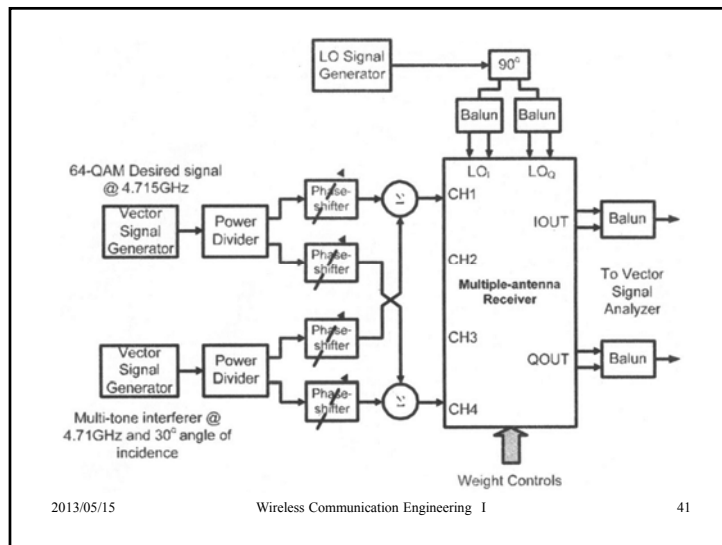
MEASURED RESULTS BEFORE AND AFTER SIGNAL PROCESSING for Interference Canceling
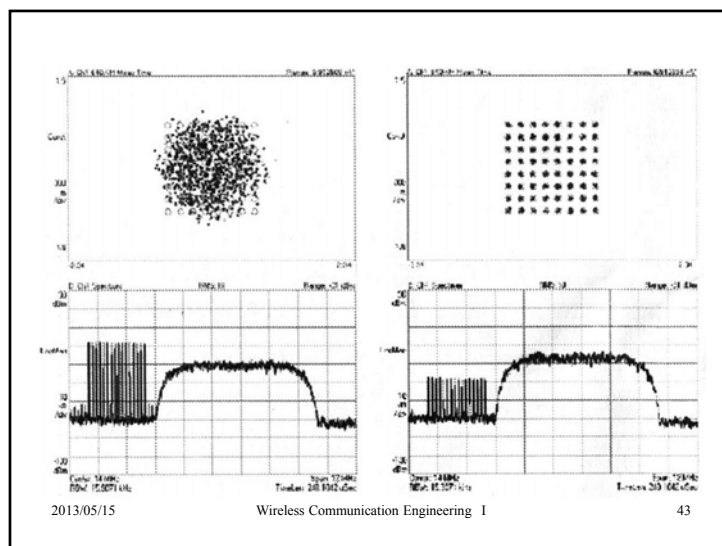
Spatial Fading Emulator

 - 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.
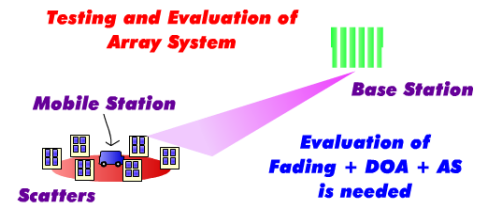 - With the use of an ESPAR antenna, the superposition of scattered waves can be made easily.

Agenda

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

Propagation of mobile communication

Testing and Evaluation of Array System

Mobile Station

Base Station

Evaluation of Fading + DOA + AS is needed

Scatters

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

ESPAR Antenna Structure

Excited Element

Base Station

Fading wave with AngularSpread

6 Parasitic Elements

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

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

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

Y : Array Antenna Admittance Matrix : fixed
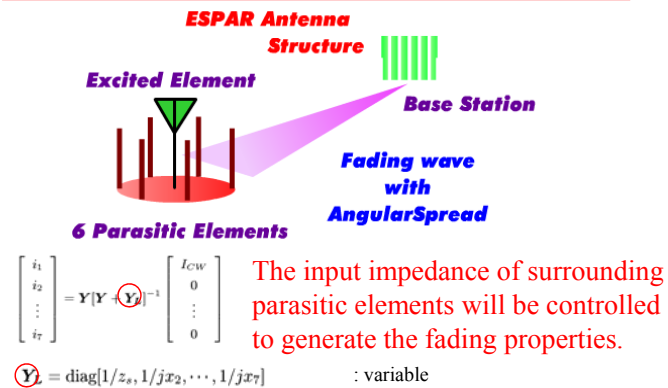
Control of bias voltages to varactors

⬇

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

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

→ Number of estimate parameters is 2 × N (β_i, θ_i)

[approximated by Taylor Series Expansion]

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

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

$$\sum_{i=1}^{N} \beta_i \mathbf{a}(\tilde{\theta} + \Delta\theta_i) \simeq \sum_{i=1}^{N} \beta_i [\mathbf{a}(\tilde{\theta}) + \Delta\theta_i \frac{\partial \mathbf{a}(\tilde{\theta})}{\partial \theta}]$$

$$= (\sum \beta_i)\mathbf{a}(\tilde{\theta}) + (\sum \beta_i \Delta\theta_i)\frac{\partial \mathbf{a}(\tilde{\theta})}{\partial \theta}$$

$$= \gamma \mathbf{a}(\tilde{\theta}) + \eta \frac{\partial \mathbf{a}(\tilde{\theta})}{\partial \theta} \qquad \gamma = \sum_{i=1}^{N} \beta_i$$

$$= \gamma [\mathbf{a}(\tilde{\theta}) + \xi \frac{\partial \mathbf{a}(\tilde{\theta})}{\partial \theta}] \qquad (6) \qquad \eta = \sum_{i=1}^{N} \beta_i \Delta\theta_i$$

$$\simeq \gamma [\mathbf{a}(\tilde{\theta} + \xi)] \qquad \xi = \frac{\eta}{\gamma}$$

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

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

Parameter Estimation

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

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

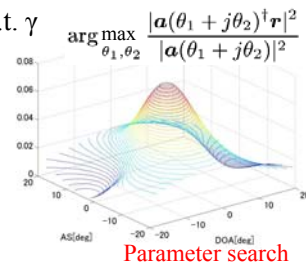→ Estimate γ and θ where f is minimum　　$(\theta = \theta_1 + j\theta_2)$

1. Least mean square w.r.t. γ

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

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

2. The cost function is

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

$$= |\mathbf{r}|^2 - \frac{|\mathbf{a}(\theta)^\dagger \mathbf{r}|^2}{|\mathbf{a}(\theta)|^2}$$

→ Minimum

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

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

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

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.

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- Random FM noise

  $\theta(t)$ fluctuates randomly $\rightarrow$ 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])
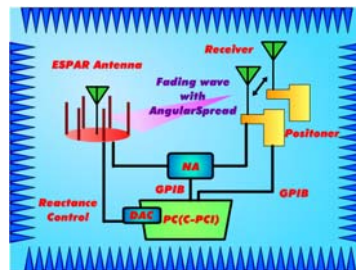
The fading wave from an ESPAR antenna is measured by a synthetic array with 6 elements.

Experiments in an anechoic chamber
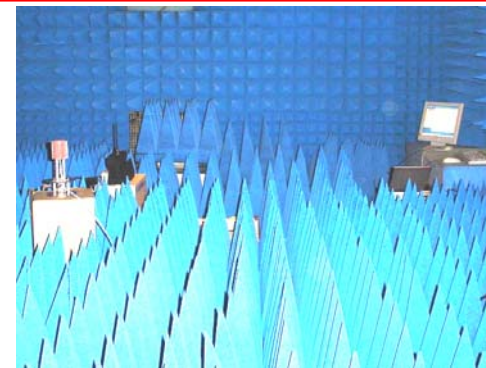
- Time property –Received power
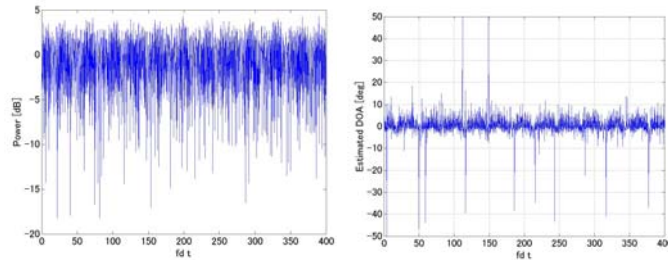
Received Signal Power

Estimated DOA
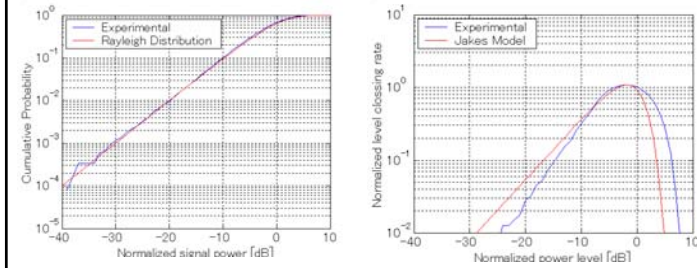
Cumulative Probability of Received Signal power

Level Crossing Rate of Received Signal Power

- Spatial property -DOA&AS
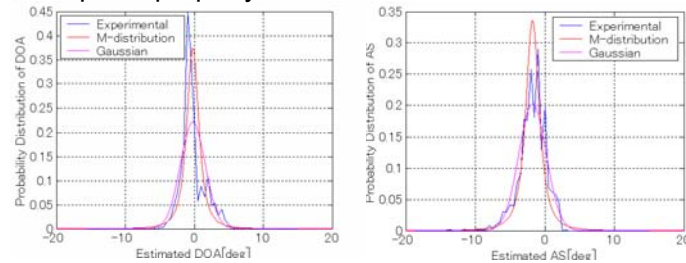
Probability Distribution of DOA

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