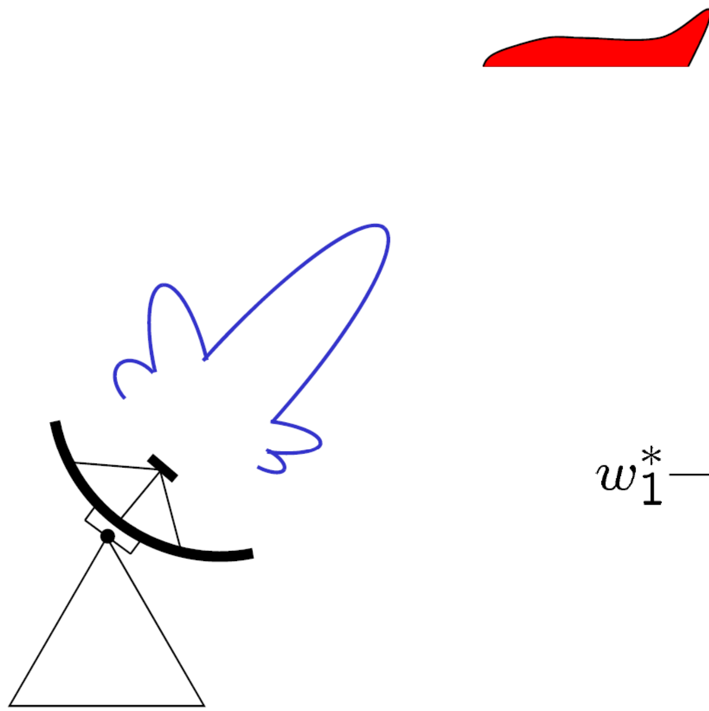
上海科技大学 ShanghaiTech University

ADSP Advanced digital signal processing

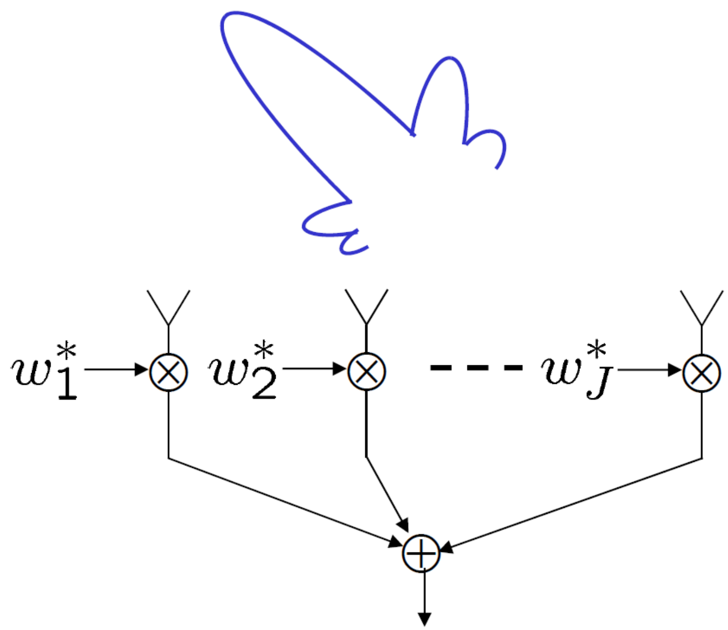
Main content ADSP course

- Part A: Stochastic Signal Processing
- Part B: Adaptive Signal Processing
- **Part C: Array Signal Processing (ASP) (including DOA)**
- Part D: Adaptive Array Signal Processing (AASP)

Introduction

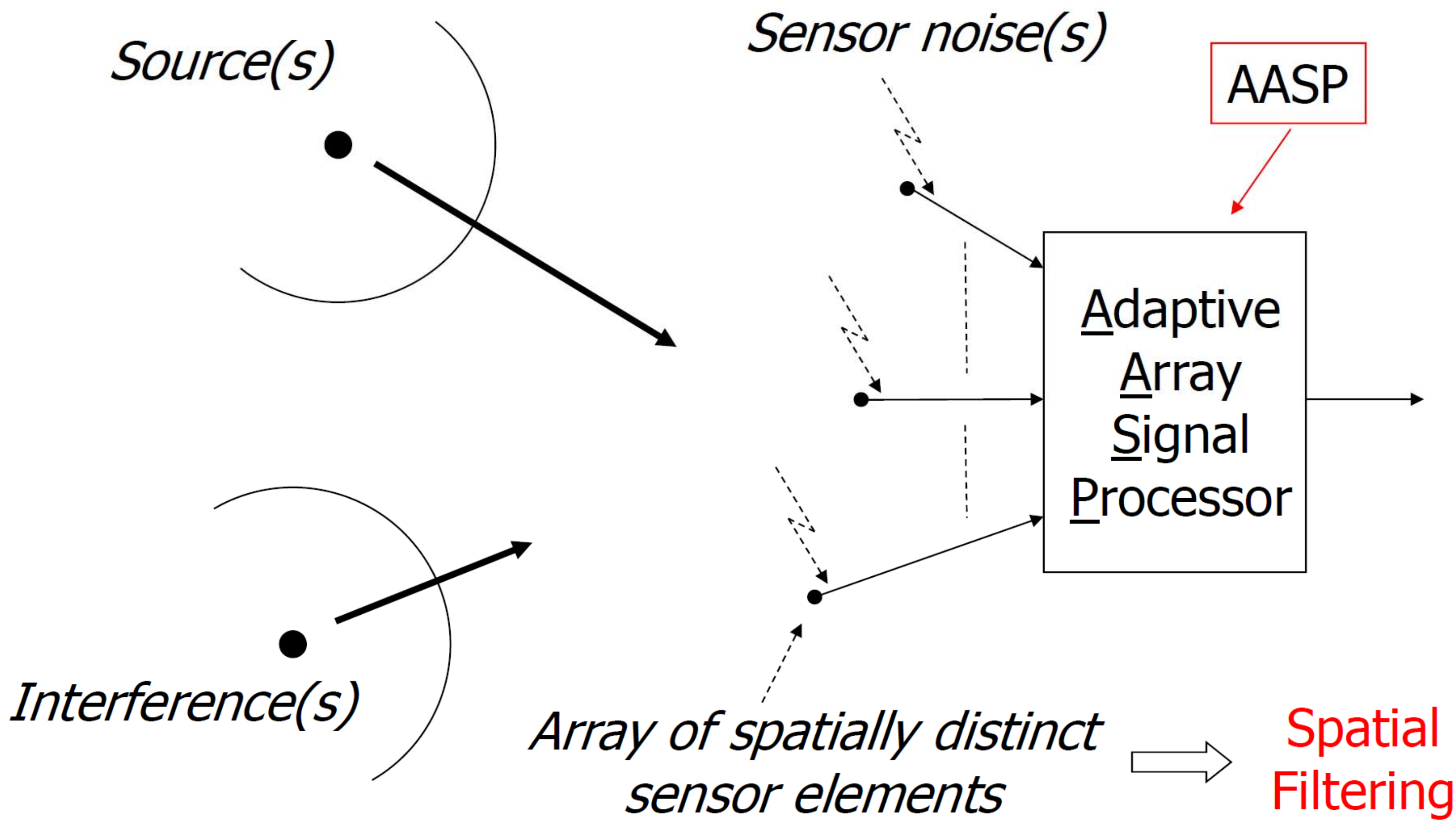


Parabolic dish antenna
(continuous aperture)



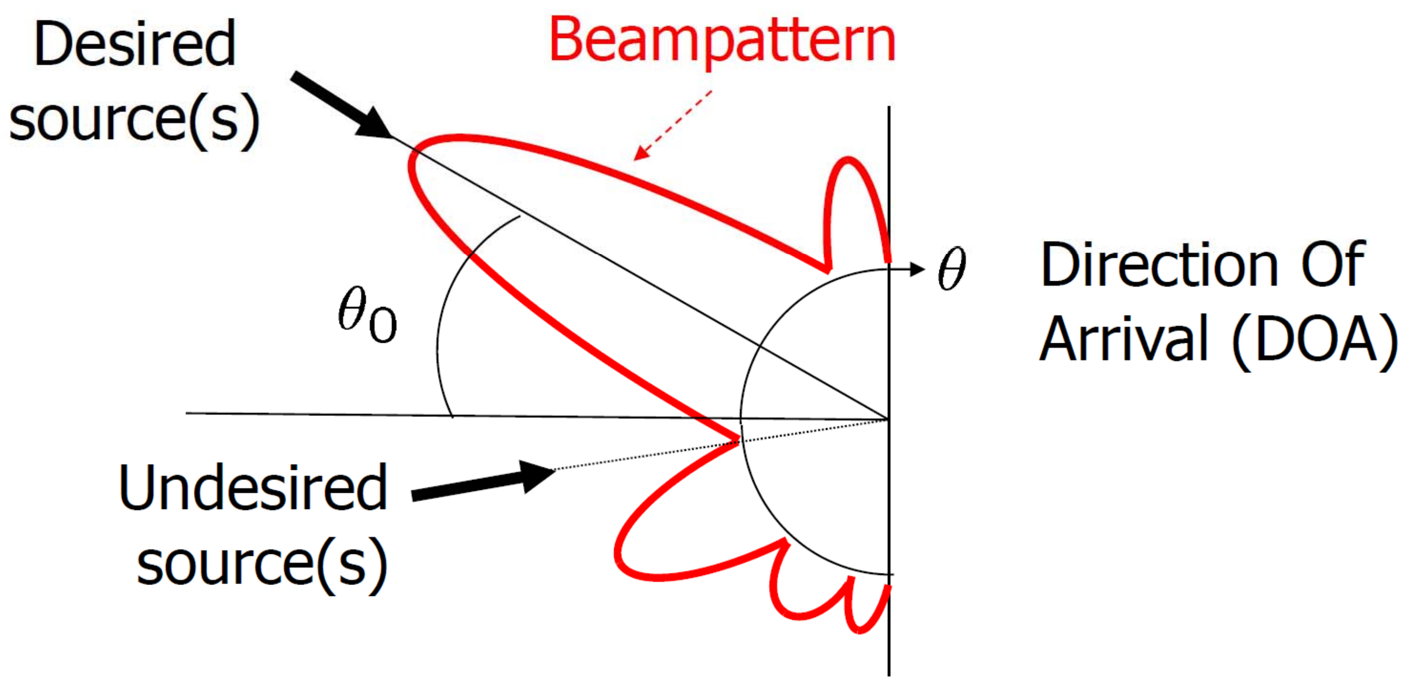
Sensor array antenna
(discrete spatial aperture)

Introduction



Introduction

Result of spatial filtering:



Introduction

<u>Beamforming:</u>

Spatio temporal filtering to either direct or block the radiation or reception of signals in specified directions.

<u>Result Array Signal Processing:</u>

Spatial filtering: Separate signals with possible overlapping frequency content but from different spatial locations.

Introduction

Furthermore:

- Able to ‘look’ in several directions simultaneously
- Signal enhancement: averaging different sensor measurements improves SNR
- Flexible spatial discrimination: size of spatial aperture can be adapted.
- Adaptivity --> able to adapt response

AASP is versatile and flexible

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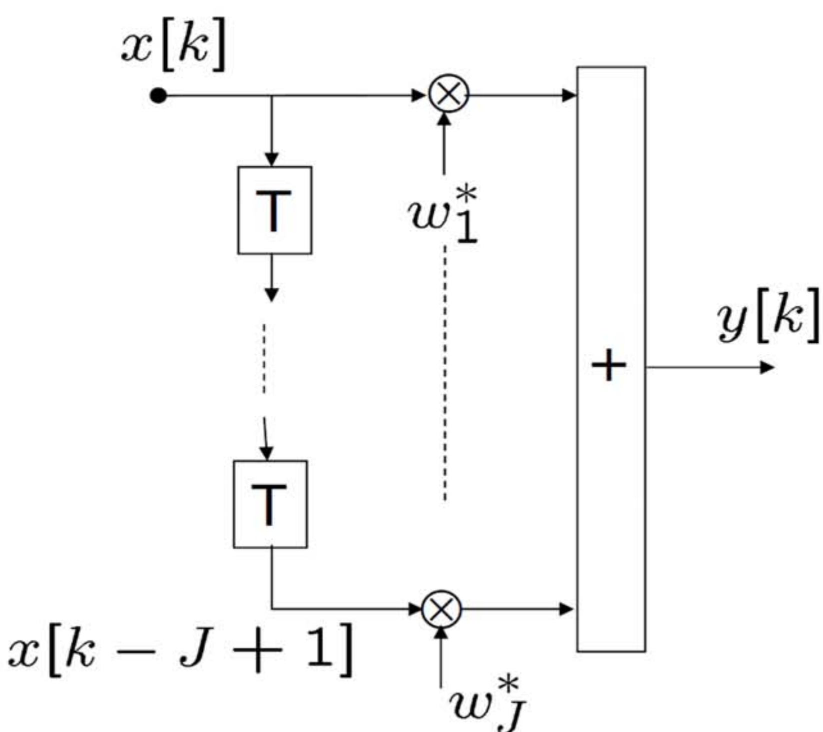
Introduction

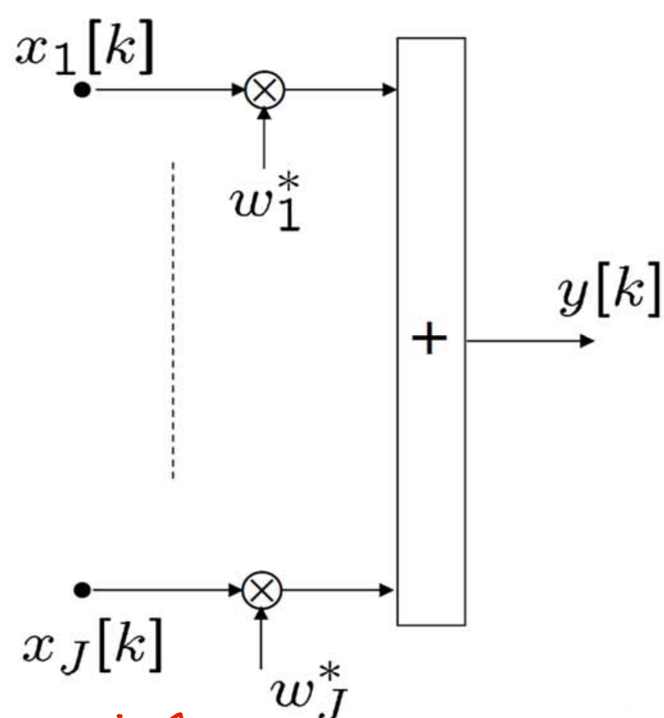
To provide insight into various aspects of AASP we use familiar methods and techniques from FIR filtering.

FIR:



时间

Array:



空间

Introduction

However main differences ASP and FIR filtering:

- Source can have several parameters of interest (e.g. range, azimuth and elevation angle, polarization, temporal frequency content)
- Different signal often mutually correlated (multipath)
- Spatial sampling often nonuniform and multidimensional
- Uncertainty must often be included in characterization of individual sensor response and location (robust ASP techniques required)

Introduction

General objective of AASP:

Detect or enhance desired signal(s) (increase SNR), while simultaneously reducing unwanted interference.

Physical form array varies according to medium:

Microphone for pressure variations in air
Hydrophone for pressure variations in water (sonar)
Geophone for land base seismology
Radar of electromagnetic waves
Etc.

Information of interest:

- Signal itself (teleconferencing, communications)
- Location of source (=DOA) (radar, sonar)
- Number of sources

Introduction

AASP applications:

Radar: Phased-array, air traffic control

Sonar: Source localization and classification

Communication: Directional transmission and reception

Imaging: Ultrasonic, optical, tomographic

Geophysical exploration: Earth crust mapping, oil exploration

Astrophysical exploration: High resolution imaging of universe

Biomedical: Fetal heart monitoring

Acoustic: Hearing aids, transparent communication

Different scenario's

Bandwidth source 带宽信号
Source position
Array geometry
Discrete-time signal representation
Array signal model
ASP unit

<u>Assumptions:</u>
<u>Superposition principle applies to propagating wave signals</u> 叠加原理可用
<u>Homogeneous, lossless medium, neglect dispersion,</u> 不计媒介损失···

<u>diffraction, changes in propagation speed</u>

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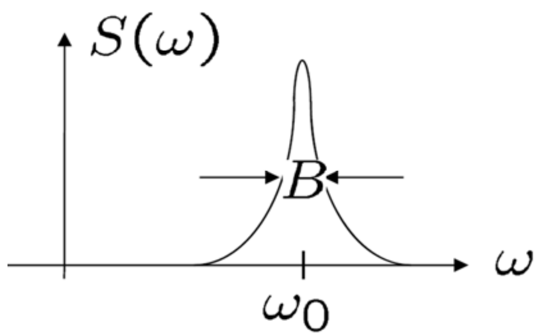
Scenarios

Bandwidth source

Analytical representation: $s(t) = A(t)e^{j(\omega_0 t + \phi(t))}$

窄带 **Narrowband:** $A(t)$ and $\phi(t)$ vary slower than $e^{j\omega_0 t}$



Narrowband: $|\tau| \ll 1/B \Rightarrow$ 时间 带宽

$A(t-\tau) \approx A(t) = 1$ (usually) 幅值短时间不变

$\phi(t-\tau) \approx \phi(t) = 0$ (usually)

$\Rightarrow \quad s(t-\tau) = A(t-\tau)e^{j\phi(t-\tau)}e^{j\omega_0(t-\tau)} \approx e^{-j\omega_0\tau} \cdot s(t)$

不变

Thus for narrow band: Time delay $\Rightarrow$ phase shift

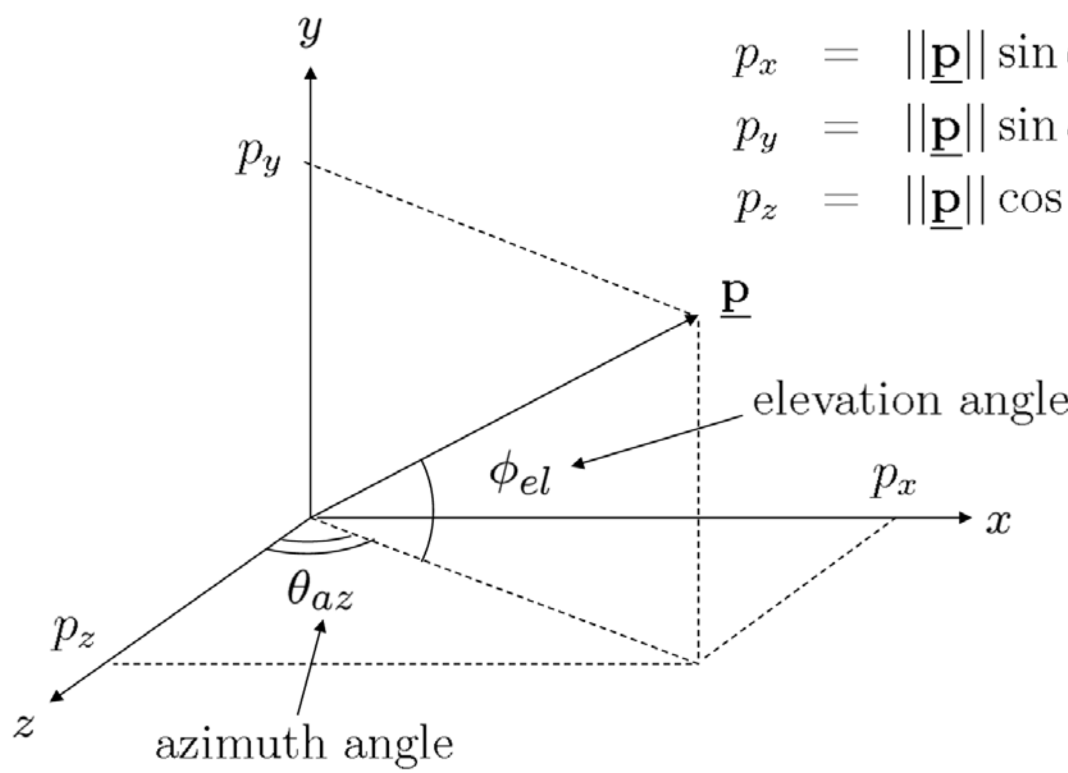
In this course: **mainly narrowband** 时延等于相移

Scenarios

Source position

$$\underline{\mathbf{p}} = (p_x, p_y, p_z)^t$$

$$\begin{aligned} p_x &= \|\underline{\mathbf{p}}\| \sin\theta_{az} \cos\phi_{el} \\ p_y &= \|\underline{\mathbf{p}}\| \sin\phi_{el} \\ p_z &= \|\underline{\mathbf{p}}\| \cos\theta_{az} \cos\phi_{el} \end{aligned}$$

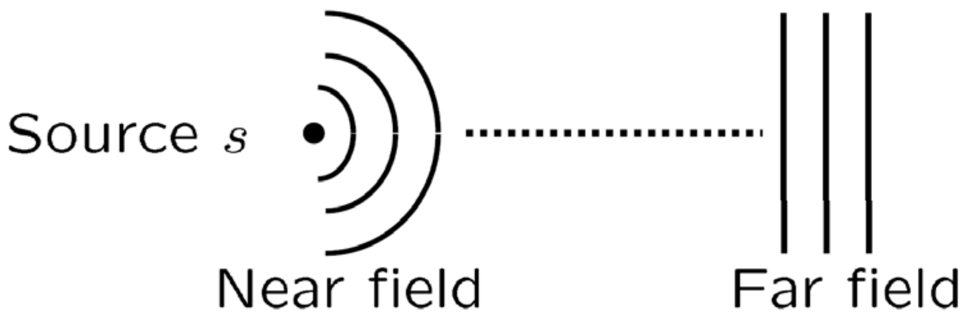


Scenarios

Array aperture: Volume (1D length) that collects incoming energy

Far field:
- Distance source - array $\gg$ array aperture
- Plane wavefront

Near field:
- Distance source - array $\ll$ array aperture
- Spherical wavefront



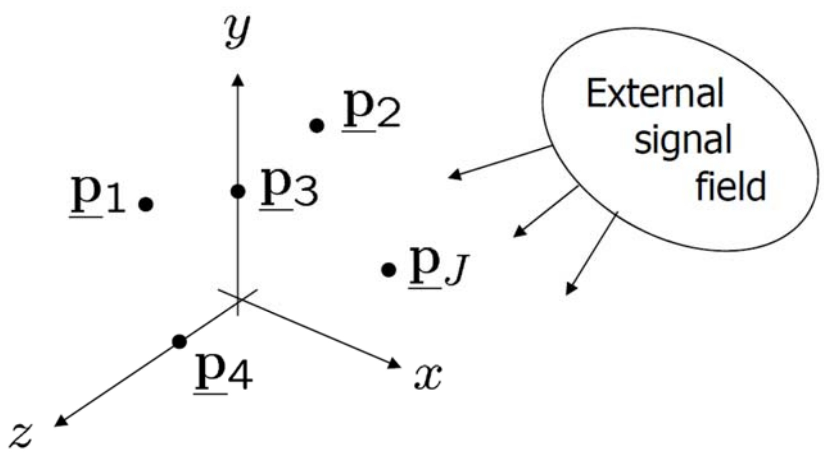
In this course mainly **Far field**

Scenarios

Array geometry

Array can be uniform, nonuniform, linear, circular, ...

Sensors at J locations $\underline{\mathbf{p}}_i$



In this course mainly: **Uniform Linear Array (ULA)**

Scenarios

Propagation for **near field** (single frequency) source

$$s(t, \underline{\mathbf{p}}) = \frac{A}{||\underline{\mathbf{p}}||^2} e^{j\omega\left(t - \frac{||\underline{\mathbf{p}}||}{c}\right)}$$

源为坐标中心？

with $\omega = 2\pi f$ and $f = \dfrac{c}{\lambda}$

$\lambda =$ wavelength; $c =$ speed in medium

Note: For acoustic sound in air $c \approx 334$[m/sec]

$\Longrightarrow$ Amplitude decays proportional to distance from source

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Scenarios

时 空

In **far field** at position $\underline{\mathbf{p}}_i$ monochromic plane wave:

$$s(t, \underline{\mathbf{p}}_i) = A e^{\mathrm{j}\omega(t-\tau_i)} = A e^{\mathrm{j}\omega(t - \frac{\underline{\mathbf{v}}^t}{c} \cdot \underline{\mathbf{p}}_i)} = A e^{\mathrm{j}(\omega t - \underline{\mathbf{k}}^t \cdot \underline{\mathbf{p}}_i)} = A e^{jwt} \cdot e^{-j\underline{k}^T \cdot \underline{p}_i}$$

Direction vector $\underline{\mathbf{v}}$; Wave number vector $\underline{\mathbf{k}} = \frac{\omega}{c} \cdot \underline{\mathbf{v}}$

$\|\underline{v}\| = 1$

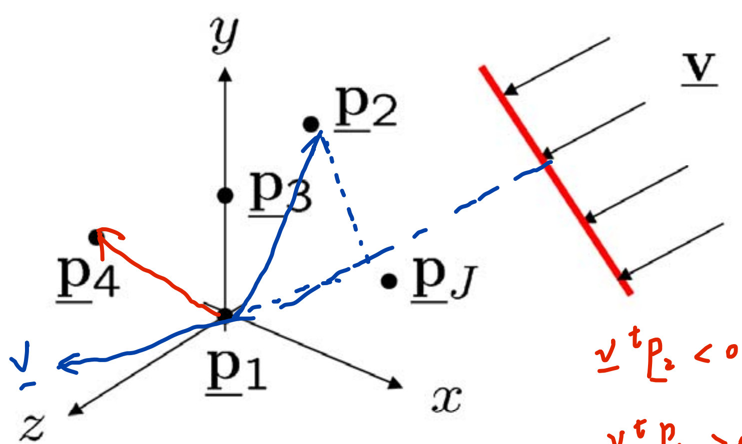
- Propagation expressed as function of time and space
- Information is preserved while propagating

⟹ Band-limited signal can be reconstructed over all space and time by either:
- *temporally sampling* at given location in space
- *spatially sampling* at given instant of time

Basis for all aperture and sensor array processing techniques

Scenarios

Propagation between two points for **plane wave**:



Assume reference $\underline{\mathbf{p}}_1$:

$s(t)$ arrives at $\underline{\mathbf{p}}_1$

$\underline{\mathbf{p}}_1$ in origin

$\underline{v}^t \underline{p}_2 < 0$, $\tau_i < 0$

$\underline{v}^t \underline{p}_4 > 0$, $\tau_i > 0$ 说明平面波先到p_2再到p_4

Analog signal at location $\underline{\mathbf{p}}_i$: $s(t-\tau_i) = s(t)\mathrm{e}^{-\mathrm{j}\omega\tau_i}$

with delay: $\tau_i = \underline{\mathbf{v}}^t \cdot \underline{\mathbf{p}}_i / c$ Direction vector v $\|\underline{v}\| = 1$

with $\omega = 2\pi f$ and $f = \dfrac{c}{\lambda}$ $c \to$ 单位t振动的距离 $\lambda \to$ 每次振动的长度 $s(t) = A e^{j\omega t}$

单位时间振动次数

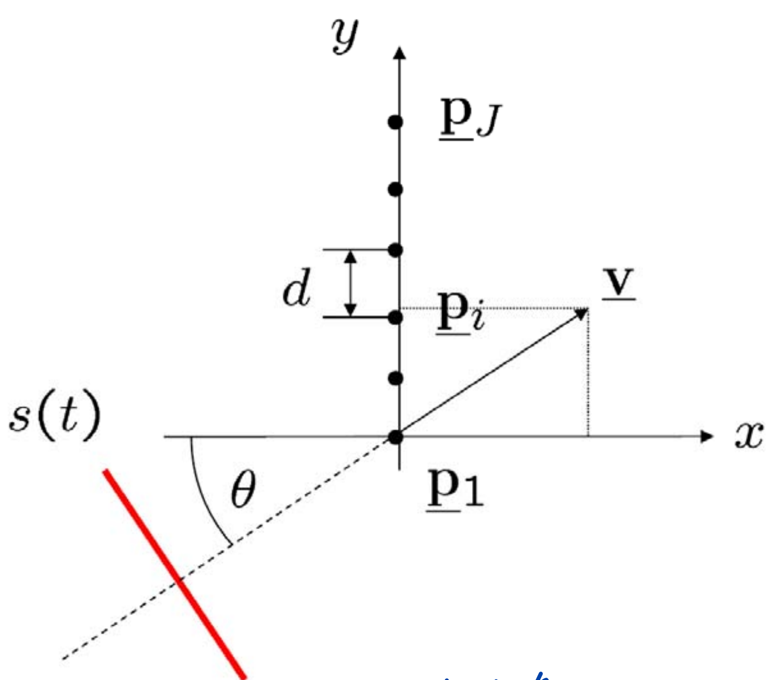
$\lambda =$ wavelength; $c =$ speed in medium

$s(t, \underline{p}_i) = s(t - \tau_i) = A e^{j\omega(t-\tau_i)} = A e^{j\omega(t - \frac{\underline{v}^t p_i}{c})}$

Scenarios

Note: Location is 3D quantity

In practice: Direction Of Arrival (DOA) 2D



θ是平面波法线与ULA法线的夹角
也是平面波与ULA的夹角

ULA:

If reference $\underline{\mathbf{p}}_1$ at $(0,0)$

$$\Rightarrow \quad \underline{\mathbf{p}}_i = (0, (i-1)\cdot d)^t$$

Directional vector:

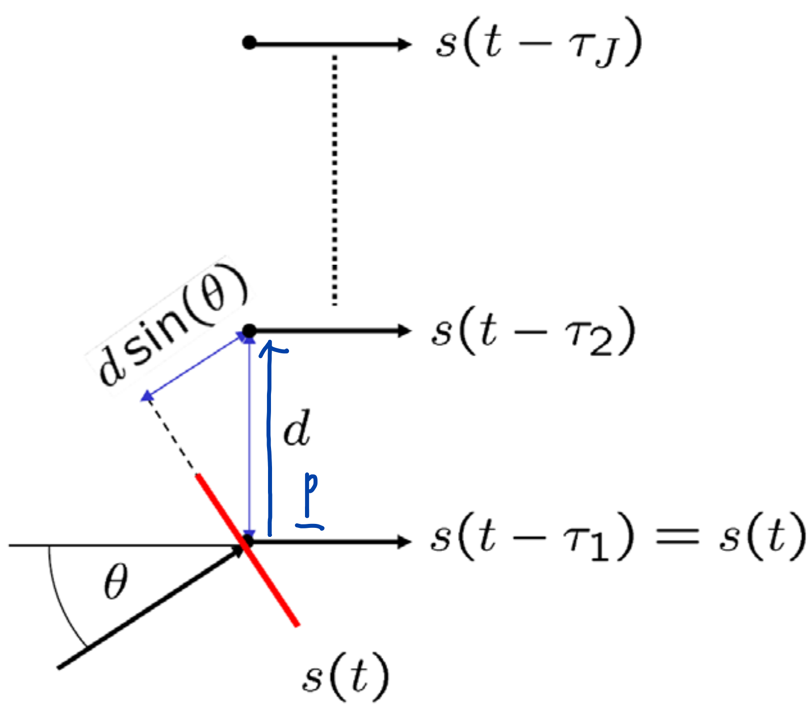
$$\underline{\mathbf{v}} = (\cos(\theta), \sin(\theta))^t$$

$$|\underline{\mathbf{v}}| = 1$$

Scenarios

Example: **Plane wave, ULA**

For far field only one parameter (DOA) characterizing position



$$\Rightarrow \tau_i = \tau_i(\theta)$$
$$= \underline{\mathbf{v}}^t \underline{\mathbf{p}}_i / c$$
$$= (i-1)\frac{d\sin(\theta)}{c}$$

$\underline{p}_i = (0, (i-1)d)$ 坐标

$\underline{v} = (\cos\theta, \sin\theta)$

$\underline{v}^t \underline{p}_i = (i-1) d \sin\theta$

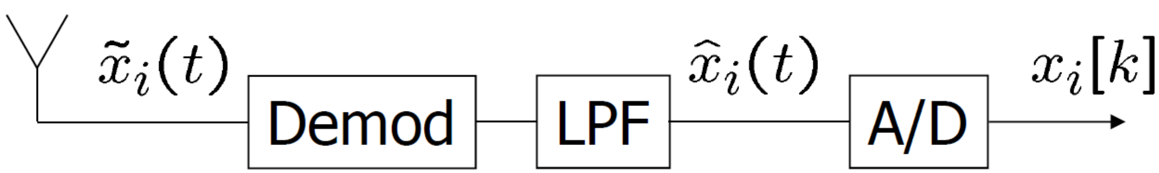
坐标对应相乘相加

Scenarios

Discrete-time signal representation

- Analog sensor signal at J locations: $\tilde{x}_i(t)$
- In each sensor $i = 1 \cdots J$ ideal demodulation and LPF takes place to baseband signal $\hat{x}_i(t)$
- After A/D:

  Complex valued discrete-time signal $x_i[k]$



低通滤波，滤去噪音

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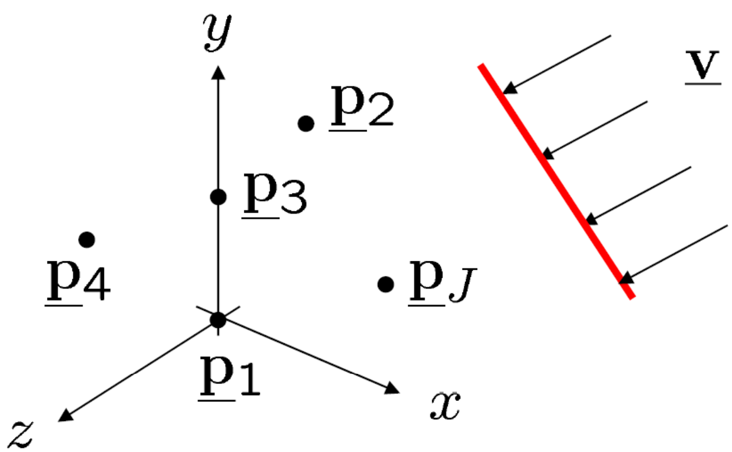
Scenarios

Propagation between two points for **plane wave**:



Assume reference $\underline{\mathbf{p}}_1$:

$s(t)$ arrives at $\underline{\mathbf{p}}_1$

$\underline{\mathbf{p}}_1$ in origin

Analog signal at location $\underline{\mathbf{p}}_i$: $s(t-\tau_i) = s(t)\mathrm{e}^{-\mathrm{j}\omega\tau_i}$

with delay: $\tau_i = \underline{\mathbf{v}}^t \cdot \underline{\mathbf{p}}_i / c$

$\Rightarrow$ Discrete-time signal at $\underline{\mathbf{p}}_i$: $\boxed{s[k]\cdot\mathrm{e}^{-\mathrm{j}\omega\tau_i}}$

$s[k] = A e^{j\omega k}$

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Scenarios

$\Rightarrow$ Discrete-time signal in sensor i (for ULA):

$$s[k] \cdot e^{-j\omega\tau_i} \equiv s[k] \cdot \underline{a_i(\omega,\theta)}$$

空间

$$\text{with } a_i(\omega,\theta) = e^{-j\omega\tau_i}$$
$$= e^{-j\omega(i-1)\frac{d\sin(\theta)}{c}}$$
$$= e^{-j2\pi\frac{c}{\lambda}(i-1)\frac{d\sin(\theta)}{c}}$$
$$= e^{-j2\pi(i-1)\frac{d\sin(\theta)}{\lambda}}$$

Note: Usually simplified notation

$$a_i(\omega,\theta) \rightarrow a_i(\theta)$$

steering vector : $(\underline{a}(\theta))_i = a_i(\theta) = e^{-j2\pi(i-1)\frac{d\sin\theta}{\lambda}}$

Scenarios

Array signal model

Array sensor vector: $\underline{\mathbf{x}}[k] = (x_1[k], x_2[k], \cdots, x_J[k])^t$

Noise vector: $\underline{\mathbf{n}}[k] = (n_1[k], n_2[k], \cdots, n_J[k])^t$

Steering vector: $\underline{\mathbf{a}}(\theta) = (a_1(\theta), a_2(\theta), \cdots, a_J(\theta))^t$

with $a_i(\theta) = \mathrm{e}^{-\mathrm{j}\omega\tau_i(\theta)}$

Note: for ULA: $a_i(\theta) = \mathrm{e}^{-\mathrm{j}2\pi(i-1)\frac{d\sin(\theta)}{\lambda}}$

$\underline{a}(\theta) = \left(1,\ e^{-j2\pi\frac{d\sin\theta}{\lambda}},\ e^{-j2\pi\cdot\frac{2d\sin\theta}{\lambda}},\ \cdots,\ e^{-j2\pi(i-1)\frac{d\sin\theta}{\lambda}},\ \cdots\ e^{-j2\pi(J-1)\frac{d\sin\theta}{\lambda}}\right)^t$

Scenarios

Case: Noisy observation, one source, J sensors

空间 时间

for $i = 1, 2, \cdots, J$: $x_i[k] = a_i(\theta) \cdot s[k] + n_i[k] \;\Rightarrow$

$$\boxed{\underline{\mathbf{x}}[k] = \underline{\mathbf{a}}(\theta) \cdot s[k] + \underline{\mathbf{n}}[k]}$$

Covariance structure: 已减均值 mean

$$\mathbf{R}_x = E\{\underline{\mathbf{x}} \cdot \underline{\mathbf{x}}^h\} = \sigma_s^2 \cdot (\underline{\mathbf{a}} \cdot \underline{\mathbf{a}}^h) + \mathbf{R}_n$$

J×J

mean 为 0

with $\underline{\sigma_s^2 = E\{|s|^2\}}$ and $\mathbf{R}_n = E\{\underline{\mathbf{n}} \cdot \underline{\mathbf{n}}^h\}$

For spatially white noise: $\mathbf{R}_n = \sigma_n^2 \mathbf{I}$

Note: Time indices are skipped for simplicity

Scenarios

$e^{-j2\pi(i-1)\frac{d\sin\theta_p}{\lambda}}$

Case: Noisy observation, P sources, J sensors

$$\text{for } i = 1, 2, \cdots, J : \; x_i[k] = \sum_{p=1}^{P} a_i(\theta_p)\cdot s_p[k] + n_i[k] \;\Rightarrow$$

$$x_i[k] = [a_i(\theta_1), a_i(\theta_2)\cdots a_i(\theta_P)]\begin{bmatrix} s_1[k] \\ s_2[k] \\ \vdots \\ s_P[k] \end{bmatrix}$$

$$\boxed{\underline{\mathbf{x}}[k] = \mathbf{A}\cdot\underline{\mathbf{s}}[k] + \underline{\mathbf{n}}[k]}$$

$J\times P$ steering matrix $\mathbf{A} = (\underline{\mathbf{a}}(\theta_1), \underline{\mathbf{a}}(\theta_2), \cdots, \underline{\mathbf{a}}(\theta_P))_{J\times P}$

$P\times 1$ signal vector $\underline{\mathbf{s}}[k] = (s_1[k], s_2[k], \cdots, s_P[k])^t$

Covariance structure:

$$\mathbf{R}_x = E\{\underline{\mathbf{x}}\cdot\underline{\mathbf{x}}^h\} = \mathbf{A}\mathbf{R}_s\mathbf{A}^h + \mathbf{R}_n$$

with $\mathbf{R}_s = E\{\underline{\mathbf{s}}\cdot\underline{\mathbf{s}}^h\}$ and $\mathbf{R}_n = E\{\underline{\mathbf{n}}\cdot\underline{\mathbf{n}}^h\} = \sigma_n^2\mathbf{I}$ 满秩

Scenarios

General case:

Noisy observation, desired + undesired signals:

$$\boxed{\underline{\mathbf{x}}[k] = \underline{\mathbf{x}}_d[k] + \underline{\mathbf{x}}_u[k] + \underline{\mathbf{n}}[k]}$$

$\underline{\mathbf{x}}_d[k]$: P independent desired sources

$\underline{\mathbf{x}}_u[k]$: Q independent undesired sources

$\underline{\mathbf{n}}[k]$: Spatially white noise

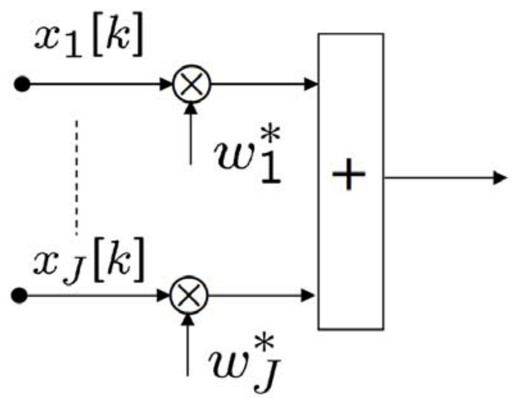
Covariance structure: 独立，可以分开

$$\mathbf{R}_x = E\{\underline{\mathbf{x}} \cdot \underline{\mathbf{x}}^h\} = \mathbf{R}_{x_d} + \mathbf{R}_{x_u} + \mathbf{R}_n$$

Scenarios

Case: <u>Single complex weight for each sensor</u>

空间滤波



$$y[k] = \sum_{i=1}^{J} w_i^* x_i[k]$$

Short notation: $y[k] = \underline{\mathbf{w}}^h \cdot \underline{\mathbf{x}}[k]$

$$\underline{\mathbf{x}}[k] = (x_1[k], \cdots, x_J[k])^t$$

$$\underline{\mathbf{w}} = (w_1, \cdots, w_J)^t$$

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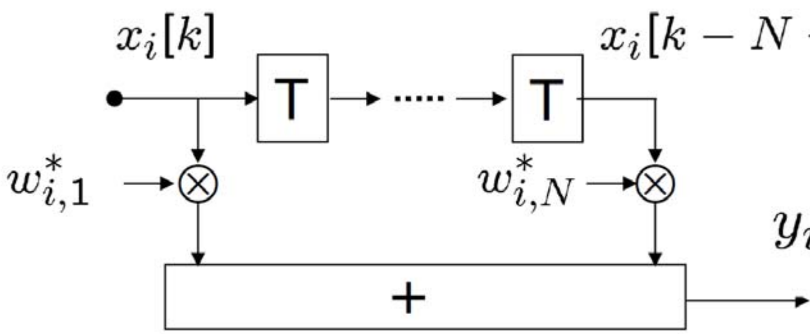
Scenarios

Case: FIR filter for each sensor

时间滤波



$$y_i[k] = \sum_{l=1}^{N} w_{i,l}^* x_i[k-l+1]$$

Short notation for $i = 1, 2, \cdots, J$:

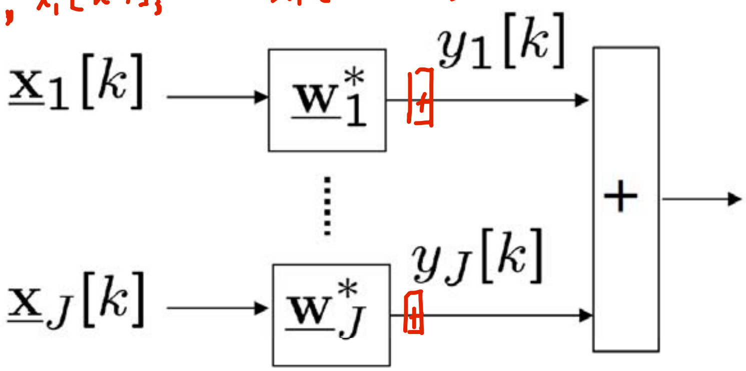
$$\underline{\mathbf{x}}_i[k] \longrightarrow \boxed{\underline{\mathbf{w}}_i^*} \longrightarrow \qquad y_i[k] = \underline{\mathbf{w}}_i^h \cdot \underline{\mathbf{x}}_i[k]$$

$$\underline{\mathbf{x}}_i[k] = (x_i[k], \cdots, x_i[k-N+1])^t$$ 列向量

$$\underline{\mathbf{w}}_i = \left(w_{i,1}, \cdots, w_{i,N}\right)^t$$

Scenarios

$\underline{x}_1[k] = (x_1[k], x_1[k-1], \cdots \quad x_1[k-N+1])^t$ 列向量， $\underline{w}_1^* = (w_1^*[k], w_1^*[k-1] \cdots \quad w_1[k-N+1])^t$



$$y[k] = \sum_{i=1}^{J} \underline{w}_i^h \underline{x}_i[k]$$

$y_i[k] = \underline{w}_i^{*h} \underline{x}_i[k]$

Short notation: $y[k] = \underline{w}^h \cdot \underline{x}[k]$

$$\underline{x}[k] = (\underline{x}_1[k], \cdots \underline{x}_J[k])^t_{J\times N}$$

$$\underline{w} = (\underline{w}_1, \cdots, \underline{w}_J)^t_{J\times N}$$

$$\underline{x}[k] \longrightarrow \boxed{\underline{w}^*} \longrightarrow y[k]$$

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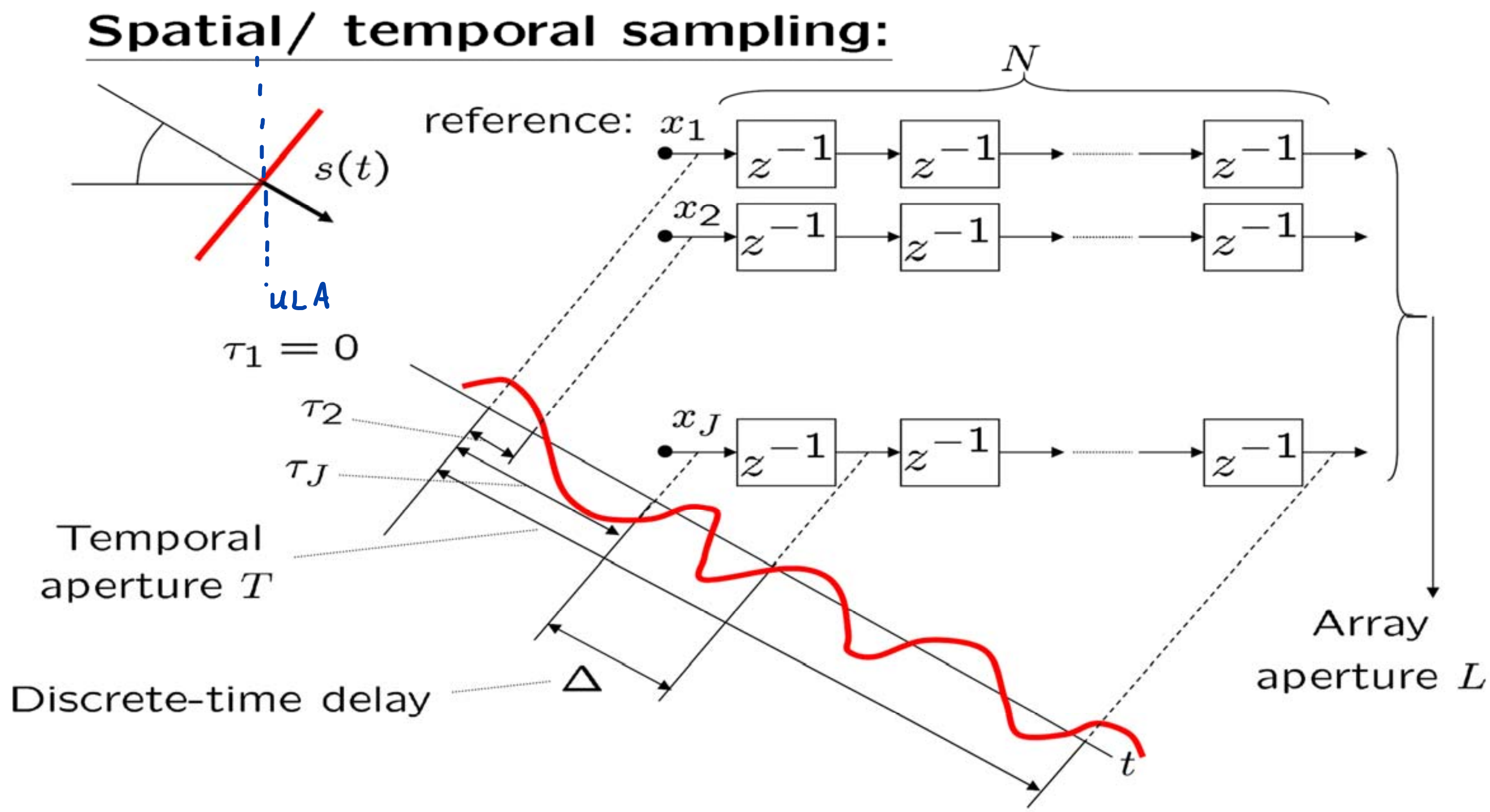
Scenarios



Temporal aperture: $T = \tau_J + (N-1)\Delta$

$= (J-1)\tau_2 + (N-1)\Delta = (J-1)\dfrac{d\sin\theta}{c} + (N-1)\Delta$

Scenarios

Notes:

- Propagating source signal is sampled at $J \cdot N$ nonuniformly spaced points
- Temporal aperture: $T(\theta)$
- Array aperture L: array length in wave length

  For ULA: $L = J \cdot d$ $(J-1)d$
- FIR provide not simple frequency depending weighting of each channel. Weights effect **both** temporal and spatial response

Scenarios

How to cope with broadband signals: