Principle of Communications
--- The Wireless Channel

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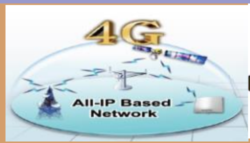
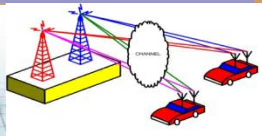
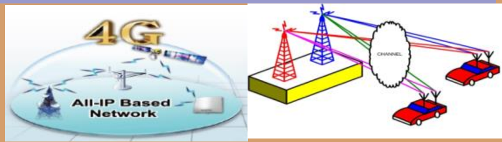




Teaching Contents



I. Why Study Wireless Channels?

- Any w

System

Transmitter (Tx)

Wireless Channel

STOP

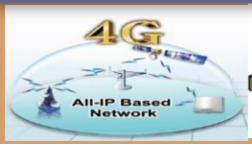
工作中…

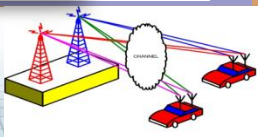
- Tx ar ...en **reliability** and

- **W**

Knowledge of Wireless Channels

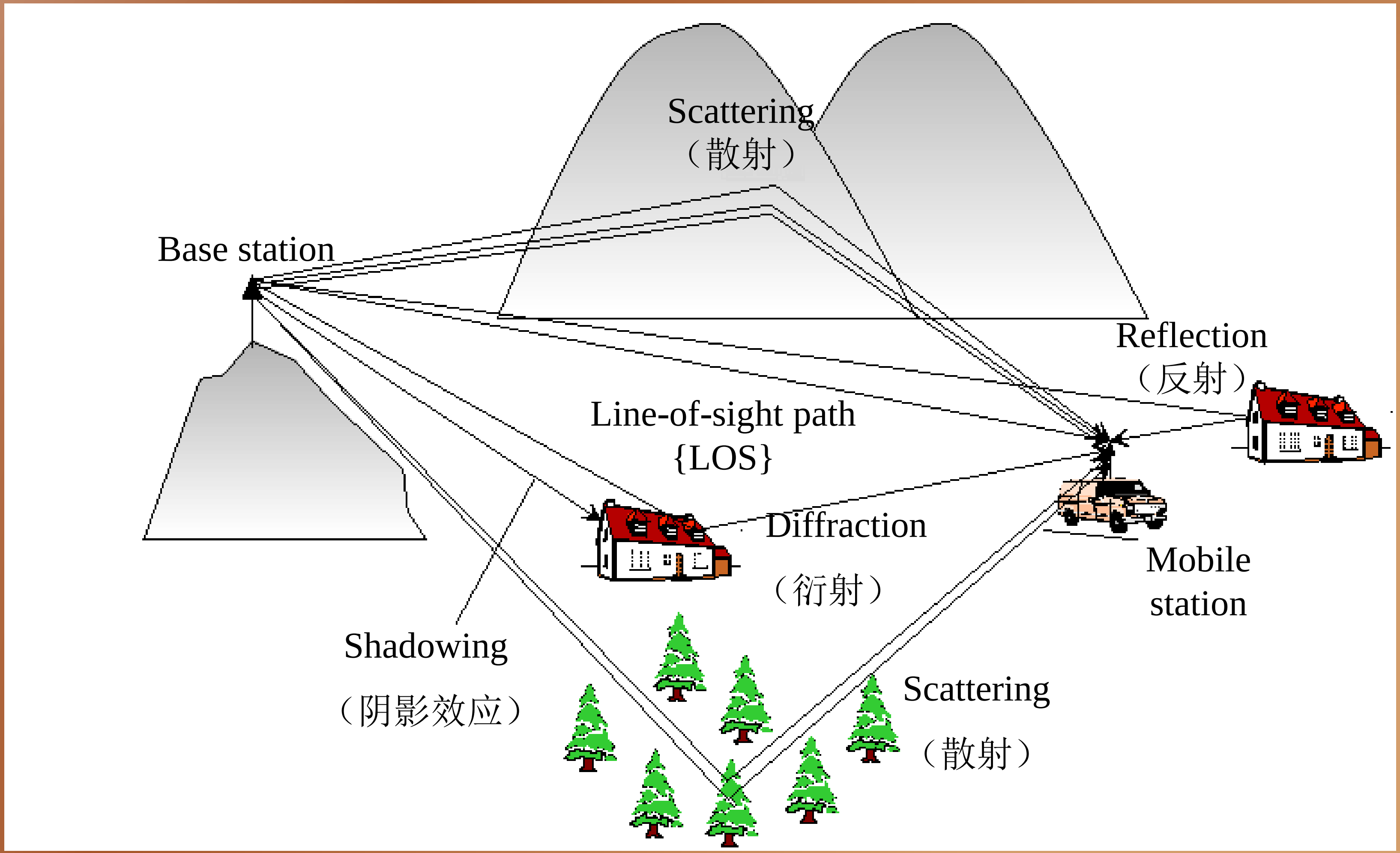
Enabling foundation for successful analysis and design of any wireless system!



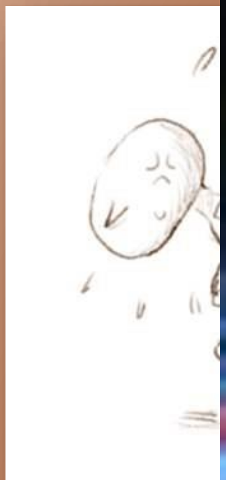


II. What Are Wireless Channels?

- Wireless channels are the **real environments** in which the Tx and Rx are operating.



Common Problems



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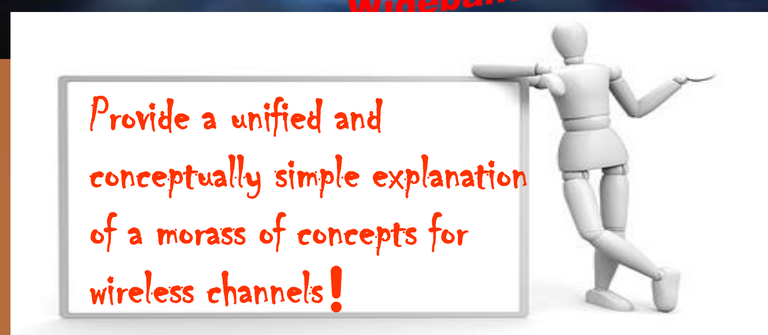

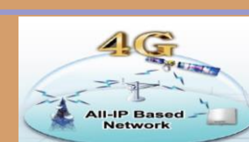

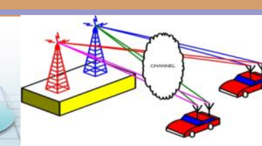

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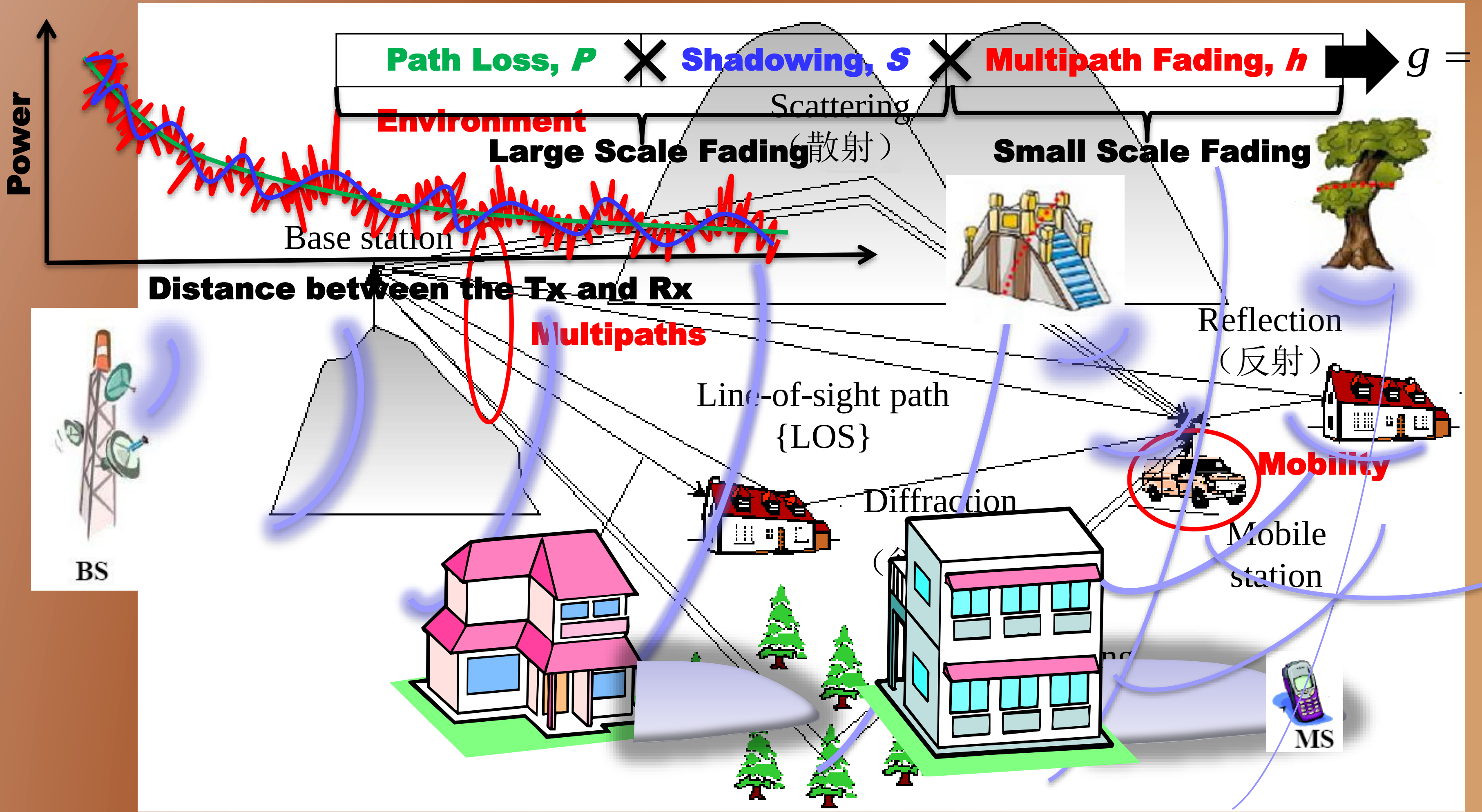
III. Three Phenomena in Wireless Channels

- **Fading**: variation of the received signal power due to the environment, multipaths, and mobility.



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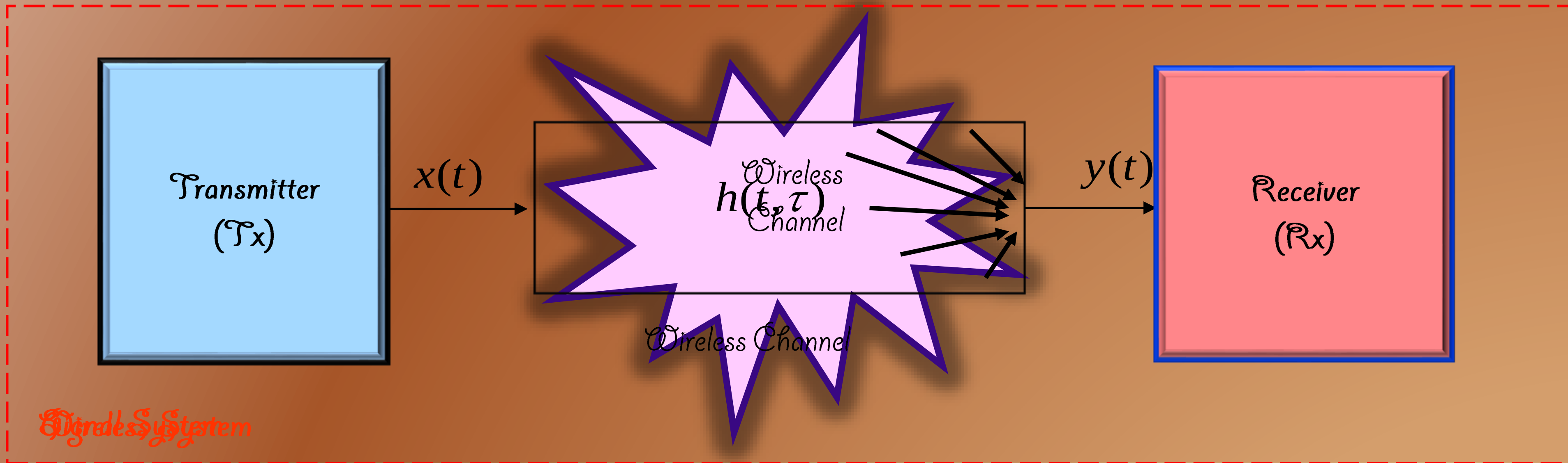
IV. Multipath Fading



$$y(t) = h(t,\tau) \otimes x(t) \qquad y(t) = \sum_n c_n(t) e^{-j\phi_n(t)} x(t - \tau_n(t))$$ **(Linear TV system)**

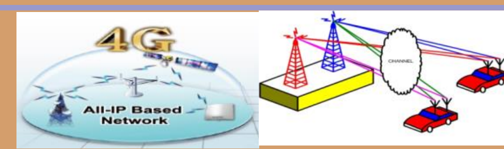
TV channel impulse response

(system function): $h(t,\tau) = \sum_n c_n(t) e^{-j\phi_n(t)} \delta(\tau - \tau_n(t))$

Time-invariant

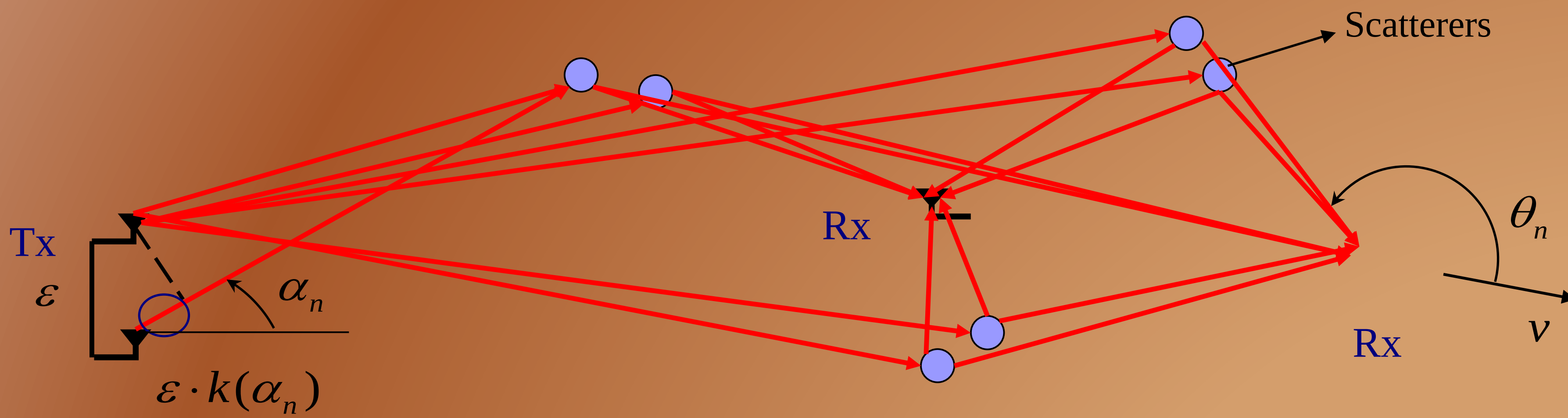
$$h(\tau) = \sum_n c_n e^{-j\phi_n} \delta(\tau - \tau_n)$$

- c_n: amplitude of the nth propagation path.
- τ_n : time delay of the nth propagation.
- ϕ_n : phase of the nth propagation.
- TV: time-varying



Channel Impulse Response

- **Assumption**: The distance between the BS and the MS is sufficiently large so that the radio propagation environment can be modeled as two-dimensional (2-D).



Fixed Rx: / Moving Rx: / Mixed Rx: (multiple antennas)

$$h(t) = \sum_n c_n e^{-j\phi_n} \delta(\tau - \tau_n)$$

$$h(\tau, t) = \sum_n c_n e^{j(2\pi f_D \cos(\theta_n) t - \phi_n)} \delta(\tau - \tau_n(t))$$

$$2\pi f_c \frac{d'_n}{c} \qquad 2\pi f_c \frac{d'_n + d''_n}{c} \qquad 2\pi f_D \cos(\theta_n) t \qquad \lambda^{-1} = \frac{f_c}{c}$$

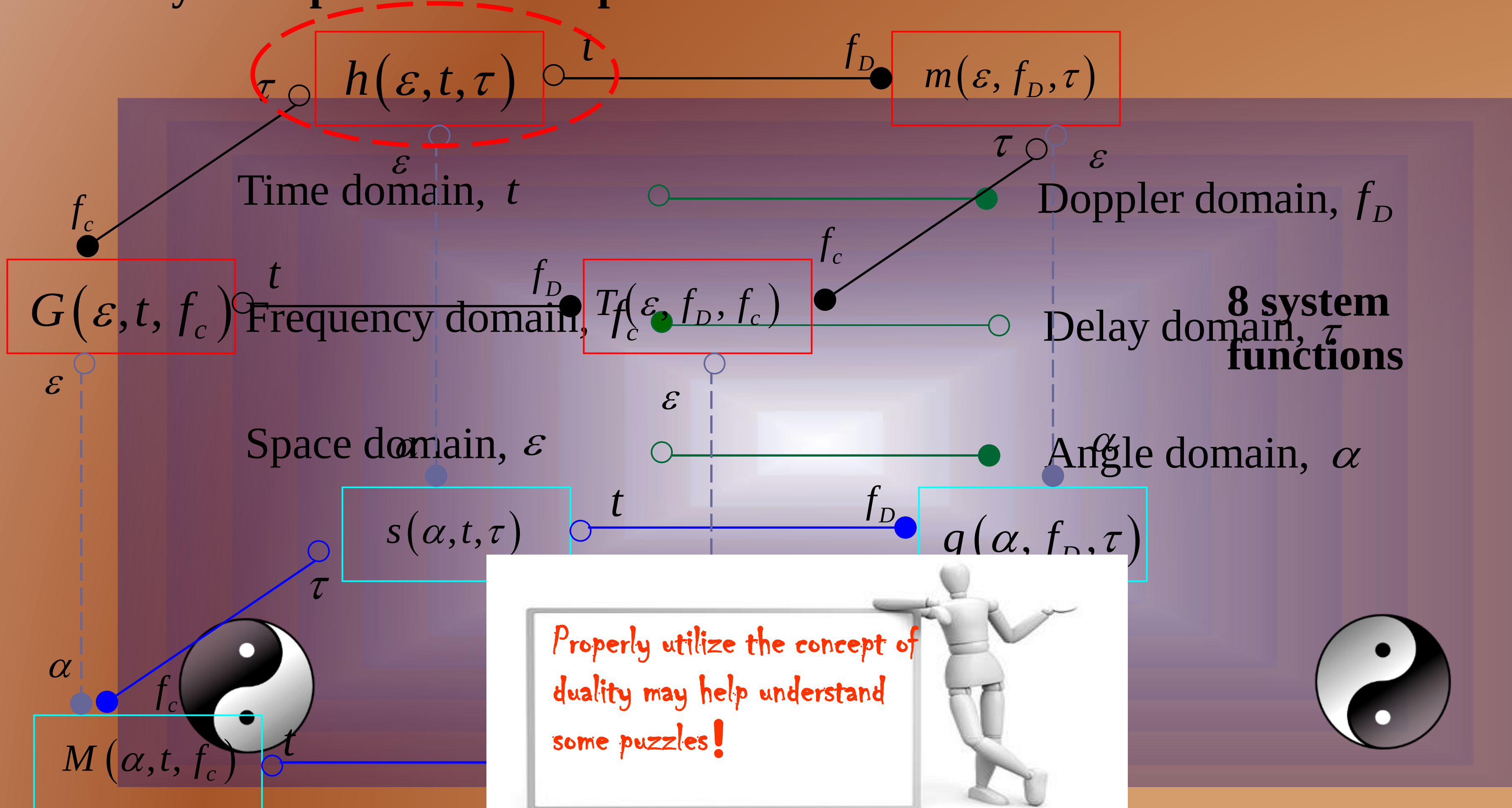
c : speed of light

f_D : Maximum Doppler frequency

Multipath **Motion of the Rx** **Multiple antennas**

Duality of Wireless Channels

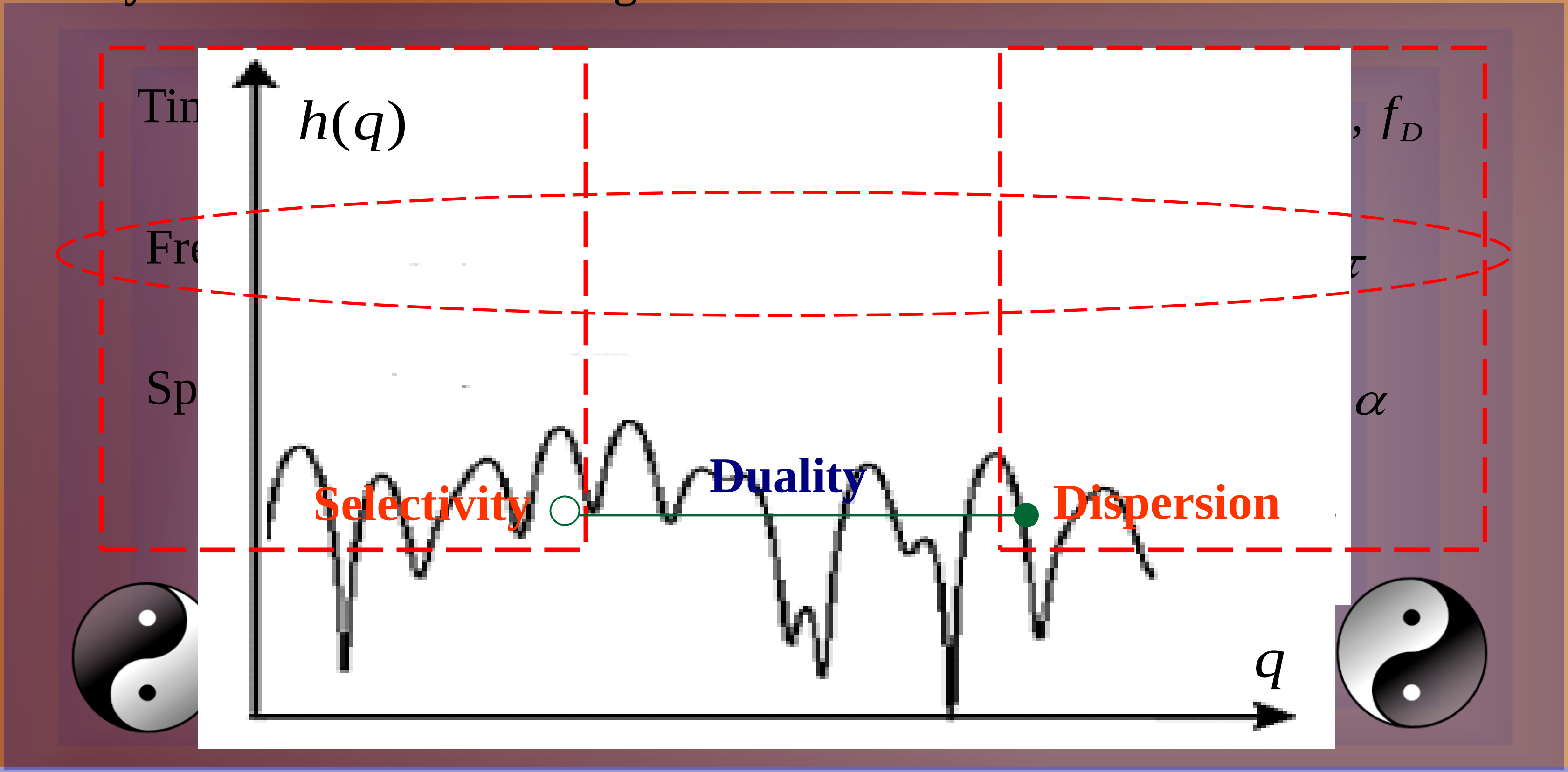
- **Duality: to express the same phenomena in different domains.**



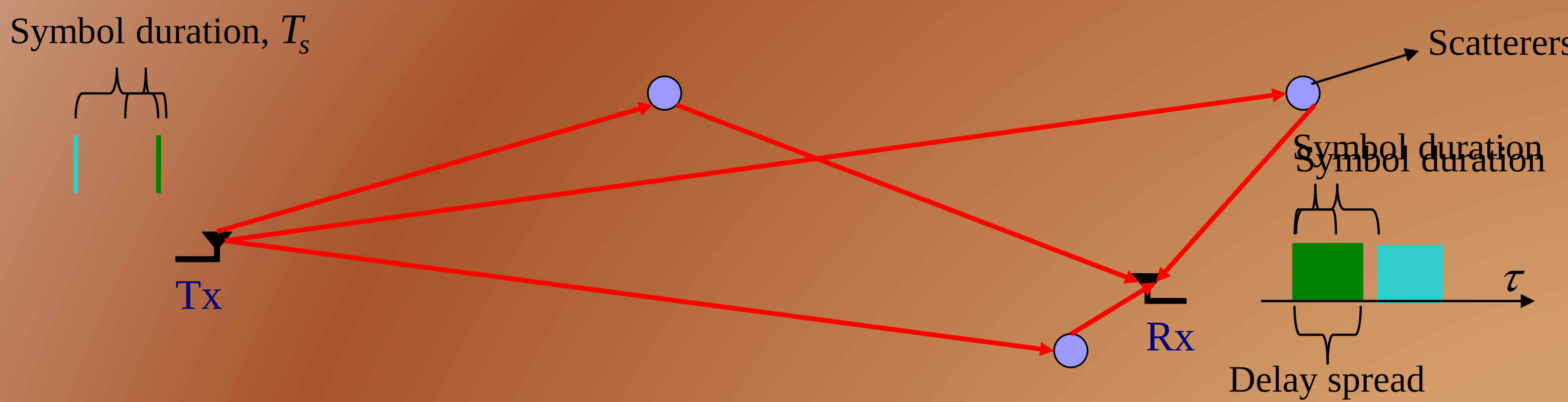
Dispersion and Seclectivity of Wireless Channels

- **Dispersion:** spread effect of wireless channels, which means that wireless channels spread the transmitted signal in a certain domain**.**

- **Selectivity:** wireless channel changes over a certain domain.



Delay Dispersion



- **Delay dispersion:** multipaths with different time delays lead to the spread of the transmitted signal.
  - **Measured by delay spread,** De_s**,** $De_s := \max\left|\tau_i - \tau_j\right|.$

Impulse response: $h(\tau) = \sum_n c_n e^{-j2\pi f_c \frac{d'_n}{c}} \delta(\tau - \tau_n)$

$T_s > De_s$	No inter-symbol interference (ISI)	Narrowband (frequency non-selective) channels
$T_s <= De_s$	Inter-symbol interference (ISI)	Wideband (frequency selective) channels

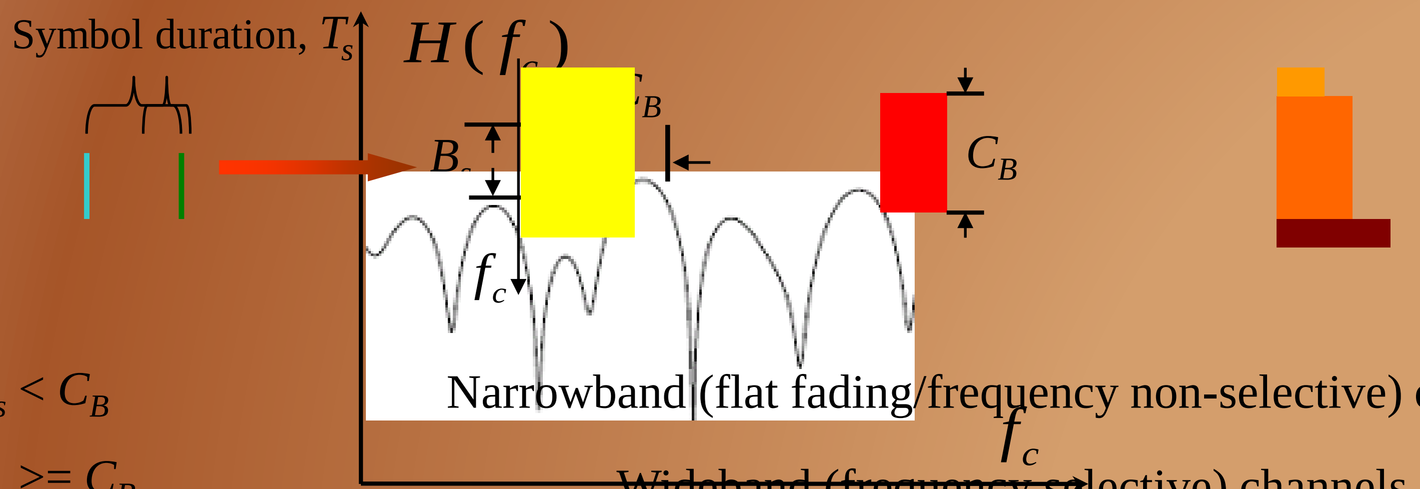
Frequency Seclectivity

$$h(\tau)=\sum_n c_n e^{-j2\pi f_c \frac{d_n'}{c}}\delta(\tau-\tau_n) \xrightarrow[\tau]{\text{Fourier transform}} H(f_c)=\sum_n c_n e^{-j2\pi f_c \frac{d_n'}{c}} e^{-j2\pi f_c \tau_n}$$

Impulse response

Transfer function

- **Frequency selectivity:** channel changes over frequency.
  - **Measured by coherence bandwidth, C_B: the bandwidth over which channels express similar characteristic.**



$B_s < C_B$ Narrowband (flat fading/frequency non-selective) channels

$B_s >= C_B$ Wideband (frequency selective) channels

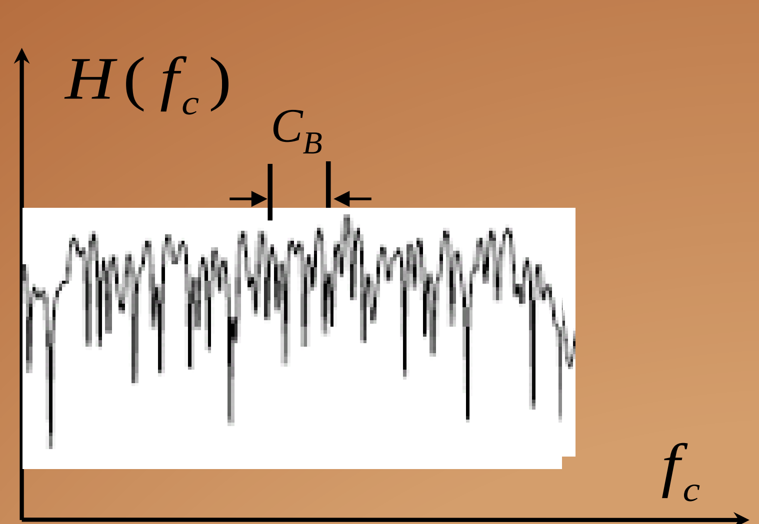
Delay Dispersion-Frequency Selectivy Duality

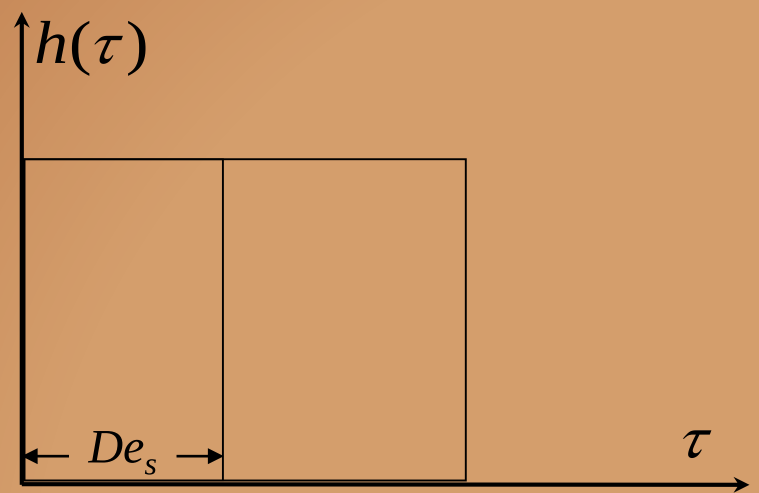
Transfer function $$H(f_c) = \sum_n c_n e^{-j2\pi f_c \frac{d'_n}{c}} e^{-j2\pi f_c \tau_n}$$

τ_n $\xrightarrow{\text{FD}}$ **Fluctuation**

DD $\downarrow$ FD: frequency domain, DD: Delay domain $\downarrow$ FD

De_s $\xleftrightarrow{\textbf{Reciprocal}}$ C_B





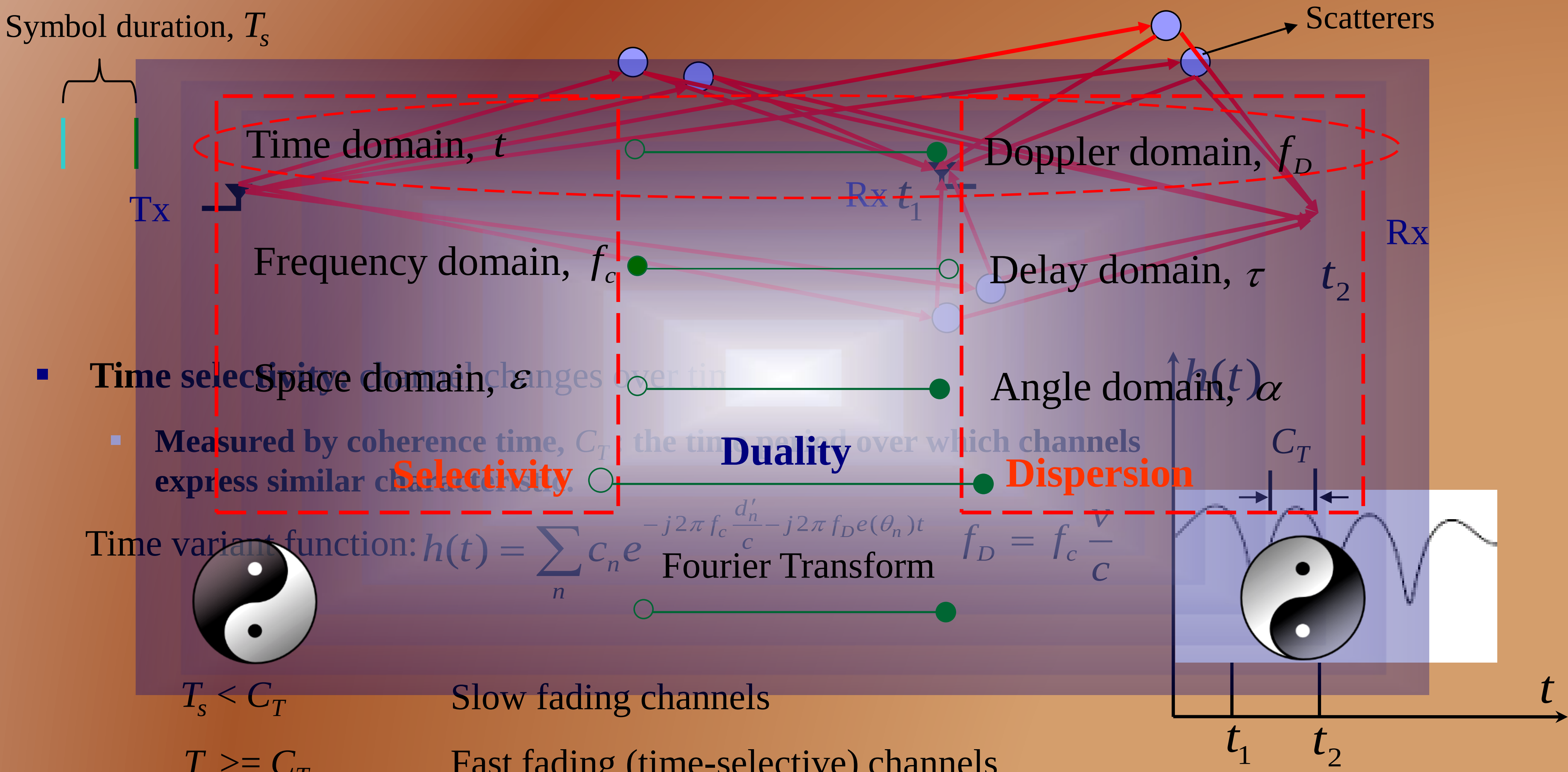
- A wireless channel with higher De_s (lower C_B) is easier to be a wideband channel.
- A wireless system with higher transmission rate (higher signal wideband) is easier to incur wideband channels.

Time Selectivity

- **Time selectivity: channel changes over time**
  - **Measured by coherence time, C_T: the time period over which channels express similar characteristic.**

Symbol duration, T_s

Time variant function: $h(t) = \sum_n c_n e^{-j2\pi f_c \frac{d'_n}{c} - j2\pi f_D e(\theta_n) t}$ $\quad f_D = f_c \frac{v}{c}$



$T_s < C_T$	Slow fading channels
$T_s >= C_T$	Fast fading (time-selective) channels

Time domain, t — Doppler domain, f_D

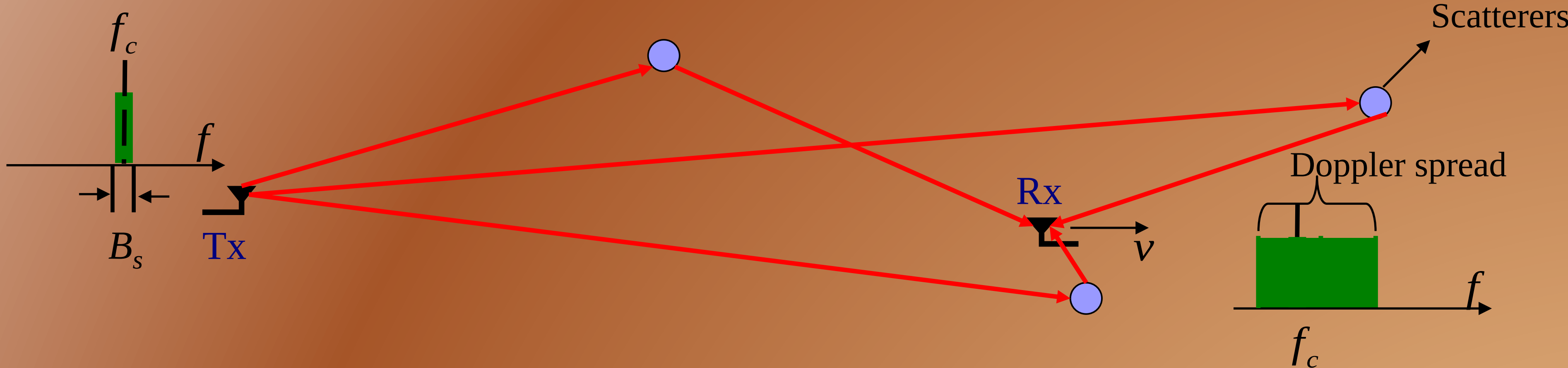
Frequency domain, f_c — Delay domain, τ

Space domain, ε — Angle domain, α

Selectivity — Duality — Dispersion

Fourier Transform

Doppler Dispersion



- **Doppler dispersion:** the motion of the Rx results in a broadening of the transmitted signal spectrum.
  - **Measured by Doppler spread,** D_s**,** $D_s := \max \left| f_D \cdot e(\theta_i) - f_D \cdot e(\theta_j) \right|$.

$$h(t) = \sum_n c_n e^{-j2\pi f_c \frac{d'_n}{c} - j2\pi f_D e(\theta_n) t} \xrightarrow[t]{\text{Inverse Fourier transform}} T(f_D) = \sum_n c_n e^{-j2\pi f_c \frac{d'_n}{c}} \delta\left(f_D - f_D^n \right)$$

$B_s > D_s$	Slow fading channels
$B_s <= D_s$	Fast fading (time-selective) channels

Doppler Dispersion-Time Selectivy Duality

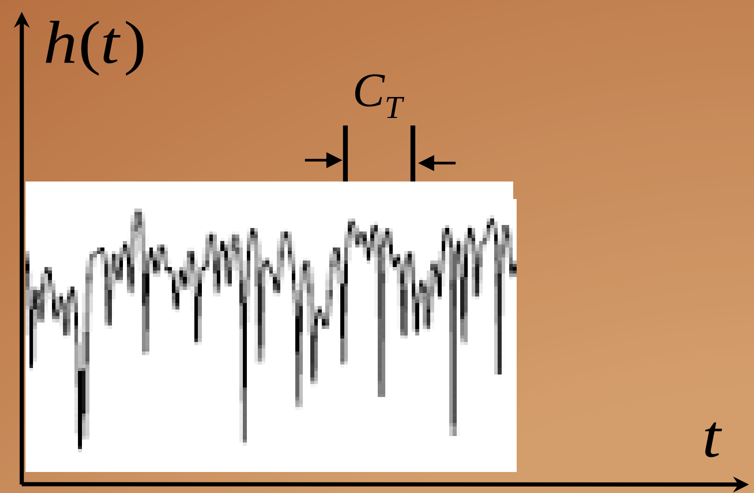
Time variant function $h(t) = \sum_n c_n e^{-j2\pi f_c \frac{d'_n}{c} - j2\pi f_D e(\theta_n)t}$

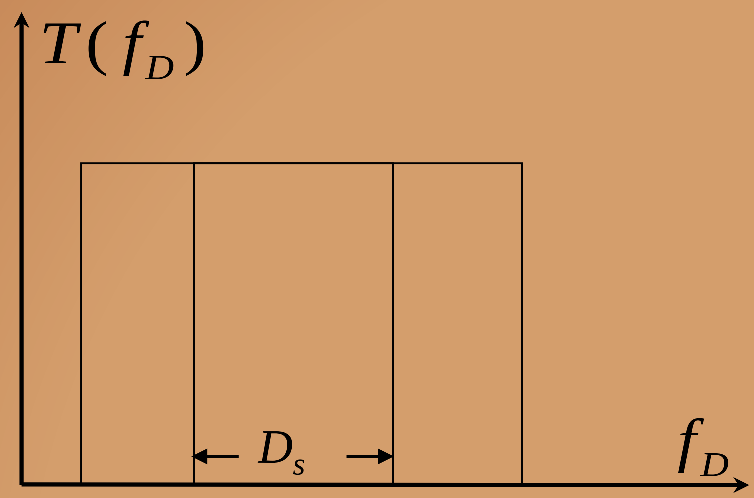
$$f_D = f_c \frac{v}{c}$$

$$\begin{tikzcd}
f_D \cdot e(\theta_n) \arrow[r, "\text{TD}"] \arrow[d, "\text{DD}"'] & \textbf{Fluctuation} \arrow[d, "\text{TD}"] \\
D_s \arrow[r, leftrightarrow, "\textbf{Reciprocal}"] & C_T
\end{tikzcd}$$

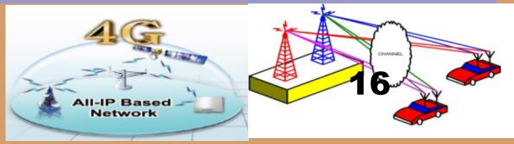
TD: time domain

DD: Doppler domain

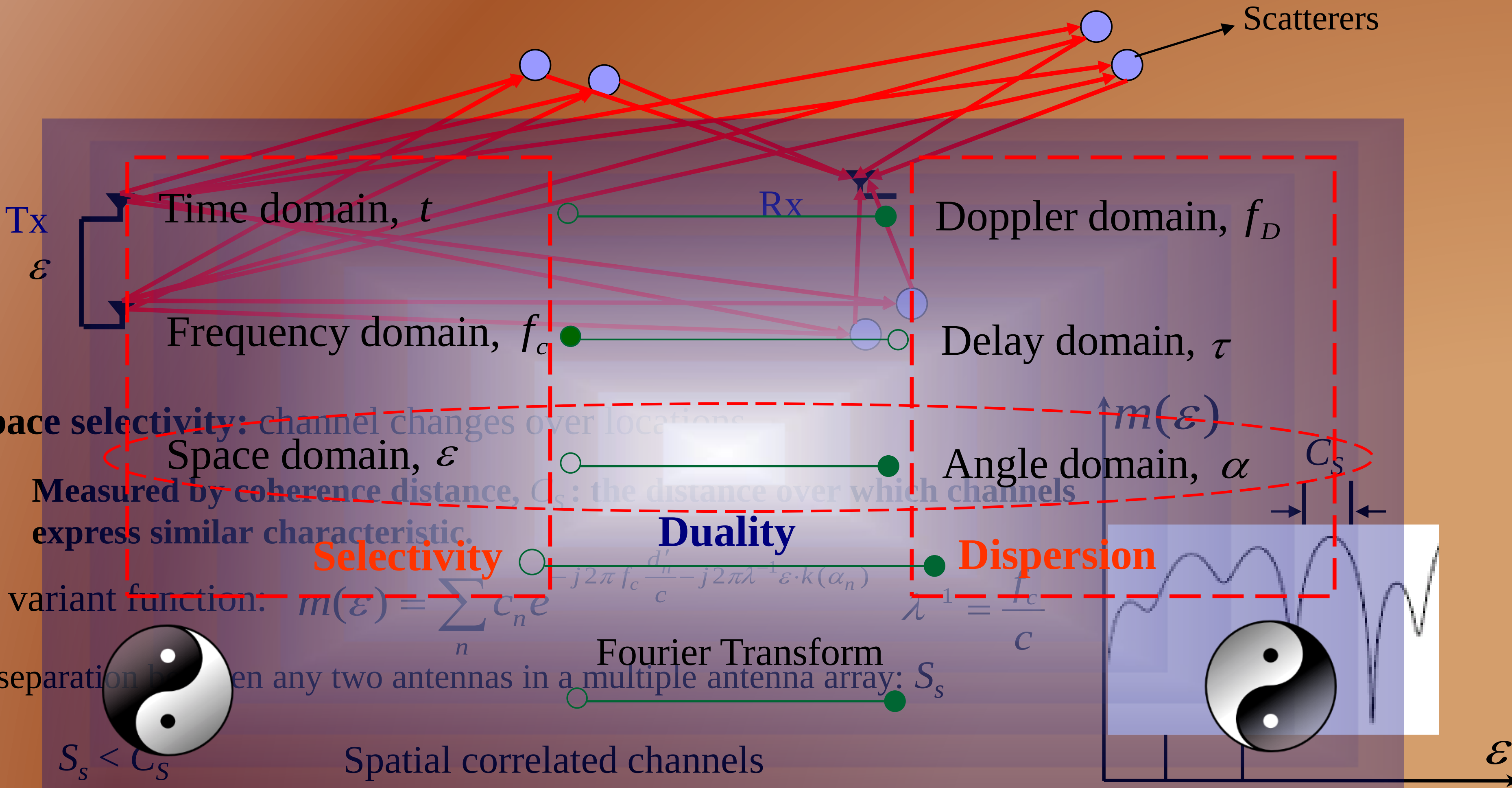




- A wireless channel with higher D_s (lower C_T) is easier to be a fast fading channel.
- A wireless system with higher transmission rate (higher signal wideband) is easier to incur slow fading channels.



Space Selectivity



- **Space selectivity:** channel changes over locations
  - **Measured by coherence distance, C_S : the distance over which channels express similar characteristic.**

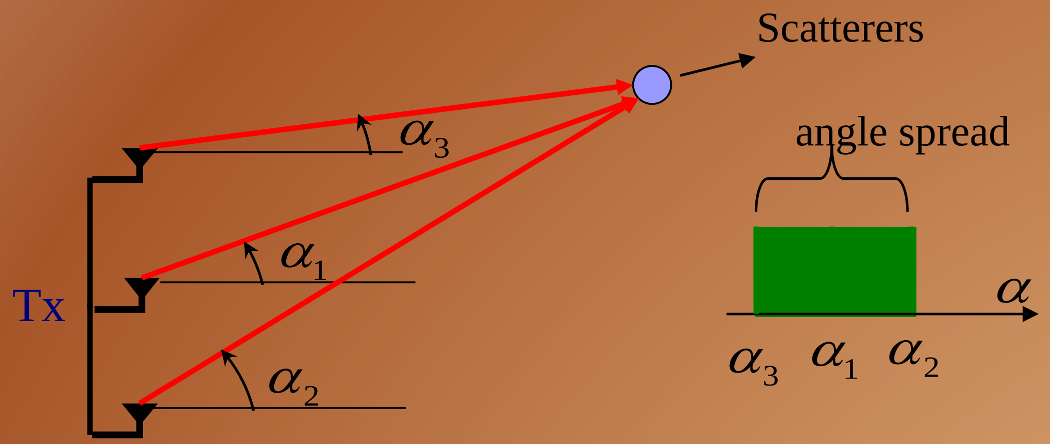
Space variant function: $m(\varepsilon)=\sum_n c_n e^{-j2\pi f_c \frac{d'_n}{c} - j2\pi\lambda^{-1}\varepsilon\cdot k(\alpha_n)}$ $\lambda^{-1}=\frac{f_c}{c}$

Space separation between any two antennas in a multiple antenna array: S_s

$S_s < C_S$ Spatial correlated channels

$S_s >= C_S$ Spatial uncorrelated channels

Angle Dispersion



- **Angle dispersion:** multiple antennas lead to the spread of the transmitted signal in angle domain.
  - **Measured by angle spread,** A_s**,** $A_s := \max\left|\alpha_i' - \alpha_j'\right|$.

$$m(\varepsilon) = \sum_n c_n e^{-j2\pi f_c \frac{d_n'}{c} - j2\pi\lambda^{-1}\varepsilon\cdot k(\alpha_n)} \xrightarrow[\varepsilon]{\text{Inverse Fourier transform}} M(\alpha) = \sum_n c_n e^{-j2\pi f_c \frac{d_n'}{c}} \delta\left(\alpha - \alpha_n'\right)$$

- **Angle dispersion also relates to the pattern of multiple antenna arrays!**

Angle Dispersion-Distance Selectivy Duality

Time variant function $m(\varepsilon)=\sum_n c_n e^{-j2\pi f_c \frac{d'_n}{c}-j2\pi\lambda^{-1}\varepsilon\cdot k(\alpha_n)}$

$$\lambda^{-1}=\frac{f_c}{c}$$

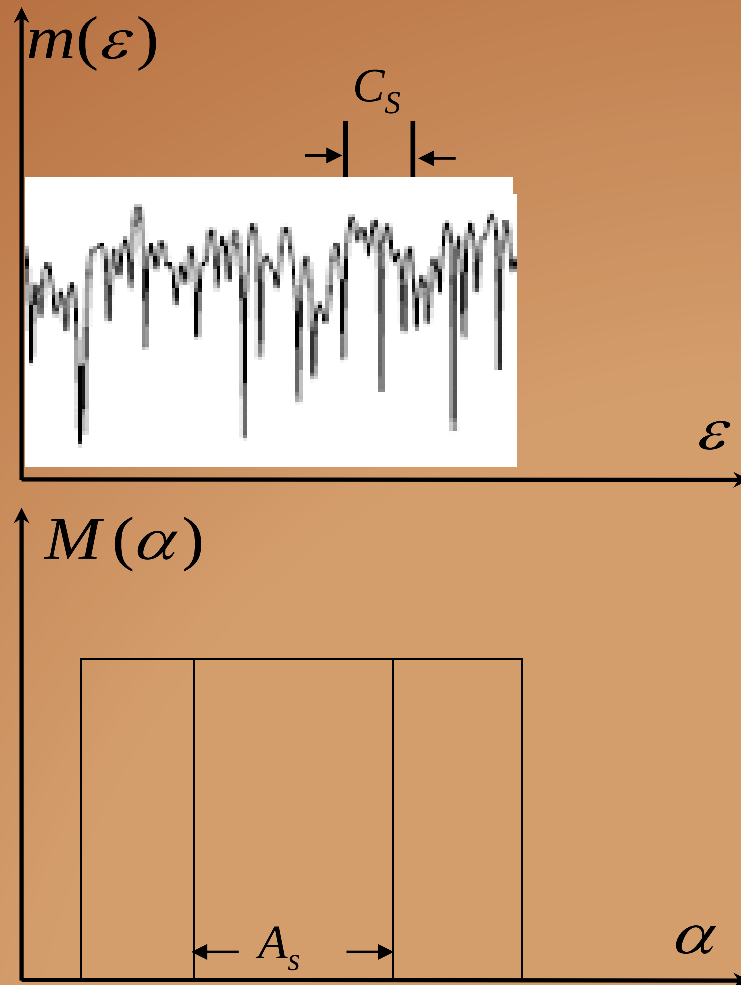
$$\alpha_n \xrightarrow{\text{SD}} \textbf{Fluctuation}$$

AD $\downarrow$ $\qquad$ $\downarrow$ SD

SD: space domain

AD: Angle domain

$$A_s \xleftrightarrow{\textbf{Reciprocal}} C_S$$



- A wireless channel with higher A_s (lower C_S) is easier to be a spatial uncorrelated channel.
- A multiple antenna wireless system with larger antenna spacing is easier to incur spatial uncorrelated channels.

V. Main Plot

Delay domain **Frequency domain**
Doppler domain **Time domain**
Angle domain **Space domain**

Fading → Large-scale fading (cell-cite plan): Path loss; Shadowing

Fading → Small-scale fading (system design)

8 system functions → Small-scale fading (system design)

Small-scale fading → Dispersion; Selectivity

Dispersion — Duality — Selectivity

Delay dispersion — Duality — Frequency selectivity

Doppler dispersion — Duality — Time selectivity

Angle dispersion — Duality — Space selectivity

De_s — Reciprocal — C_B

D_s — Reciprocal — C_T

A_s — Reciprocal — C_S

T_s — Reciprocal — B_s

B_s — Reciprocal — T_s

S_s

$<$ Narrowband channel $<$

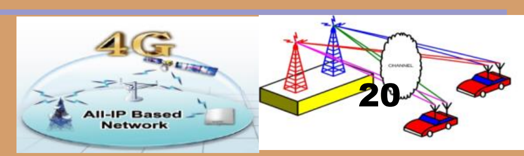
$\geq$ Wideband channel $\geq$

$<$ Slow fading channel $<$

$\geq$ Fast fading channel $\geq$

Spatial uncorrelated channel $>$

Spatial correlated channel $\leq$



Thank you for your attention!

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