114-1 電工實驗（通信專題）

OFDM

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Review

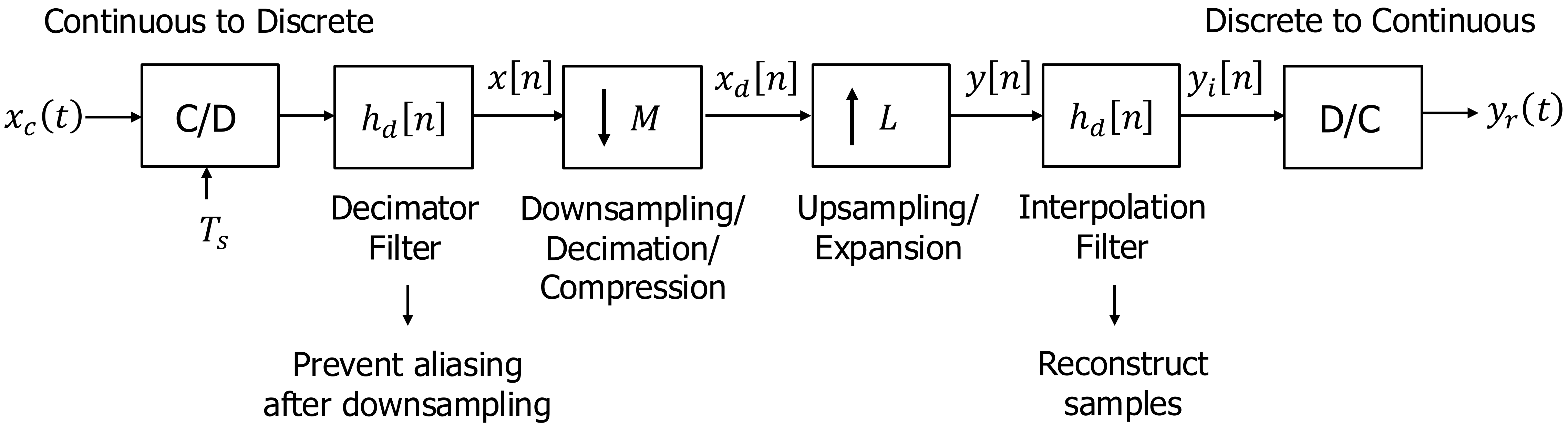
Up/Down-Sampling

Filtering

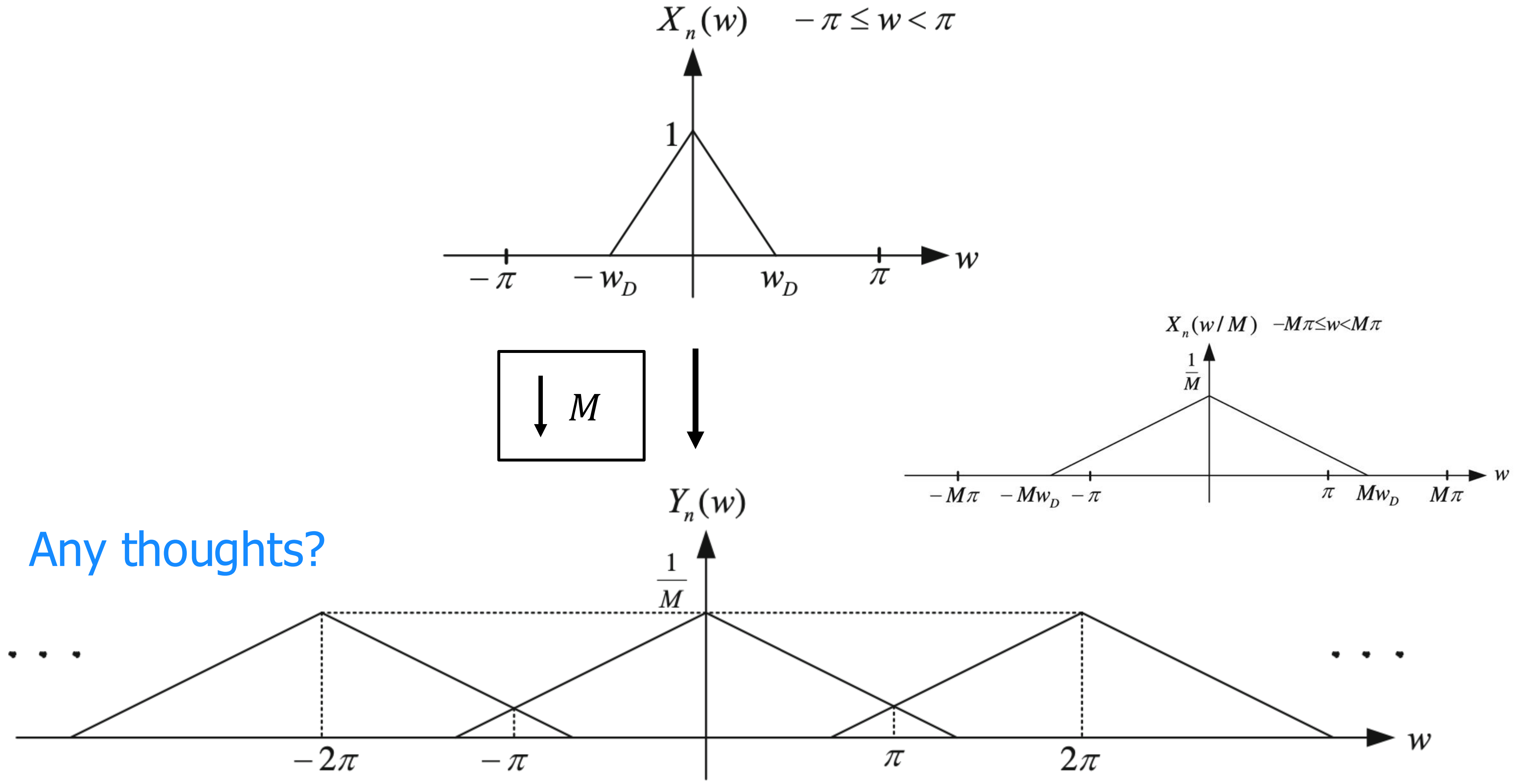
Up/Down-Sampling

Why change sampling frequency?

Compatibility between different devices

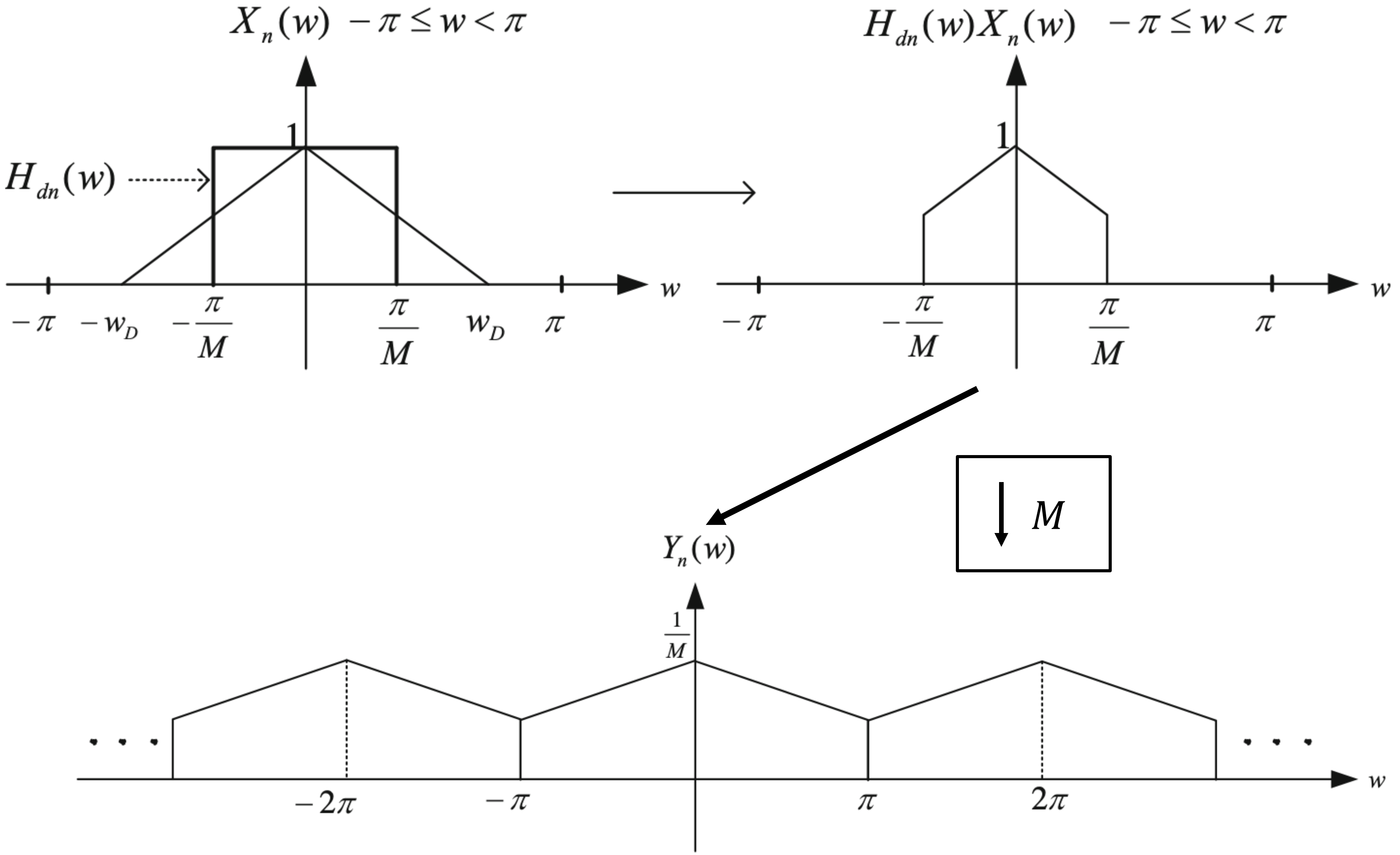


Aliasing in Downsampling

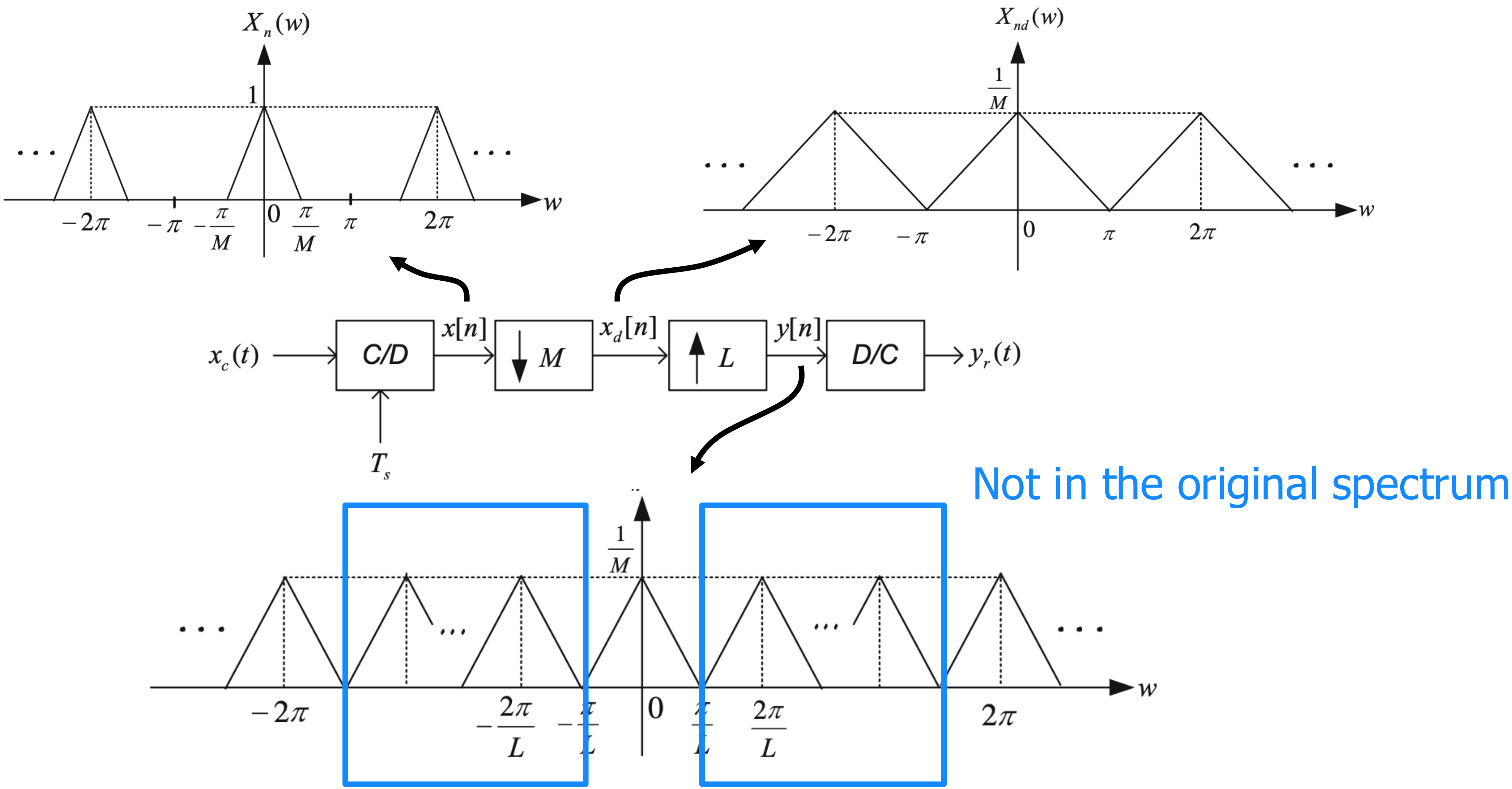


Any thoughts?

Prevent Aliasing: Lowpass filter before downsampling

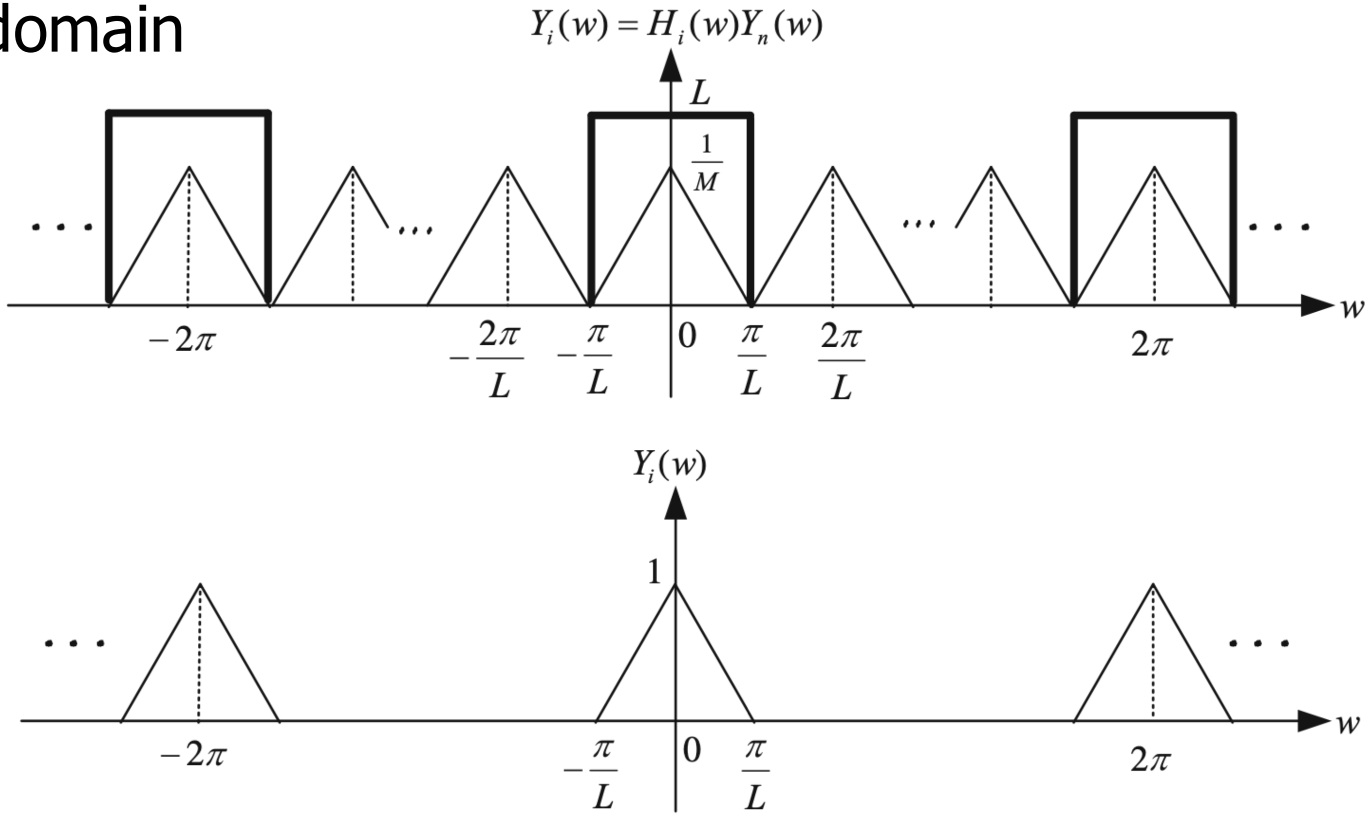


Upsampling: From Frequency Domain Perspective



Signal Reconstruction for Upsampling

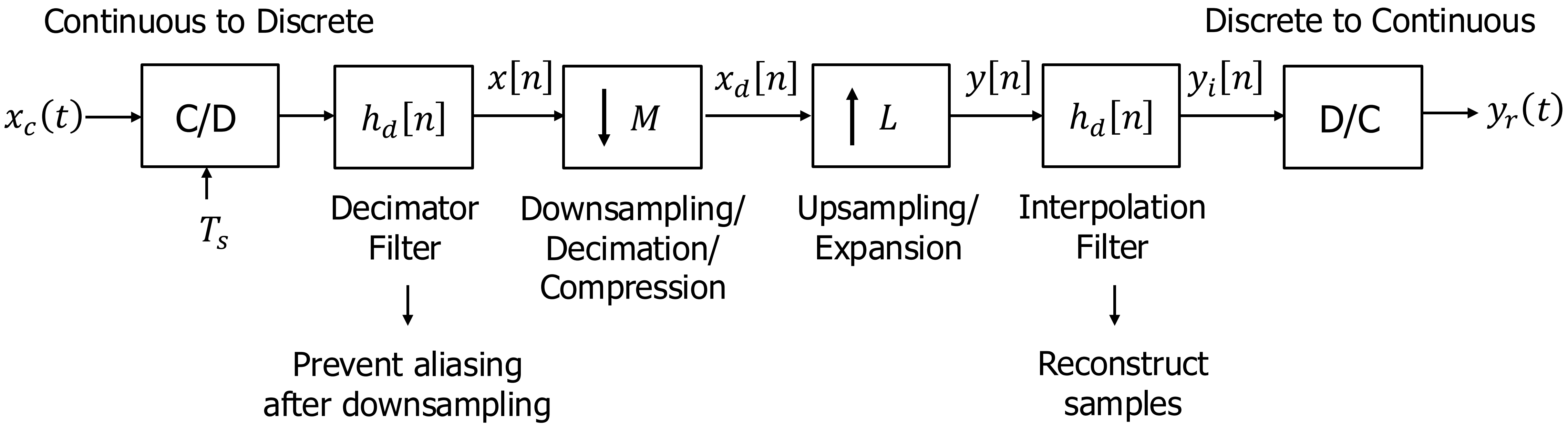
Filter from the frequency domain



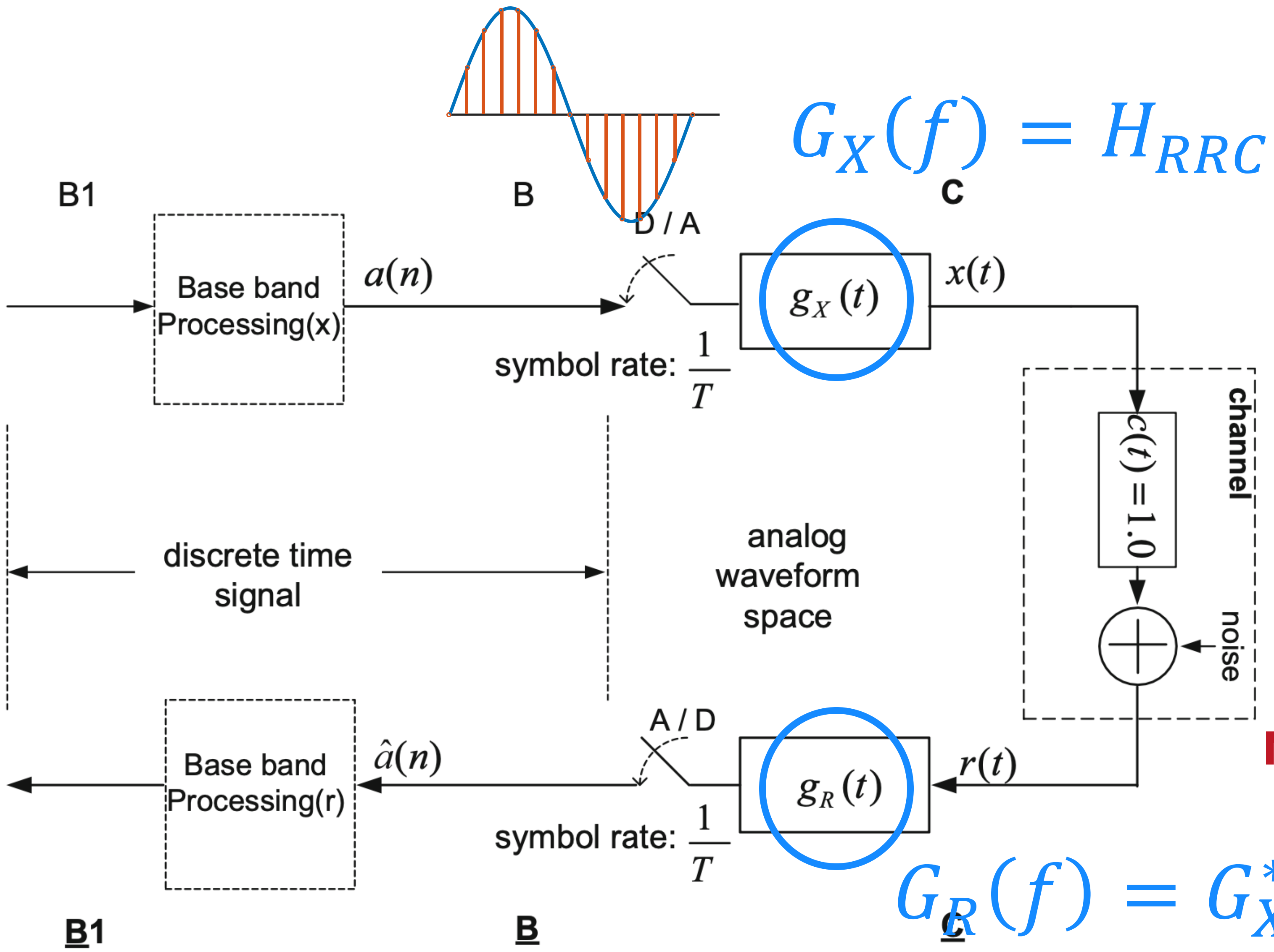
Up/Down-Sampling

Why change sampling frequency?

Compatibility between different devices



How to select the transmit and receive filter pair?



$$G_X(f) = H_{RRC}(f)$$

Band Limited

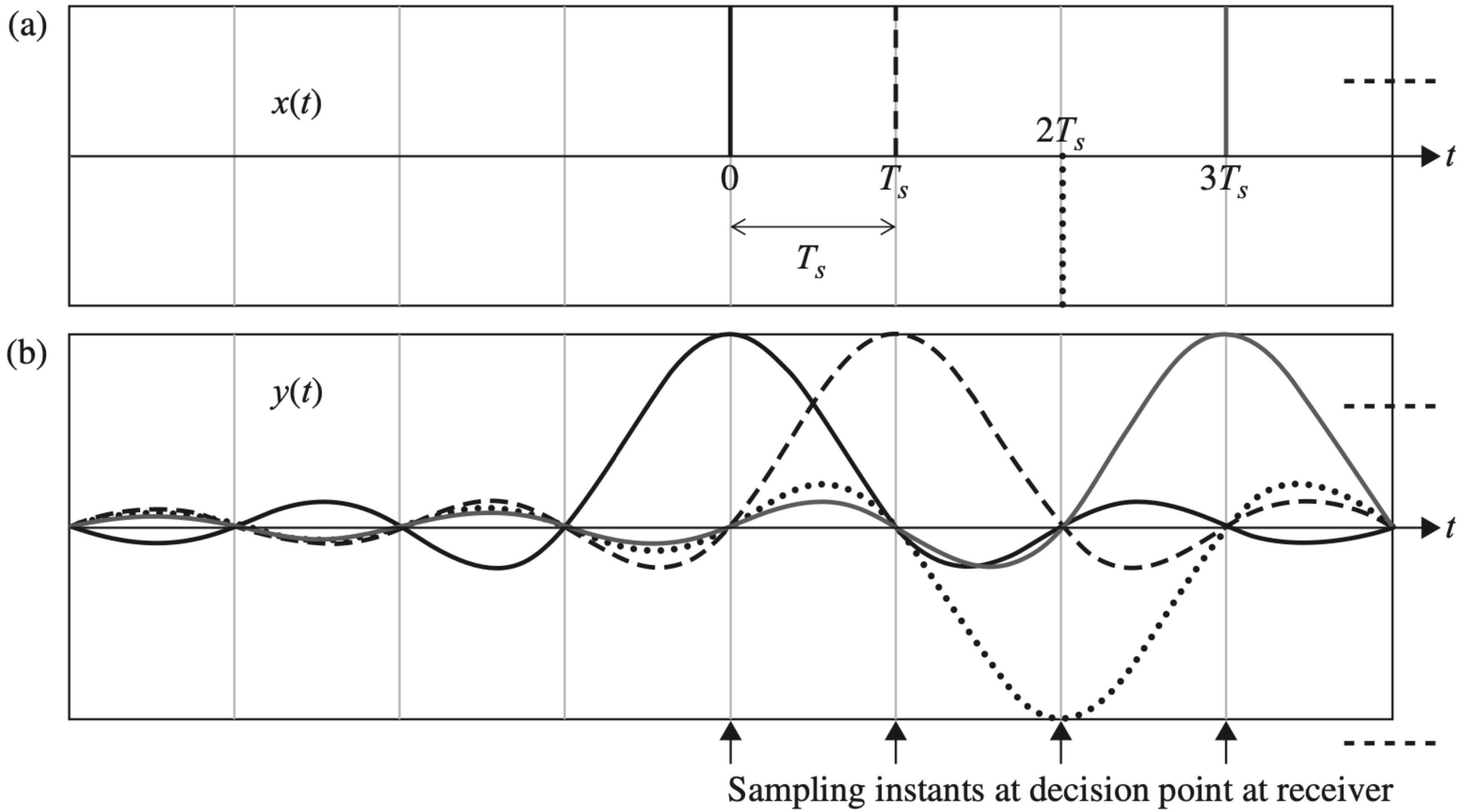
Select g_X and g_R

$$G_R(f) = G_X^*(f)$$

Achieve good SNR → **Matched Filter**

Avoid inter-symbol interference → **Nyquist criterion**

Nyquist Criterion for Zero ISI – Time Domain



All other symbols happen to be zero

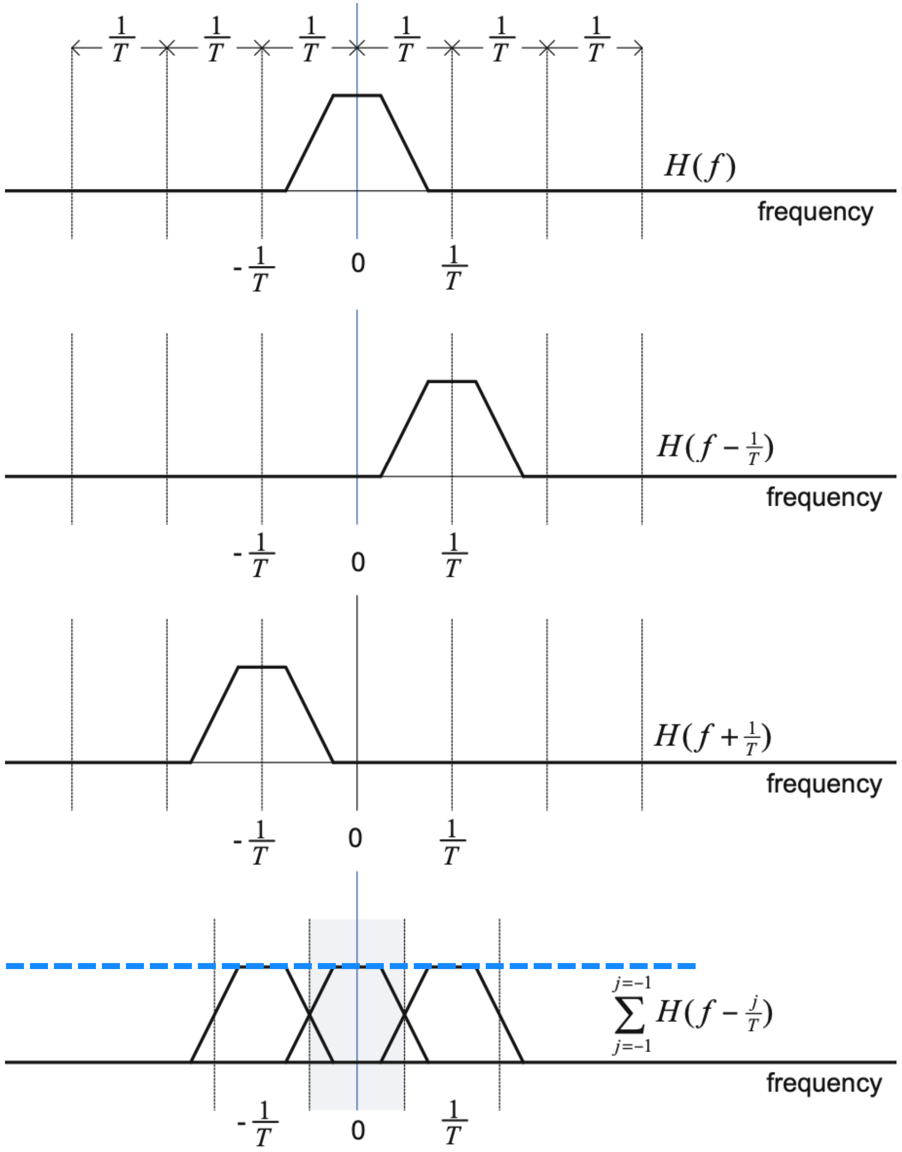
Frequency Domain Expression of Nyquist Criterion

$$\sum_{k=-\infty}^{+\infty} H\left(f - \frac{k}{T}\right) = T$$

The sum of all periodic repetitions of H is a constant

A lowpass satisfying this condition is also called a Nyquist lowpass

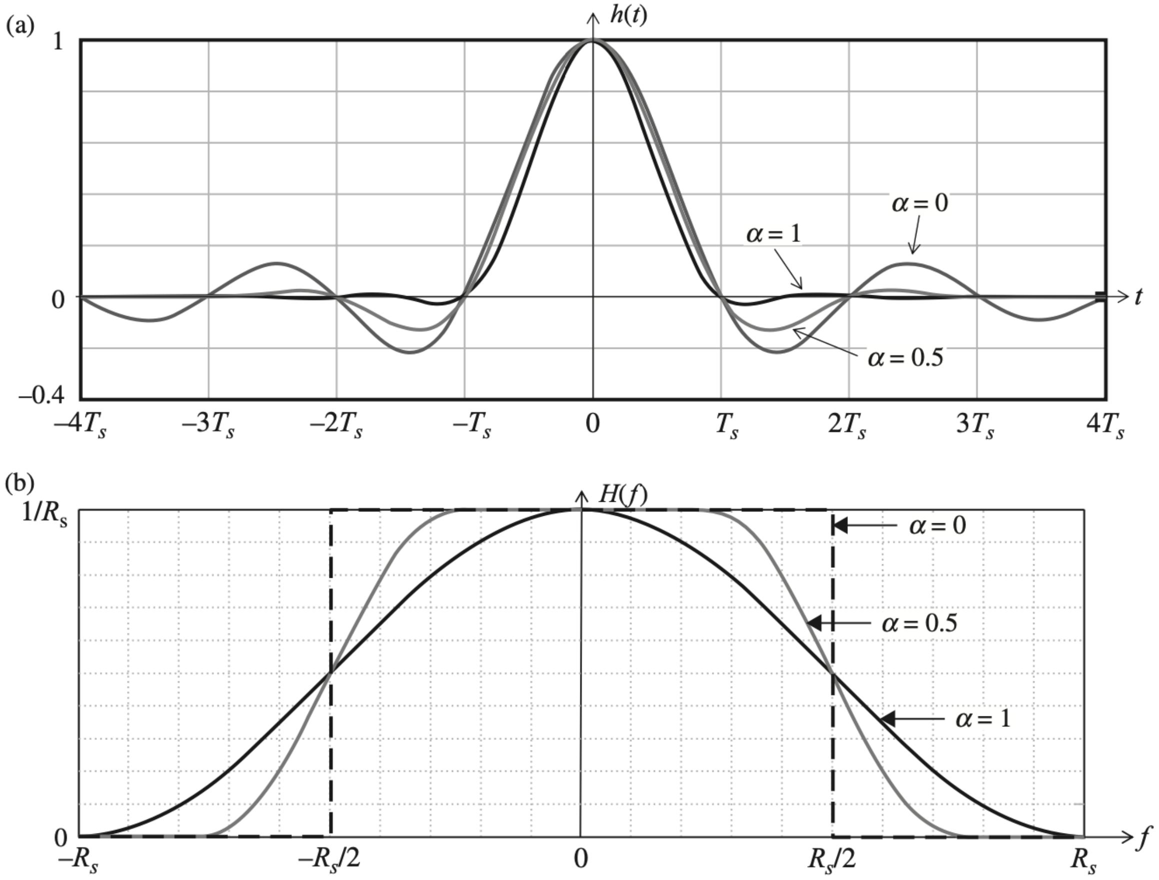
邑恒：在 Digital communications by John G. Proakis 第五版中的 605 頁有提供完整的推導。這本書在 Lab 331 中有，應該可以提供給同學做參考。



Raised Cosine Filtering

$$H(f) = \frac{1}{R_s} \times \begin{cases} 1, & |f| \le f_1 \\ \frac{1}{2}\left[1 + \cos\left(\pi \frac{|f| - f_1}{f_2 - f_1}\right)\right], & f_1 \le |f| \le f_2 \\ 0, & |f| \ge f_2 \end{cases}$$

$$f_1 = (1-\alpha)R_s/2;\ f_2 = (1+\alpha)R_s/2;\ 0 \le \alpha \le 1$$



α: roll-off factor

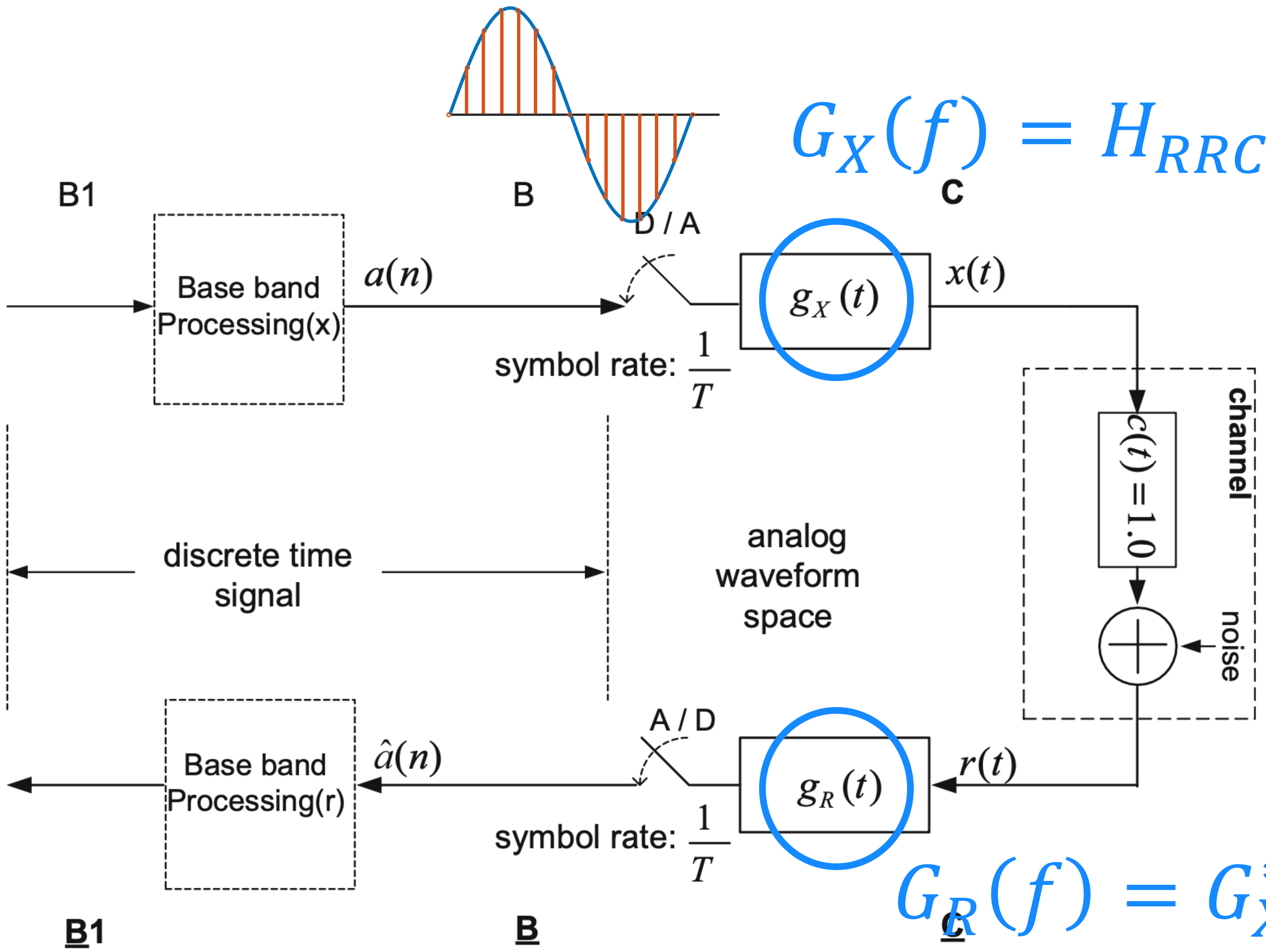
gradual roll-off makes the raised cosine filter characteristic easier to approximate than the ideal Nyquist filter

$\alpha = 0$: Nyquist Filtering

Does it satisfy the Nyquist Criterion?

Yes!

How to select the transmit and receive filter pair?



$$G_X(f) = H_{RRC}(f)$$

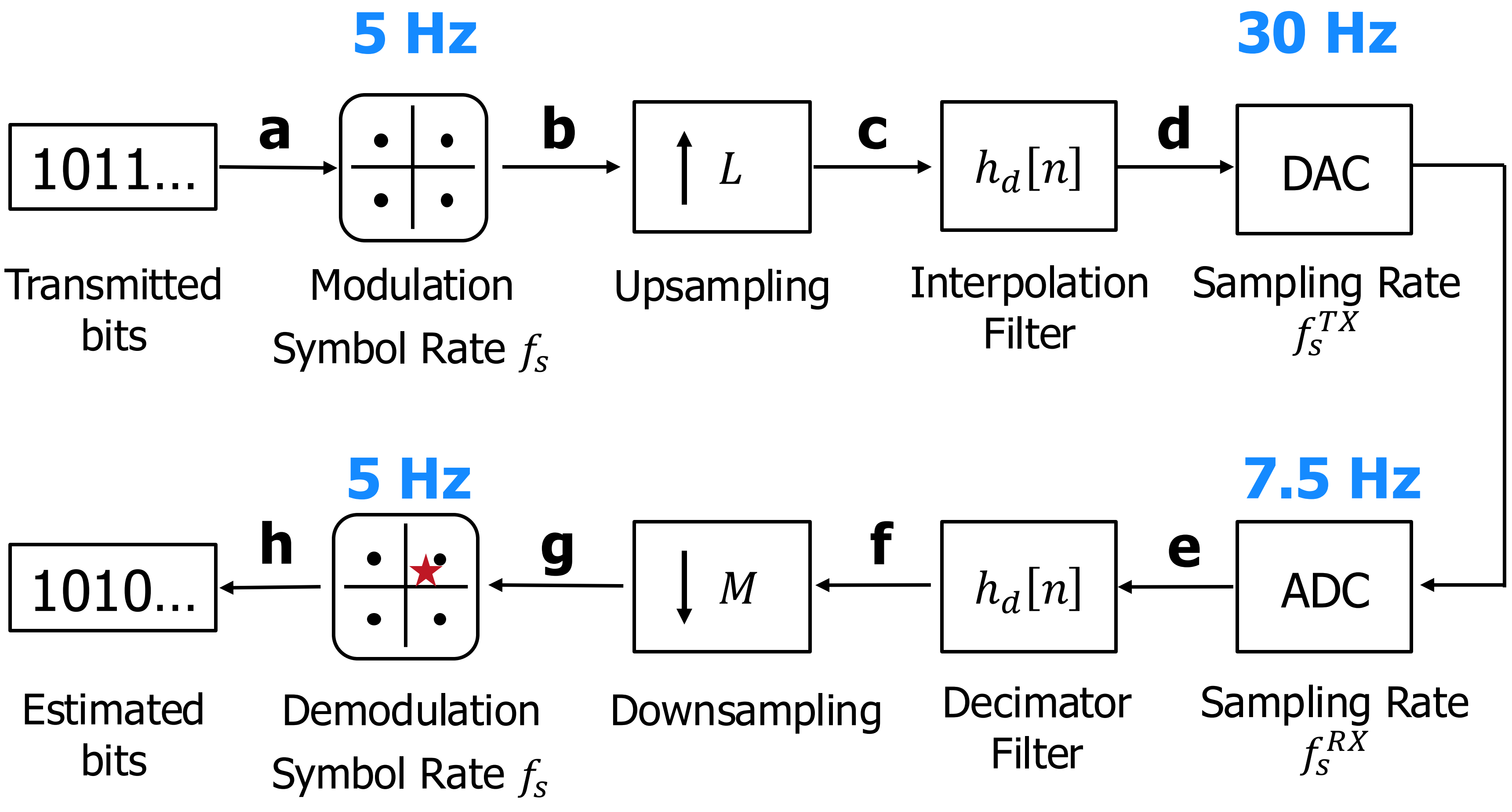
Band Limited

Select g_X and g_R

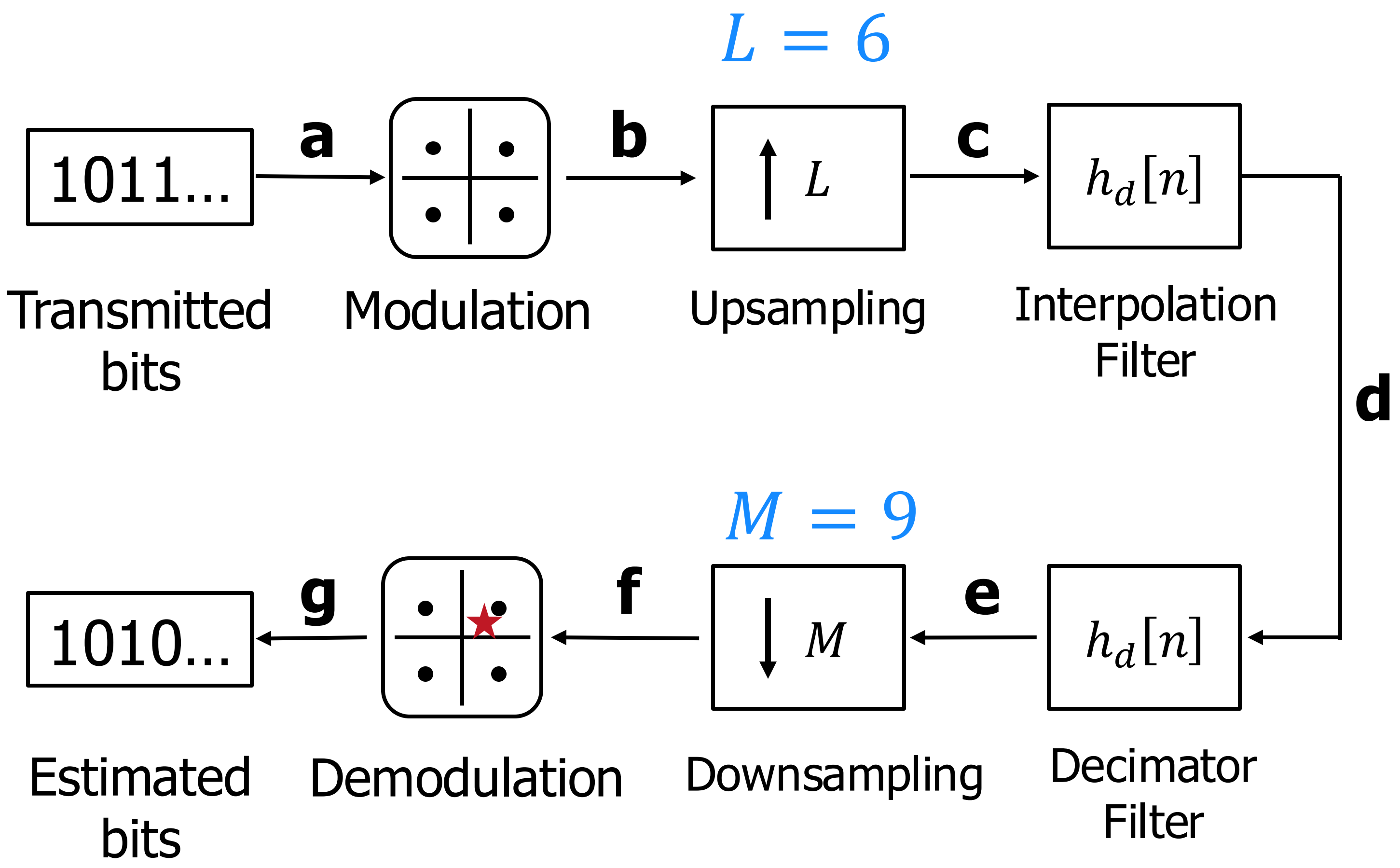
$$G_R(f) = G_X^*(f)$$

Achieve good SNR	Avoid inter-symbol interference
Matched Filter	**Nyquist criterion**

Lab 2 – Part 1 (Sampling rate adaptation)



Lab 2 – Part 2 (Aliasing)



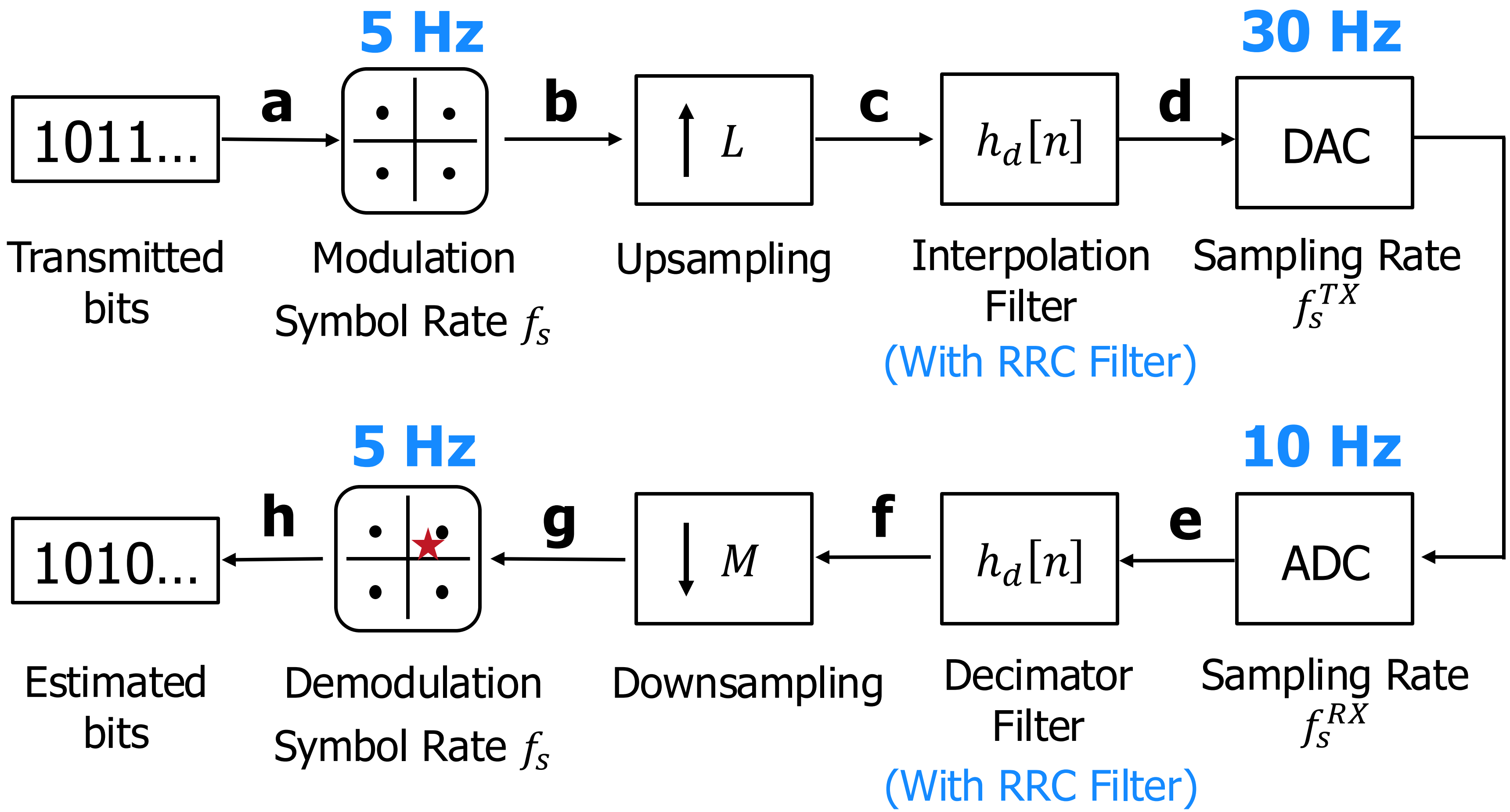
Transmitted bits:

[1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0];

[1,1,1,0,0,0,1,1,1,0,0,0,1,1,1,0,0,0];

Lab 2 – Part 3 (RRC filter)

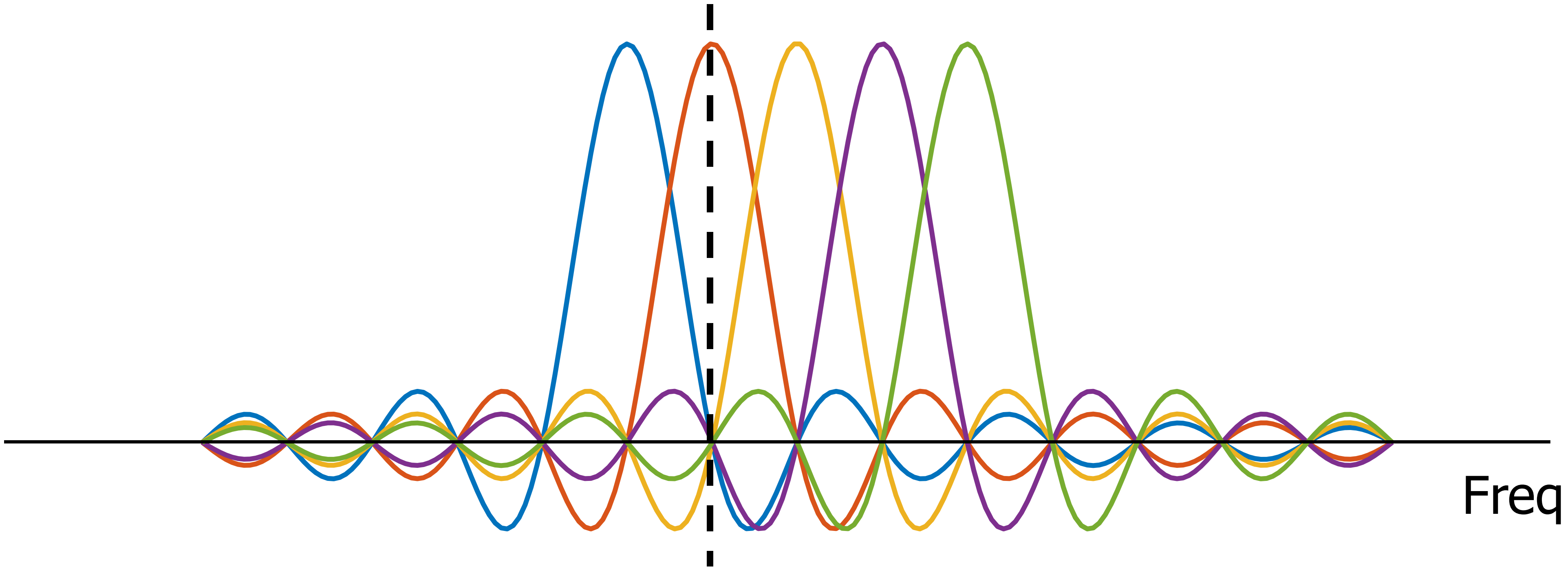
(continue the simulation in Part 1)



OFDM

Orthogonal Frequency-Division Multiplexing

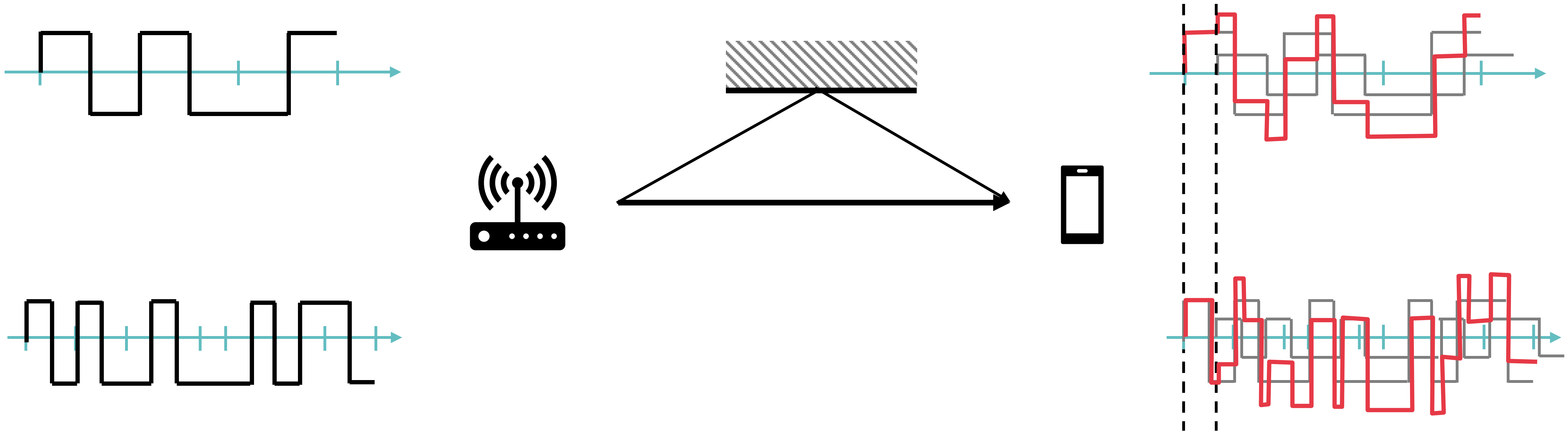
OFDM: Orthogonal Frequency-Division Multiplexing



Spectra of different modulated carriers overlap
But each carrier is in the spectral nulls of all other carriers

Wi-Fi (IEEE 802.11a, g, n, ac, ax), LTE

Motivation of OFDM

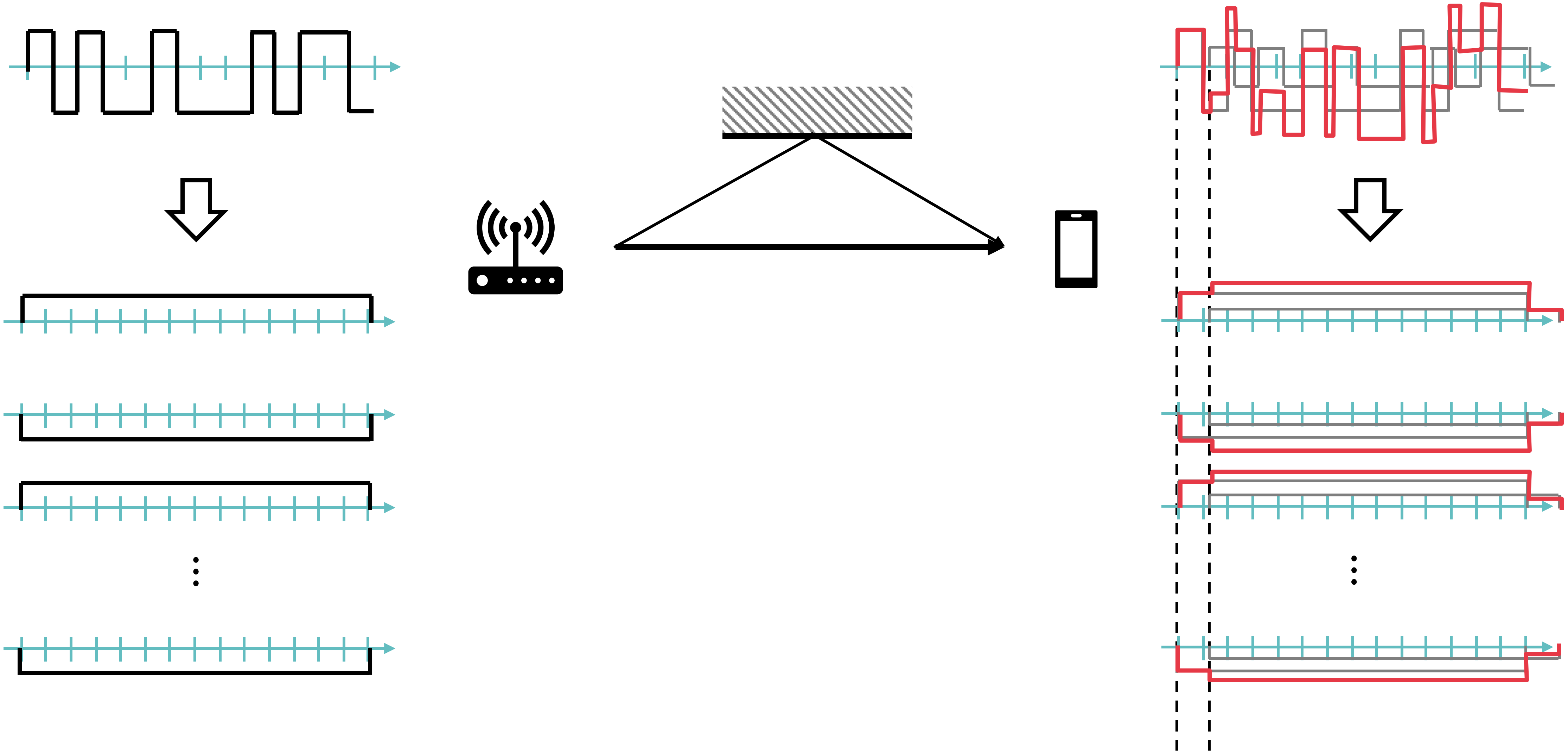


Higher data rate

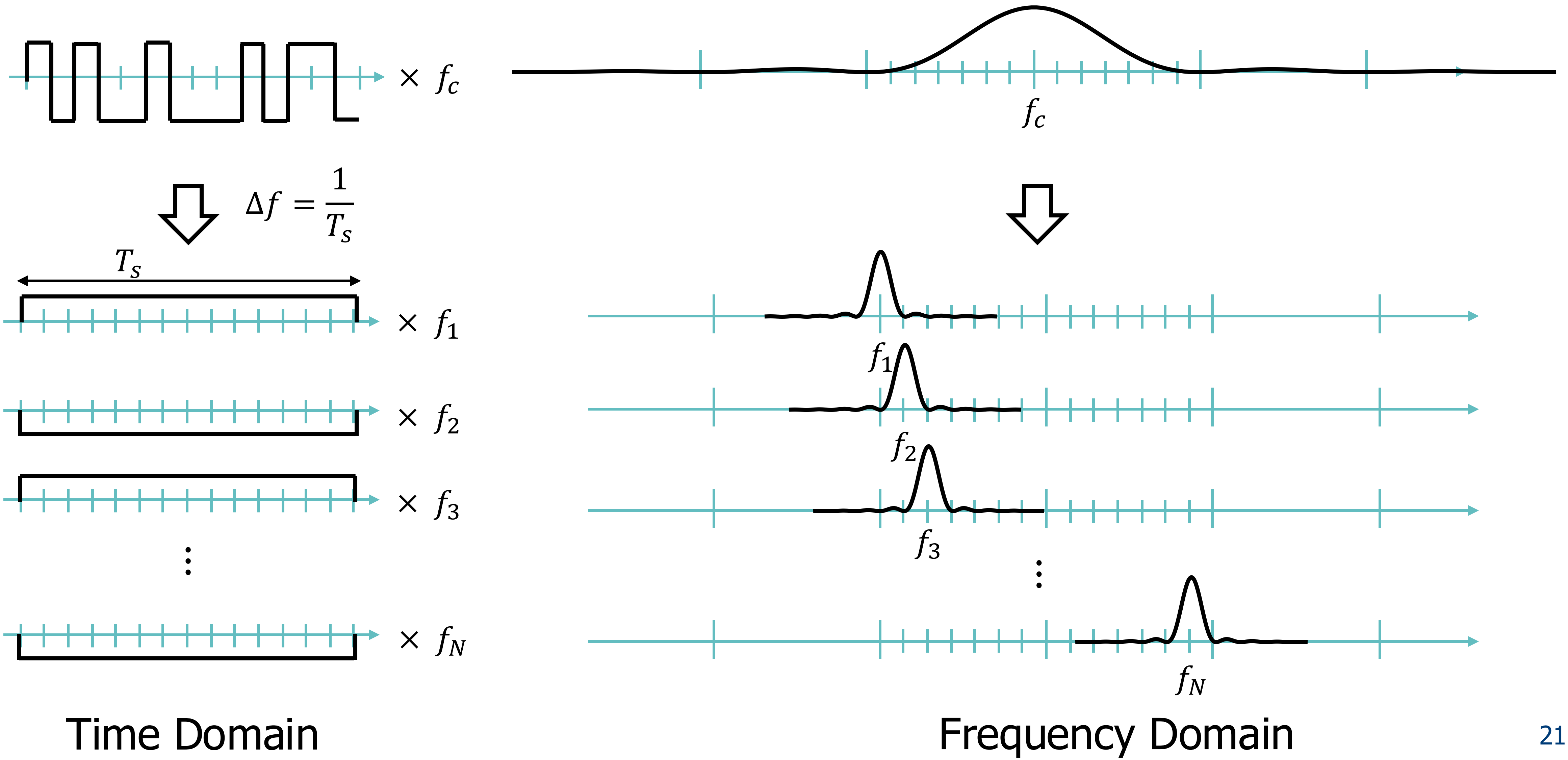
⟹ Shorter symbol time

⟹ Inter-symbol interference more significant

Motivation of OFDM



OFDM: Orthogonal Frequency-Division Multiplexing



OFDM – Analog View

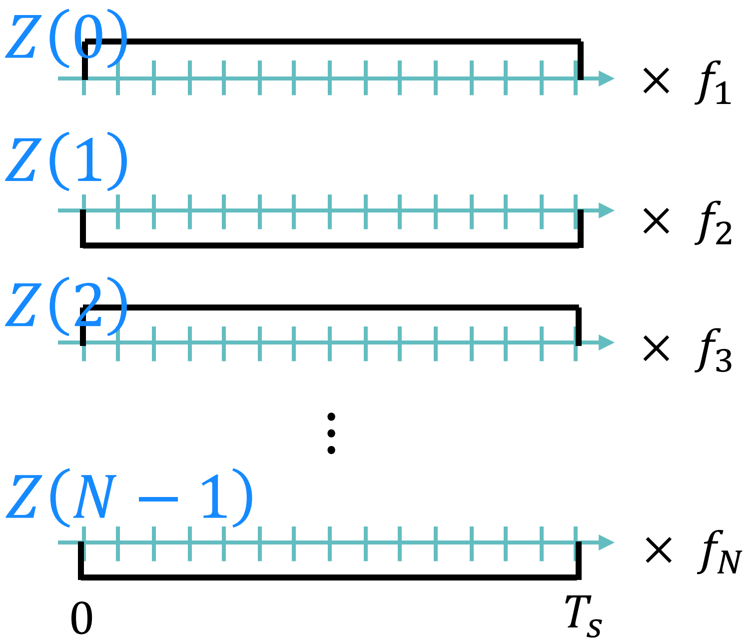
$$s_k(t) = Re\{Z(k)e^{j[2\pi(f_c+k\Delta f)t]}\},\ 0 \le t < T_s,\ \Delta f = 1/T_s$$

Modulated Subcarrier

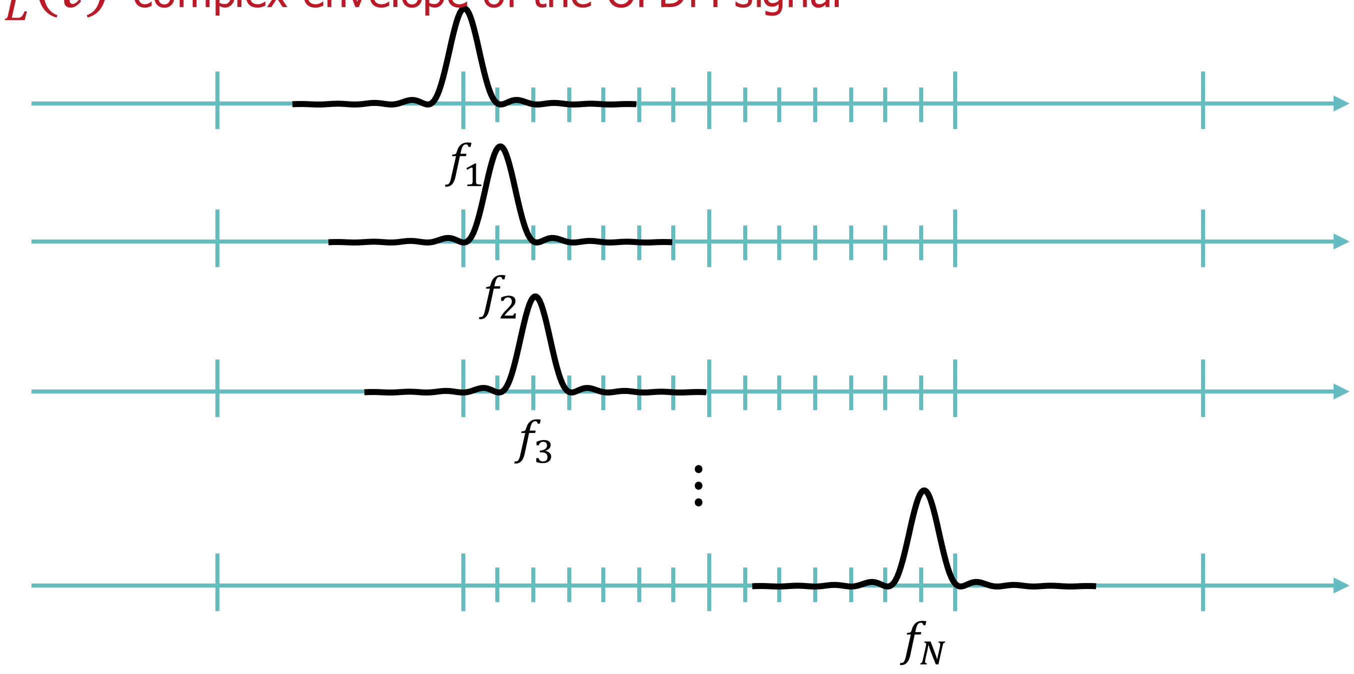
$$s(t) = \frac{1}{N}\sum_{k=0}^{N-1} s_k(t) = Re\left\{\underbrace{\left(\frac{1}{N}\sum_{k=0}^{N-1} Z(k)e^{j2\pi k\Delta f t}\right)}_{s_L(t)} e^{j2\pi f_c t}\right\}, 0 \le t < T_s$$

OFDM signal

$s_L(t)$ complex envelope of the OFDM signal



Complex envelope of the k-th subcarrier, constant during a symbol interval



OFDM – Digital View

$$s_k(t) = Re\{Z(k)e^{j[2\pi(f_c+k\Delta f)t]}\},\ 0 \le t < T_s,\ \Delta f = 1/T_s$$

Modulated Subcarrier

OFDM signal

$$s(t) = \frac{1}{N}\sum_{k=0}^{N-1} s_k(t) = Re\left\{\boxed{\left(\frac{1}{N}\sum_{k=0}^{N-1} Z(k)e^{j2\pi k\Delta f t}\right)} e^{j2\pi f_c t}\right\}, 0 \le t < T_s$$

$s_L(t)$ complex envelope of the OFDM signal

Sampling time $\frac{T_s}{N}$

(sample at $t = \frac{nT_s}{N}, n = 0, 1, \cdots, N-1$)

$$s_L(n) = \frac{1}{N}\sum_{k=0}^{N-1} Z(k)e^{j2\pi kn/N}, n = 0, 1, \cdots, N-1$$

$$= IDFT\{z_k(t)\}$$

→ Generate time sequence $s_L(n)$ from frequency samples

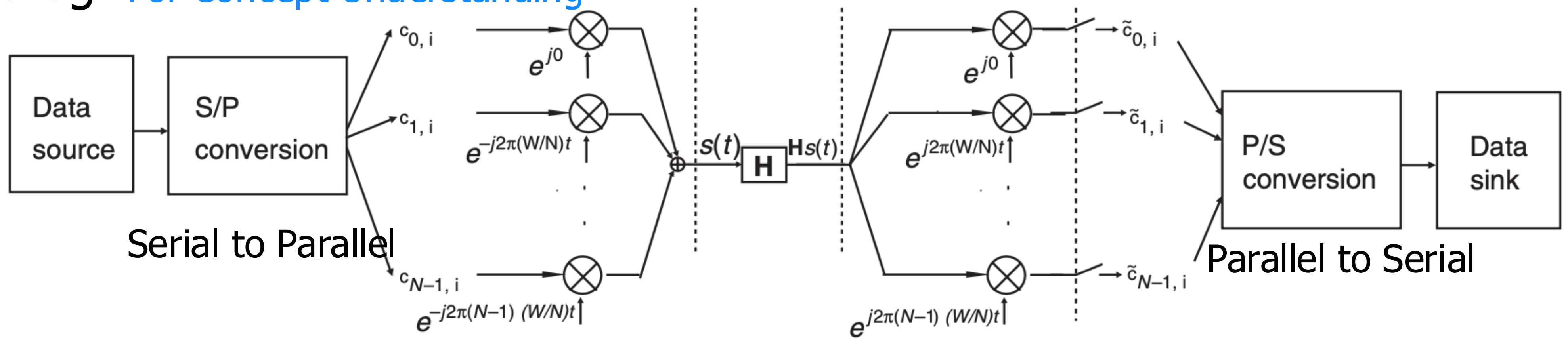
$$Z(k) = \sum_{n=0}^{N-1} s_L(n)e^{-j2\pi kn/N}, k = 0, 1, \cdots, N-1$$

$$= DFT\{s_L(n)\}$$

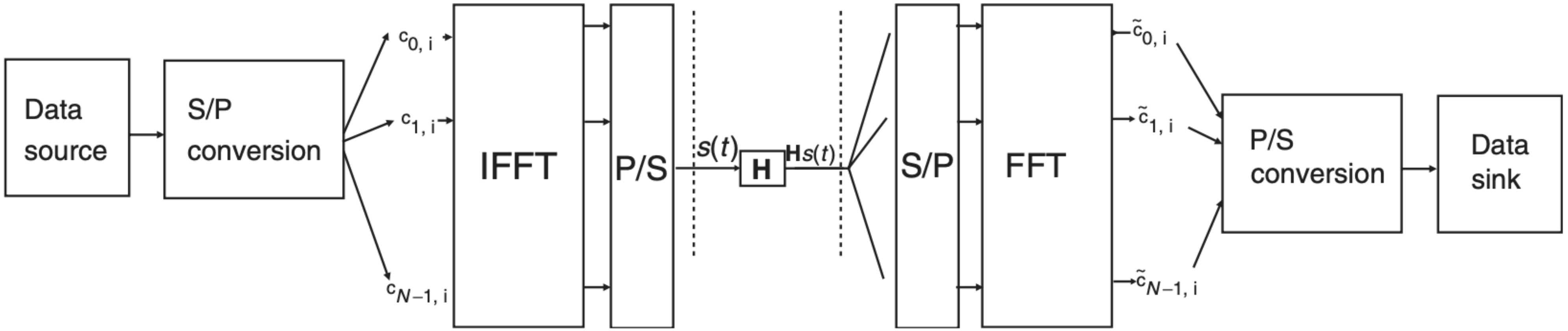
$$\boxed{\Delta f = \frac{1}{T_s}, \qquad \Delta t = \frac{T_s}{N}}$$

OFDM Representation

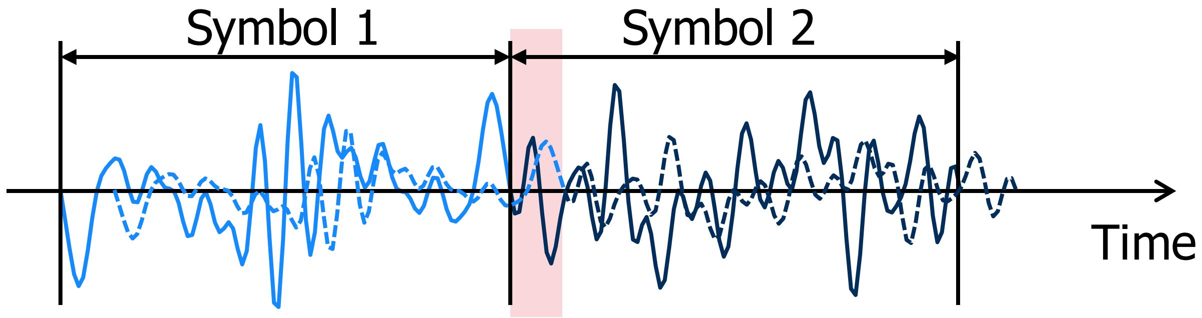
Analog For Concept Understanding



Digital Actual implementation

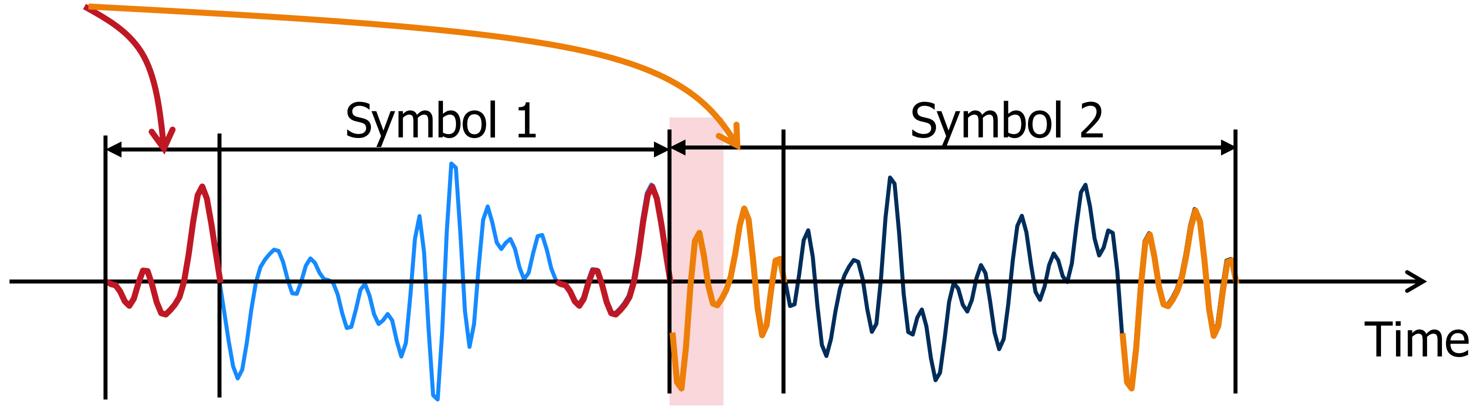


Cyclic Prefix to Combat Delay Dispersion



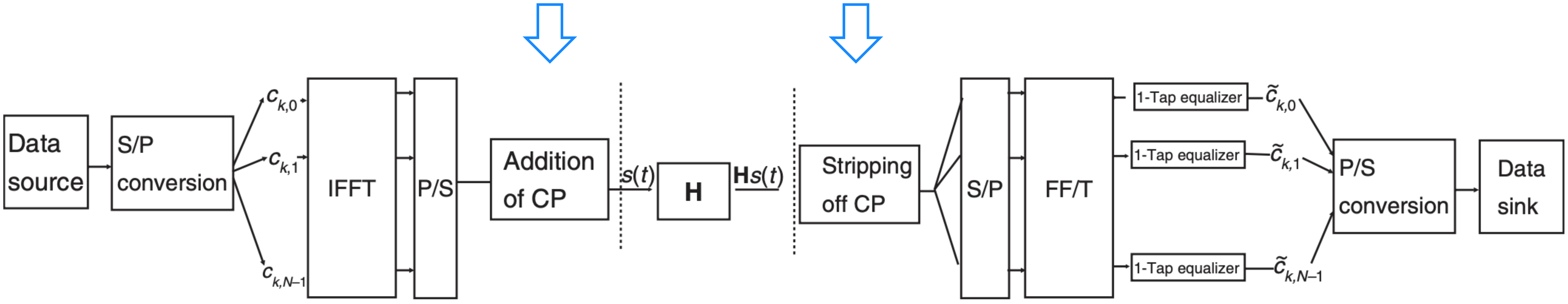
Inter-Symbol Interference

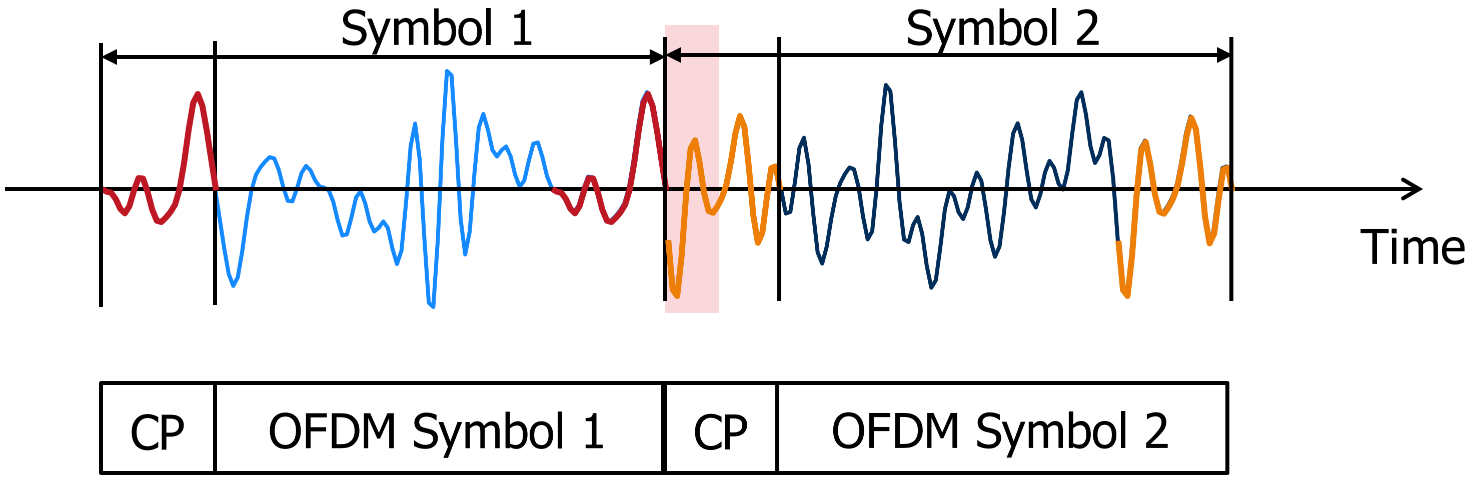
Cyclic Prefix (CP)



CP	OFDM Symbol 1	CP	OFDM Symbol 2

OFDM Implementation with CP





Reference - OFDM

- Andreas F. Molisch. *Wireless Communications*. John Wiley & Sons, 2011. [NTU Library Link]
  - Chap. 19: Orthogonal Frequency Division Multiplexing (OFDM)
- Sung-Moon Michael Yang. *Modern Digital Radio Communication Signals and Systems*. Springer, 2020. [NTU Library Link]
  - Chap. 5: OFDM Signals and Systems
- Tri T. Ha. *Theory and Design of Digital Communication Systems*. Cambridge University Press, 2010.
  - 6.18 Orthogonal frequency division multiplexing (OFDM)
  - 7.23 OFDM demodulation
- YouTube Playlist: Orthogonal Frequency Division Multiplexing (OFDM) by Iain Explains Signals, Systems, and Digital Comms [Link]

Paper Debate

Debate Format

20 minutes	Defense Team
10 minutes	Offense Team
5 minutes	Preparation time
10 minutes	Follow up arguments
5 minutes	Questions and comments from class

Timing will be strictly enforced!

Paper 1: OPTICS: Human Activity-Aware Integrated Optical Wireless Communication and Sensing

https://forms.gle/2jFMuYXXQSGVzj9s6

Only the audience vote!

Presenters: Upload your slides (With 分工表)