Project 2. Basic Principle of OFDM Technology

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Lab Schedule

2021年	周次	一	二	三	四	五	六	日	
	第10周 秋季学期	15 十一	16 十二	17 十三	18 十四	19 十五	20 十六	21 十七	← lab 5
	第11周 秋季学期	22 小雪	23 十九	24 二十	25 廿一	26 廿二	27 廿三	28 廿四	← Intro to project 1
12月	第12周 秋季学期	29 廿五	30 廿六	1 廿七	2 廿八	3 廿九	4 初一	5 初二	← Q&A
	第13周 秋季学期	6 初三	7 大雪	8 初五	9 初六	10 初七	11 初八	12 初九	← Presentation 1
	第14周 秋季学期	13 初十	14 十一	15 十二	16 十三	17 十四	18 十五	19 十六	**← Intro to project 2**
	第15周 秋季学期	20 十七	21 冬至	22 十九	23 二十	24 廿一	25 廿二	26 廿三	← Q&A
	第16周 秋季学期	27 廿四	28 廿五	29 廿六	30 廿七	31 廿八	1 元旦	2 三十	← Presentation 2

Overview

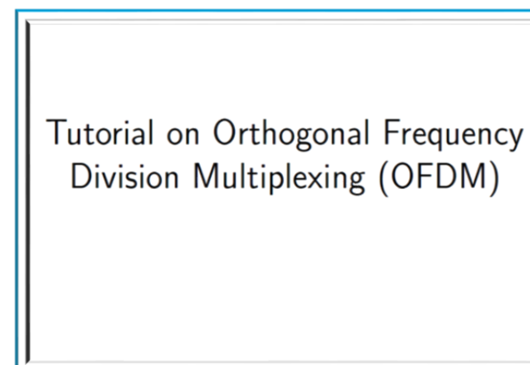
- Review of baseband signal processing of OFDM systems
- Introduction of the transmitter's DAC + RF front-end

- Your jobs include
  - Design of receiver's RF front-end + ADC
  - Simulating results
  - Discussion on real channel vs. equivalent discrete-time channel
  - Discussion on the benefits and applications of OFDM technology

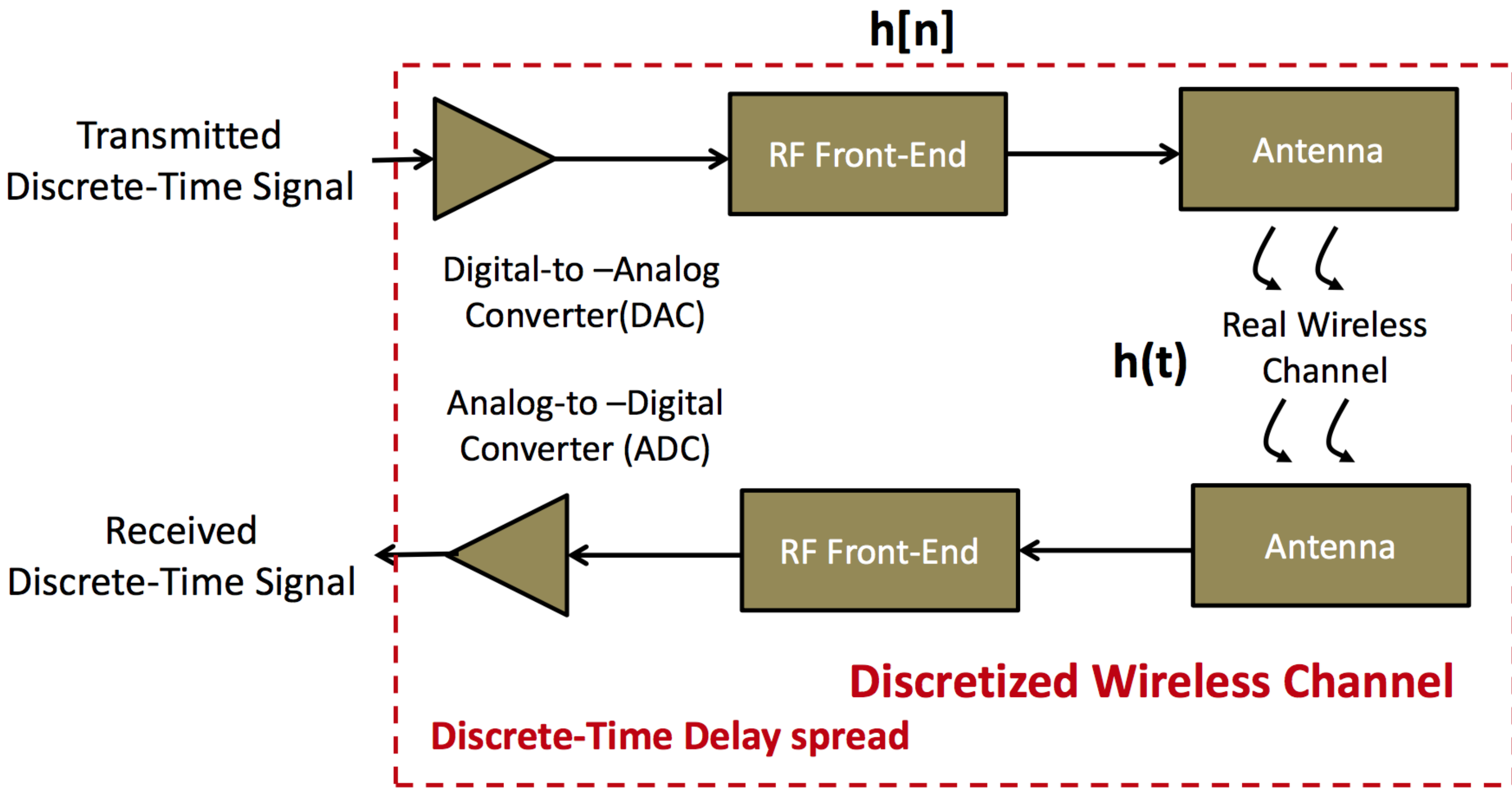
Review of Baseband Signal Processing of OFDM Systems

Review of Baseband Signal Processing of OFDM Systems

- Delay Spread in Wireless Channel
  - Inter-Symbol Interference
- DFT Helps Solving Inter-Symbol Interference
  - DFT and Periodic Convolution
  - How to Get Periodic Convolution


Tutorial on Orthogonal Frequency Division Multiplexing (OFDM)

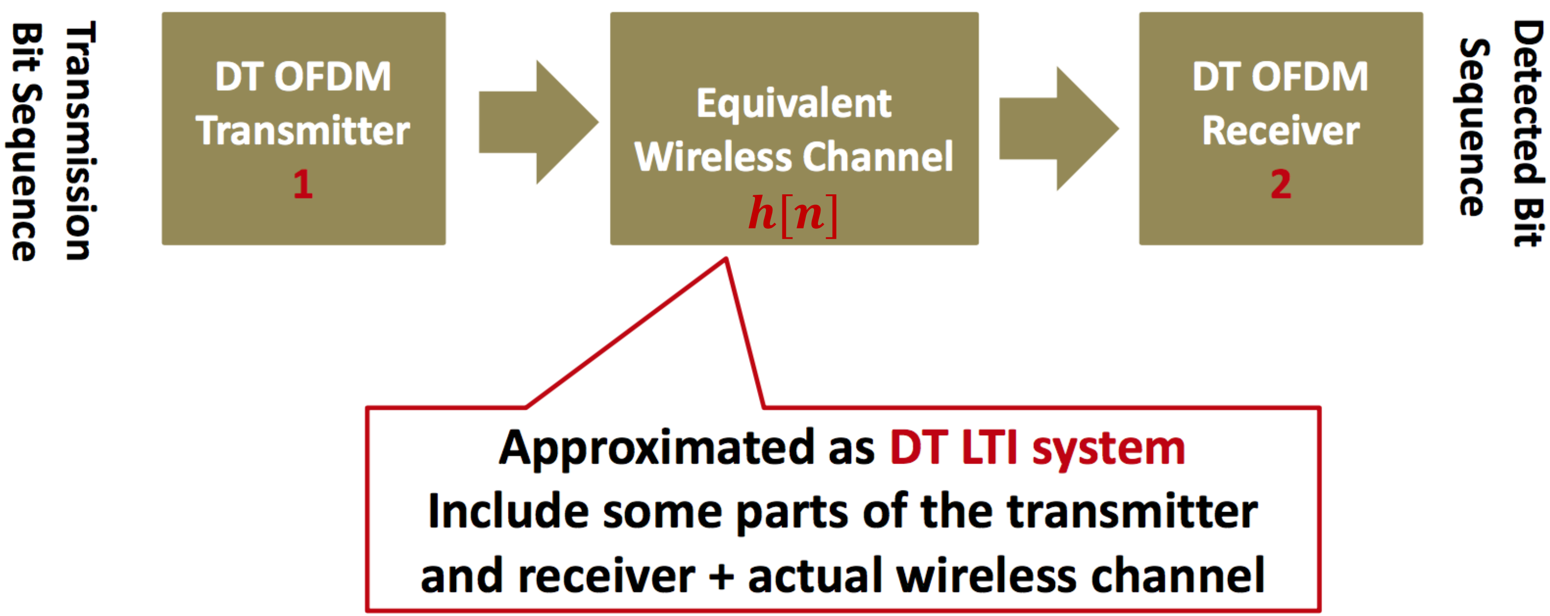
Equivalent Wireless Channel



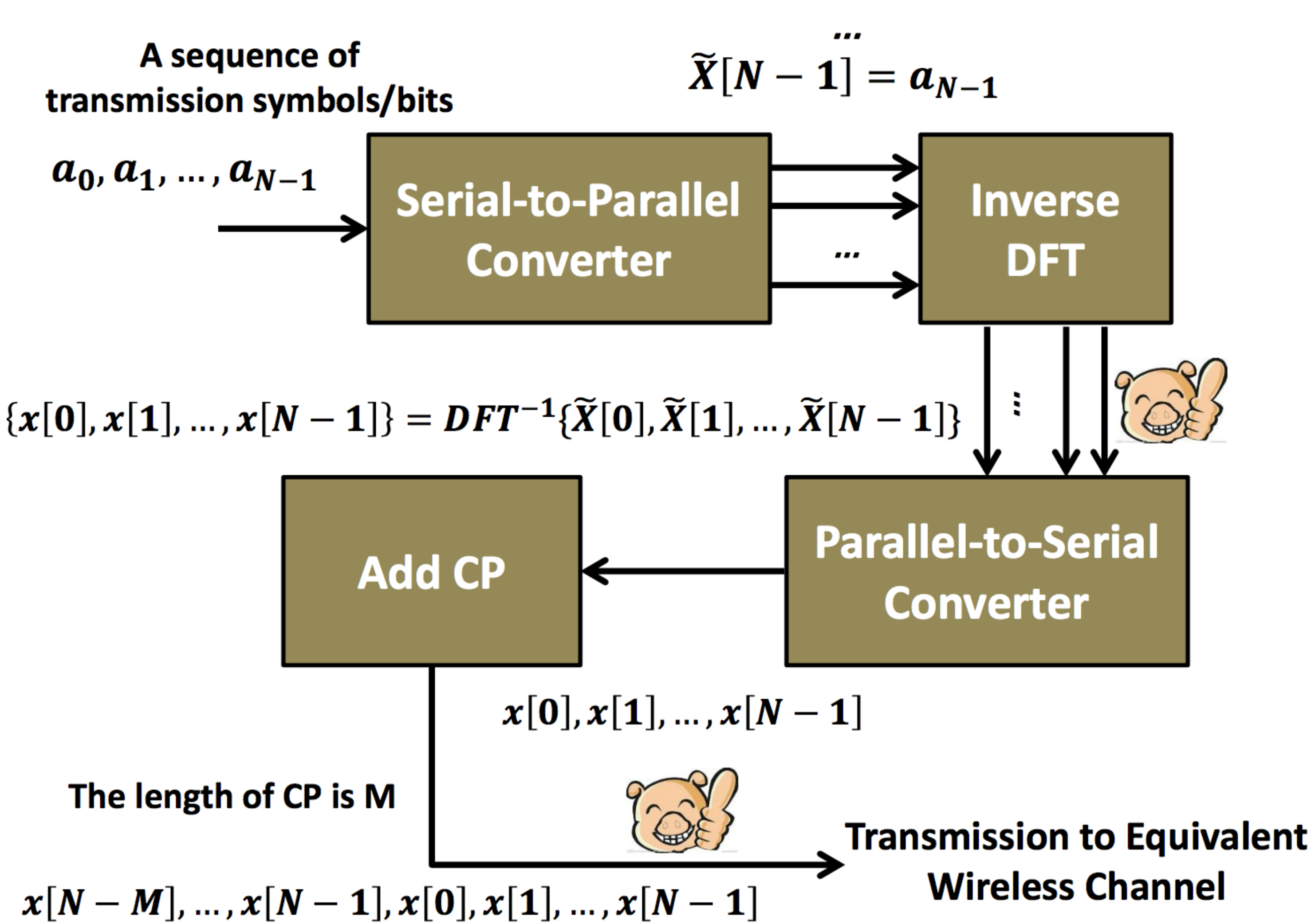
Discrete-Time OFDM Model

- The discrete-time OFDM system model is given below

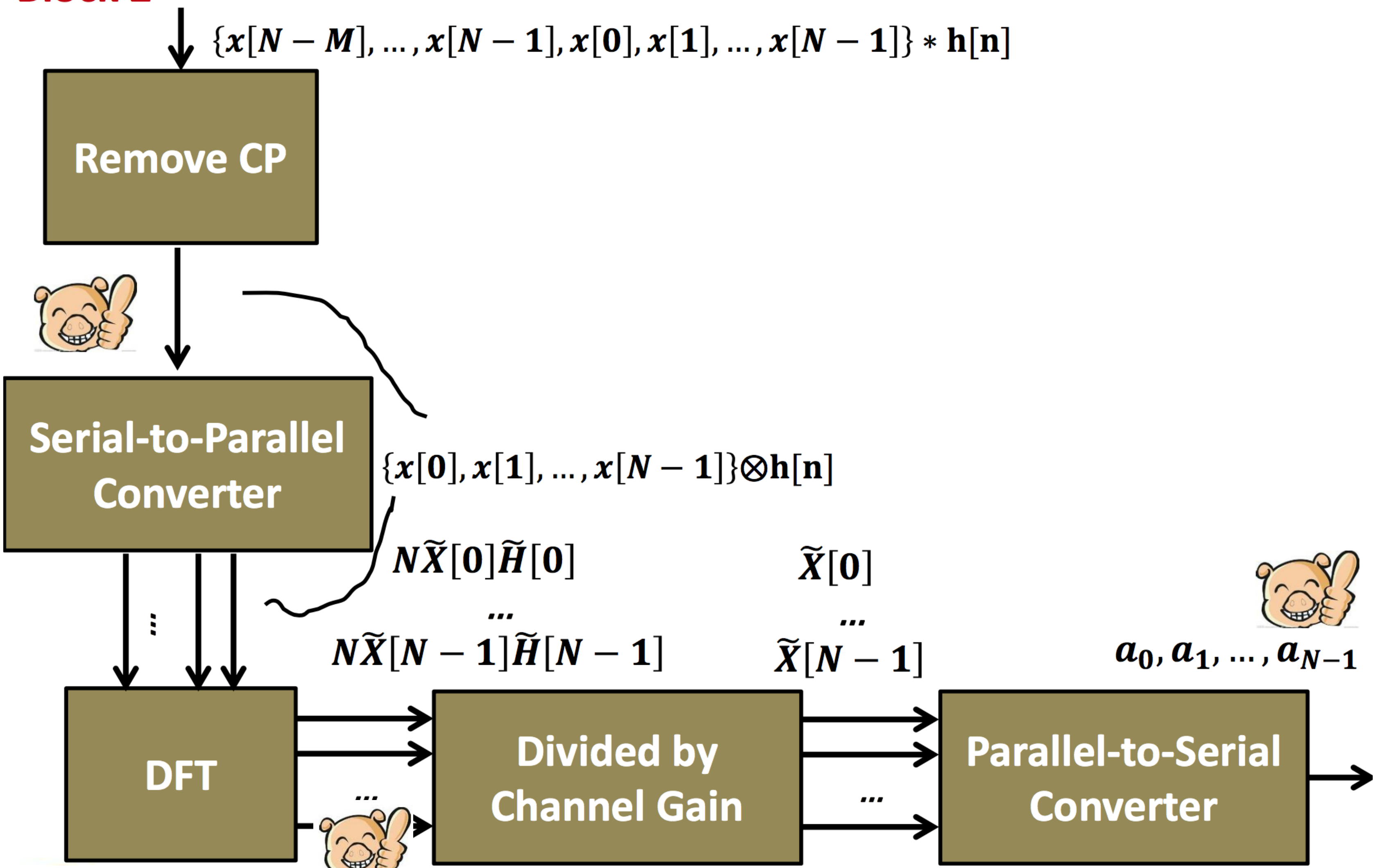
$$\widetilde{Y}[k] = N a_k \widetilde{H}[k], \qquad k = 0, 1, \dots, N-1$$



Block 1

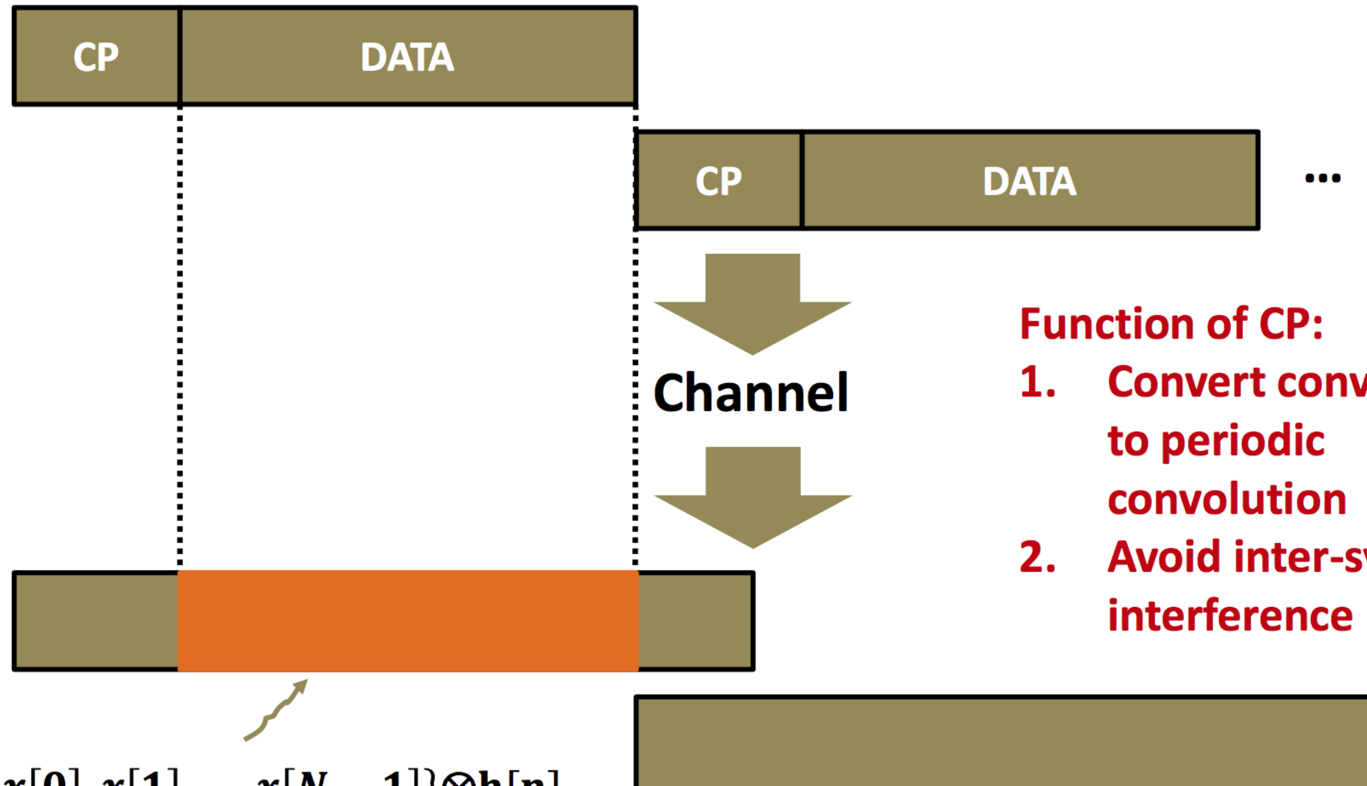

$\widetilde{X}[0] = a_0$
...
$\widetilde{X}[N-1] = a_{N-1}$
A sequence of transmission symbols/bits
$a_0, a_1, \dots, a_{N-1}$
Serial-to-Parallel Converter
Inverse DFT
$\{x[0], x[1], \dots, x[N-1]\} = DFT^{-1}\{\widetilde{X}[0], \widetilde{X}[1], \dots, \widetilde{X}[N-1]\}$
Parallel-to-Serial Converter
Add CP
$x[0], x[1], \dots, x[N-1]$
The length of CP is M
Transmission to Equivalent Wireless Channel
$x[N-M], \dots, x[N-1], x[0], x[1], \dots, x[N-1]$

Block 2


$\{x[N-M], \dots, x[N-1], x[0], x[1], \dots, x[N-1]\} * \mathbf{h[n]}$
Remove CP
Serial-to-Parallel Converter
$\{x[0], x[1], \dots, x[N-1]\} \otimes \mathbf{h[n]}$
$N\tilde{X}[0]\tilde{H}[0]$
…
$N\tilde{X}[N-1]\tilde{H}[N-1]$
$\tilde{X}[0]$
…
$\tilde{X}[N-1]$
$a_0, a_1, \dots, a_{N-1}$
DFT
Divided by Channel Gain
Parallel-to-Serial Converter

Remove Cyclic Prefix

OFDM Symbol: $\{x[N-M], \dots, x[N-1], x[0], x[1], \dots, x[N-1]\}$



$\{x[0], x[1], \dots, x[N-1]\} \otimes h[n]$

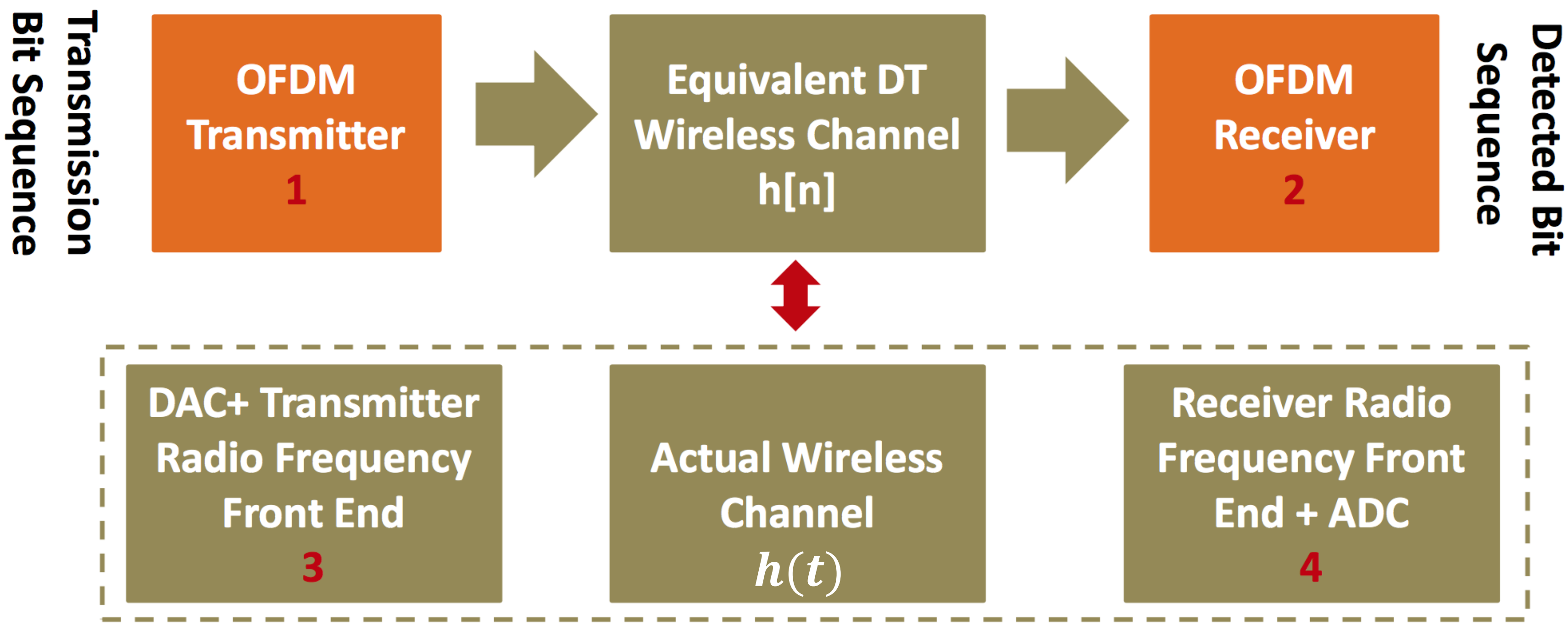
Function of CP:

1. **Convert convolution to periodic convolution**
2. **Avoid inter-symbol interference**

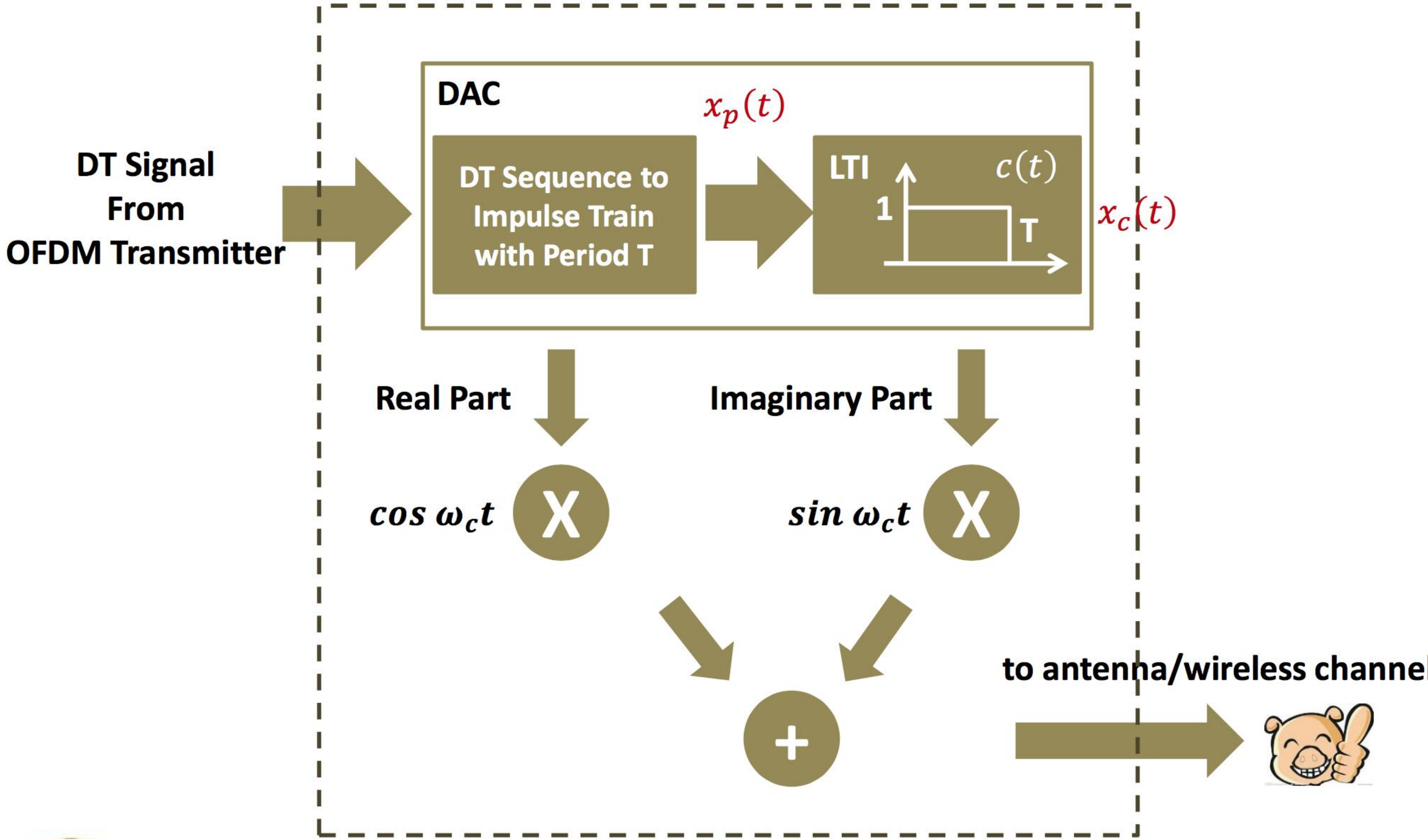
Introduction of the transmitter's DAC + RF front-end

Equivalent Wireless Channel

- The equivalent DT wireless channel includes RF front-end and real wireless channel



DAC + Transmitter RF Front-End (Block 3)



Time Domain Analysis

- Suppose the input signal to the RF front end is $x[n]$
- Convert to impulse train: $x_p(t) = \sum_n x[n]\delta(t - nT)$
- After DAC: $x_c(t) = \sum_n x[n]c(t - nT)$
  - $c(t)$ is a rectangular wave
- Real part: $x_r(t) = real[x_c(t)]$
- imaginary part: $x_i(t) = imag[x_c(t)]$
- After modulation
  - $x_{cos}(t) = x_r(t)\cos\omega_c t$
  - $x_{sin}(t) = x_i(t)\sin\omega_c t$
- After summation: $x_{tx}(t) = x_r(t)\cos\omega_c t + x_i(t)\sin\omega_c t$

How to represent all these CT signals in Matlab?

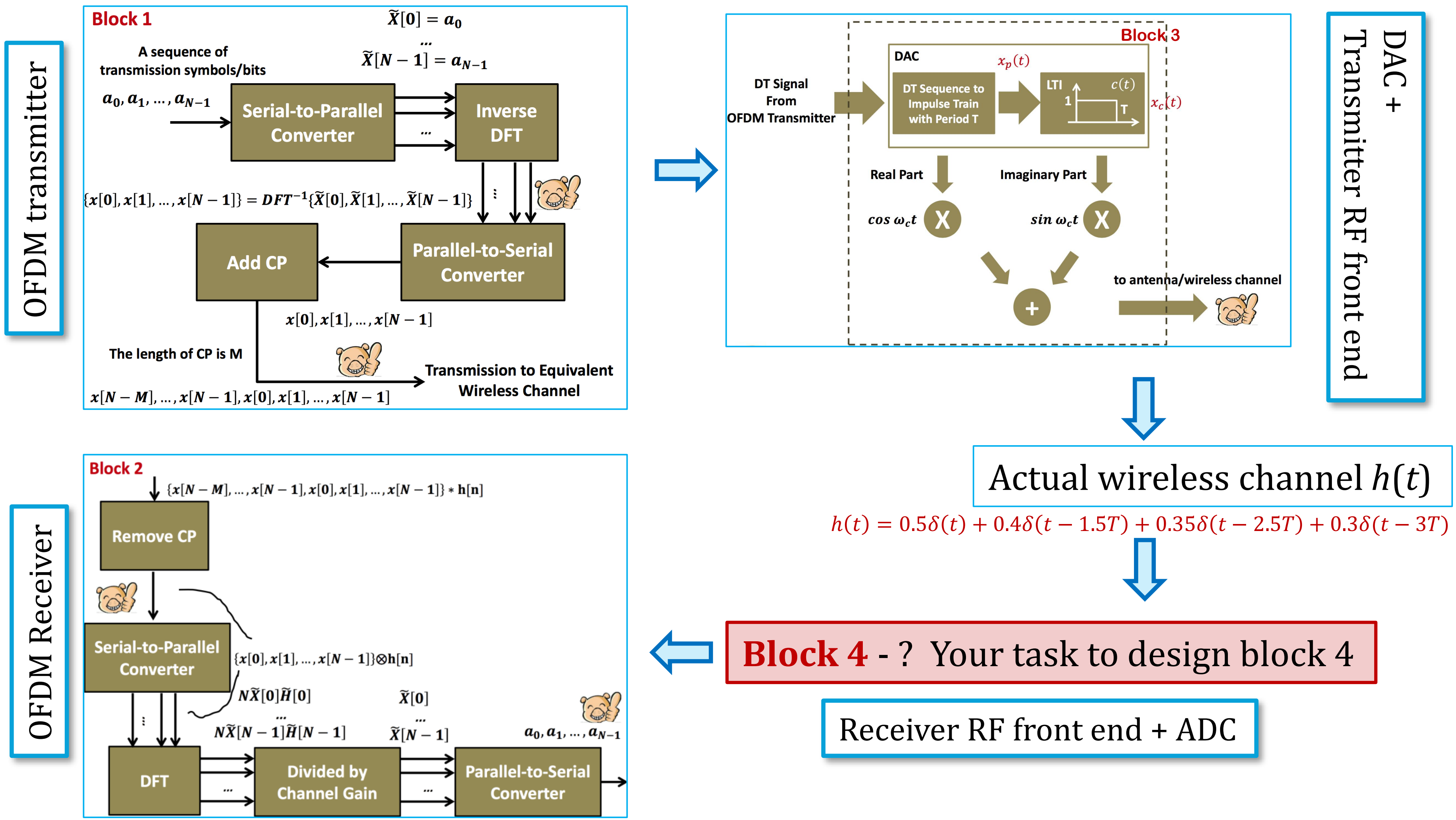
Real signal!!!

Actual Wireless Channel

- In this project, the wireless channel is approximated as a continuous-time LTI systems

- The impulse response is a causal finite-length continuous-time function

- Assume the channel impulse response is
  - $h(t) = 0.5\delta(t) + 0.4\delta(t - 1.5T) + 0.35\delta(t - 2.5T) + 0.3\delta(t - 3T)$
  - T is the sampling period


OFDM transmitter
Block 1
$\tilde{X}[0] = a_0$
...
$\tilde{X}[N-1] = a_{N-1}$
A sequence of transmission symbols/bits
$a_0, a_1, \dots, a_{N-1}$
Serial-to-Parallel Converter
Inverse DFT
$\{x[0], x[1], \dots, x[N-1]\} = DFT^{-1}\{\tilde{X}[0], \tilde{X}[1], \dots, \tilde{X}[N-1]\}$
Add CP
Parallel-to-Serial Converter
$x[0], x[1], \dots, x[N-1]$
The length of CP is M
Transmission to Equivalent Wireless Channel
$x[N-M], \dots, x[N-1], x[0], x[1], \dots, x[N-1]$
Block 3
DAC
$x_p(t)$
DT Signal From OFDM Transmitter
DT Sequence to Impulse Train with Period T
LTI
$c(t)$
1
T
$x_c(t)$
Real Part
Imaginary Part
$\cos \omega_c t$
X
$\sin \omega_c t$
X
+
to antenna/wireless channel
DAC + Transmitter RF front end
Actual wireless channel $h(t)$
$h(t) = 0.5\delta(t) + 0.4\delta(t-1.5T) + 0.35\delta(t-2.5T) + 0.3\delta(t-3T)$
Block 4 - ? Your task to design block 4
Receiver RF front end + ADC
OFDM Receiver
Block 2
$\{x[N-M], \dots, x[N-1], x[0], x[1], \dots, x[N-1]\} * \mathrm{h[n]}$
Remove CP
Serial-to-Parallel Converter
$\{x[0], x[1], \dots, x[N-1]\} \otimes \mathrm{h[n]}$
$N\tilde{X}[0]\tilde{H}[0]$
...
$N\tilde{X}[N-1]\tilde{H}[N-1]$
$\tilde{X}[0]$
...
$\tilde{X}[N-1]$
$a_0, a_1, \dots, a_{N-1}$
DFT
Divided by Channel Gain
Parallel-to-Serial Converter

Your Tasks

Your tasks

a. Design the receiver's RF front-end + ADC (Block 4), explain why your design can lead to correct signal detection.

b. Derive $h[n]$ and discuss the relation between $h(t)$ and $h[n]$ (see Page 6), determine the length of CP.
   - The impulse response of Actual Wireless Channel is given as

$$h(t) = 0.5\delta(t) + 0.4\delta(t - 1.5T) + 0.35\delta(t - 2.5T) + 0.3\delta(t - 3T)$$

c. Randomly generate two discrete time signals {xp[0],xp[1],...,xp[31]} (pilot/common information) and {x[0],x[1],...,x[31]} (data), transmit these two signals by two OFDM symbols, and at least show the following items (in the simulation, $T = 1\mu s$ and carrier frequency $\omega_c = 100MHz$).

- c1: plot the highlighted signals at Page 8 & 13.
- c2: plot and discuss the Fourier transform of signal highlighted at Page 13.
- c3: plot how the signal changes in the Block 4 step-by-step.
- c4: plot the highlighted signals at Page 9, compare the final detected signal with the original transmitted signal.

highlighted 

d. Elaborate on the applications of OFDM technology.

- Any practical communication system using OFDM? Why?

Task overview

- Simulation:
  - DAC + Transmitter Front-end (DAC and modulation)
  - Actual wireless channel: convolution (linear)
  - Receiver + ADC Front-end (demodulation and ADC)

- OFDM
  - Get periodic convolution (IDFT & DFT, add & remove CP)
  - Channel estimation – send a Pilot Signal (common signal) to estimate the channel gain (get to know the $H[k]$)
  - Signal detection – detect the received signal (via the knowledge of $H[k]$)

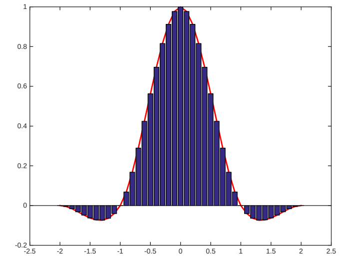
Tips on Receiver Design

- In order to demodulate the signal, receiver should
  - Multiple the received signal with carrier: $\cos\omega_c t$ and $\sin\omega_c t$ (recall lab assignment of '007')
  - You can use an ideal low-pass filter (fft → set the frequency components to be eliminated as 0 → ifft, Lab 3 slides page 31-35)
- After demodulation, the receiver should
  - Use integrator to accumulate the received power, then generate DT signal for further processing:

$$y_{int}(t) = \frac{1}{\mathrm{T}}\int_{t-T}^{t} y_{dem}(\tau)d\tau$$

$$y_{int}(nT) = y_{int}(t)|_{t=nT}$$

Average value in one sampling period as the discrete value of that time point



  - $y_{int}(nT)$ keeps all the necessary information

Lab Report

- Abstract
  - What you have done in this project
- Introduction
  - Elaborate on the baseband of OFDM (Block 1&2)
  - Elaborate on the DAC + RF front-end of the transmitter (Block 3)
- Receiver Design and Analysis
  - Task a: Elaborate on your design of receiver RF front-end + ADC (Block 4)
  - Task b: Elaborate on the relation between h(t) and h[n]

h[n]=?

- Simulations
  - Task c: show how the signal transforms step-by-step with figures
- Discussions
  - Task d: elaborate on the advantages of OFDM systems (>300 words)
- Please attach the Matlab code in your report

Organization and presentation

- $\leq$ 4 students/group.
- Each group needs to present 1 of the 2 Lab Projects (but submit reports for both projects):
  - The presentation date is Dec. 30^{th} for Project 2.
- Each presentation should be within 10 minutes
  - All team members need to contribute to the presentation.
  - Presenting in English or Chinese.

The presentation should (but not limited to) ...

- Introduce
  - team
  - objective of the project
  - background review (search more additional information)
  - methodology
- Present
  - relevant data, figure, etc.
  - the results for project tasks (e.g., with demo, Figure, etc.)
  - interpretation of project findings
- Discuss
  - what you have learned from this study?
  - problems during this project and your solution
  - investigation beyond project tasks
  - critical thinking
- Appendix (if any)
- Team effort (e.g., individual contribution)
- Reference
- Q & A (answer questions raised from audience)

Grading according to ...

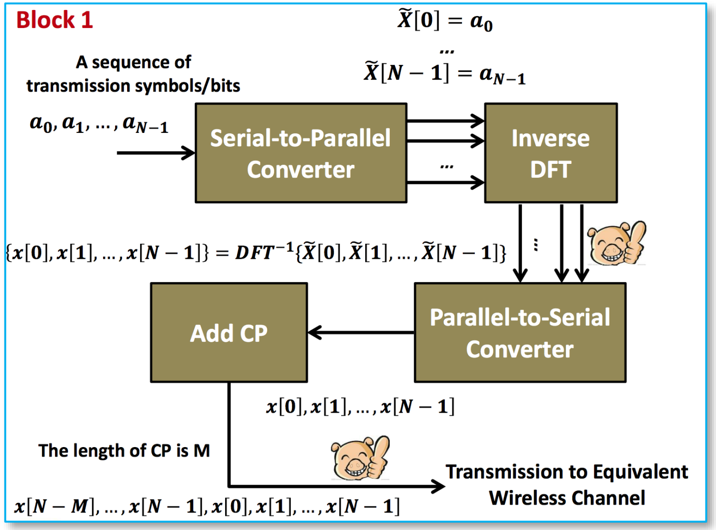
• Introduction	20%
• Results	30%
• Discussion	30%
• Q&A	10%
• Overall (e.g., PPT design and presentation)	10%

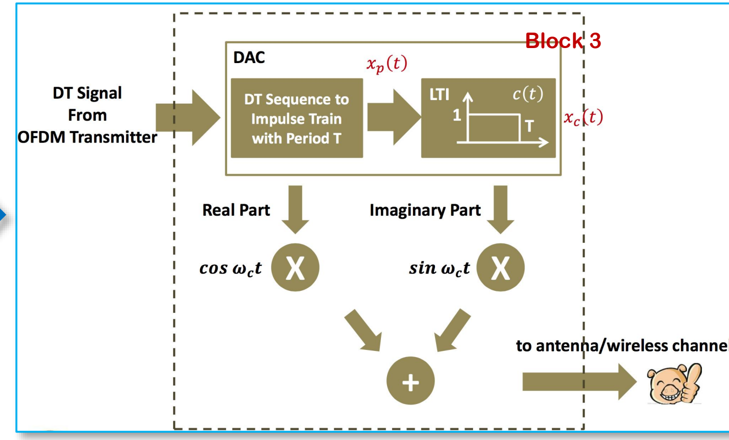
- Report deadline
  - For Project 2: Jan 2^{nd}, 2022

- Any questions?

Tips

OFDM transmitter



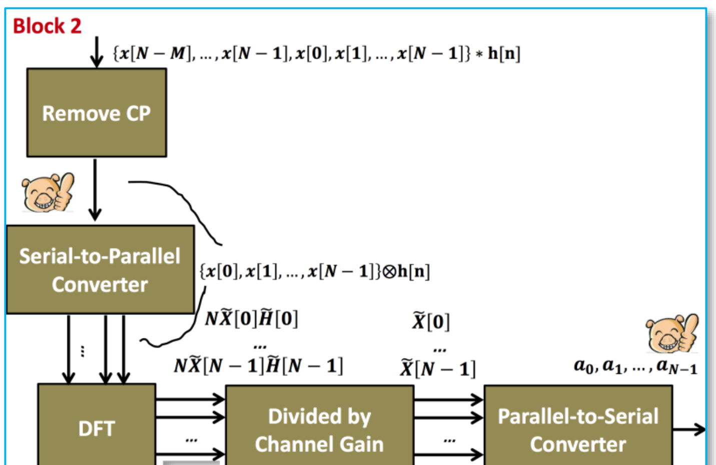


DAC + Transmitter RF front end

Actual wireless channel $h(t)$

$$h(t) = 0.5\delta(t) + 0.4\delta(t - 1.5T) + 0.35\delta(t - 2.5T) + 0.3\delta(t - 3T)$$

OFDM Receiver



Block 4 - ? Your task to design block 4

Receiver RF front end + ADC

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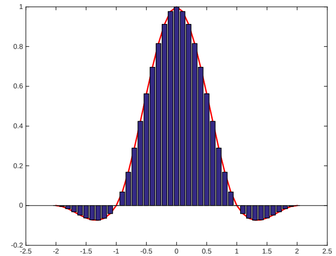
Average value in one sampling period as the discrete value of that time point

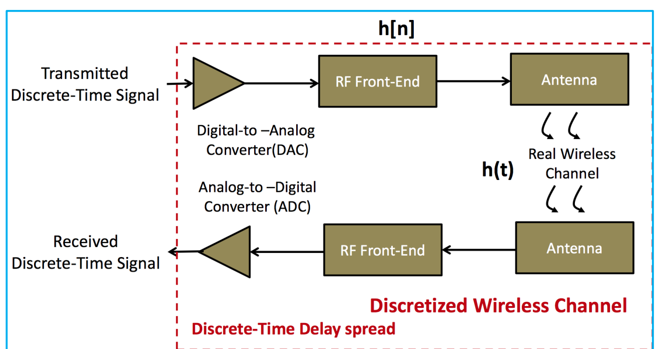


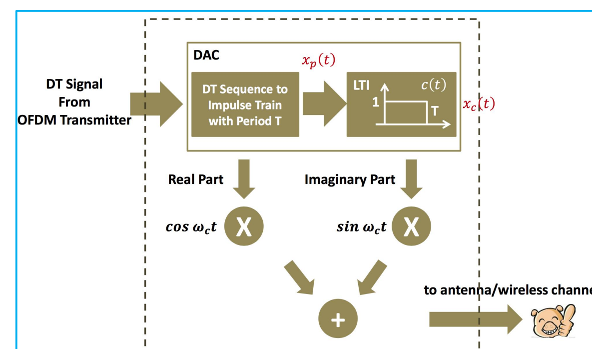
  - $y_{int}(nT)$ keeps all the necessary information

More tips

1. How to represent all these CT signals in Matlab?

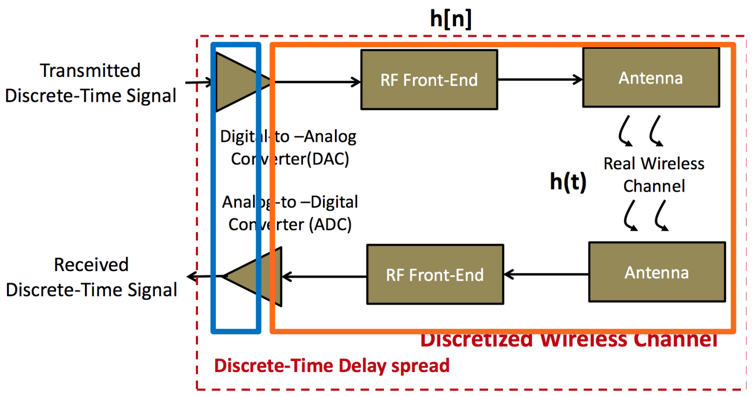
- By DT signals
- How many DT points for 1 sec CT signal? (sampling frequency / sampling period)
  - Exact value – up to you
  - Note that the carrier frequency $\omega_c = 2\pi f_c = 100MHz$, the sampling frequency here cannot be less than $\frac{2\omega_c}{2\pi} = \omega_c/\pi$ according to the sampling theory.





2. Two sampling periods (frequencies) to deal with

- Two sampling periods (so that two sampling frequencies)
  - One is the sampling period of the system ADC and DAC, $T = 1\mu s$,
    - Used in ADC, DAC
  - The other is the sampling frequency used to represent the CT signal of the system in Matlab
    - Used in real wireless channel part (between transmitter and receiver), i.e. the linear convolution part



3. What needs to be emphasized (more than once)

- Do NOT use the approach of Channel Equalizer
  - That is NOT what this project asks to do
  - The impulse response of Actual Wireless Channel is given as

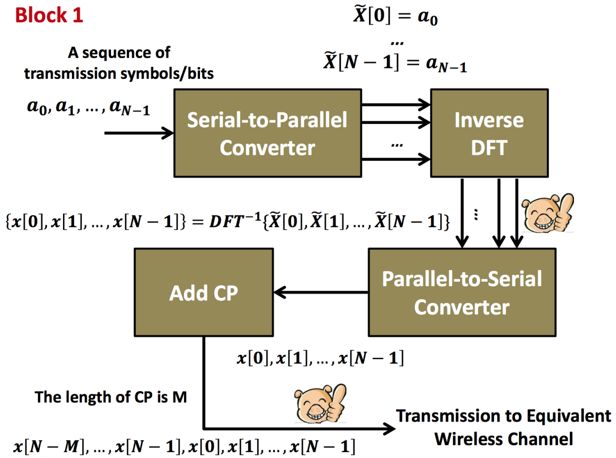
$$h(t) = 0.5\delta(t) + 0.4\delta(t - 1.5T) + 0.35\delta(t - 2.5T) + 0.3\delta(t - 3T)$$

  - It is only used to calculate the convolution in the Actual Wireless Channel, but not for detecting signal (we don't know $h(t)$ in reality)
  - AGAIN, DO NOT turn the project to a Channel Equalizer project

4. What needs to be emphasized (more than once)

- OFDM approach includes **two** steps:
  - Channel estimation – send a common signal
    - In the receiver part, you know the signal but do not know the channel gain;
    - Calculate and the channel gain H(k)
    - Save H(k) for the following signal detection
  - Signal detection – send an arbitrary signal
    - In the receiver part , you know the channel gain H(k)(from the channel estimation step) but do not know the signal

- Generate random signals (pilot signal or arbitrary signal to be sent)
  - Just use
    - pilot = randn(1,32); % or rand(1,32)
    - data = randn(1,32);
- Just ignore the parts of 'serial-to-parallel' and 'parallel-to-serial'



Maybe helpful

1. Increasing sampling frequency

- R = 1000; % 1000 points
- fct = R*fs; % fs- sampling frequency of the system, corresponding to T = 1us,
  % fct - sampling frequency you use when representing CT signal in Matlab, fct in this example is 1000MHz
  % change value of R to achieve different fct

- xp = upsample(xwithcp,R);
- xc = reshape(repmat(xwithcp,R,1),1,[]);

2. Sinusoidal signal generation

- Same to project 1
  - Sinsig = sin(2*pi*f*t) → CT signal, (f – frequency in Hz)
  - In Matlab, the Sinsig should be represented as a DT signal with sampling rate fs
  - Sinsigdt = sin(2*pi*f*n*dT), dT is the sampling interval
    - dT=1/fs

3. Ideal low pass filter for demodulation

- Lab 3 slides page 31-35

4. Pad a zero

- Pad a zero at the end of the convolution in the actual wireless channel
- $h(t) = 0.5\delta(t) + 0.4\delta(t - 1.5T) + 0.35\delta(t - 2.5T) + 0.3\delta(t - 3T)$
- If represent $h(t)$ in Matlab by 1000 points per sampling period T, you'll get 4*1000 points, denoted as $Nht * 1000$
- Represent modulated signal xmod(t) in the same manner, you'll get $Nxmod * 1000$ points
- After convolution in the actual wireless channel (simulating in Matlab), the convoluted signal will have length of
$$Nht * 1000 + Nxmod * 1000 - 1$$
- Pad a zero at the end to get an integer multiple of 1000 for the coming ADC part

- %--ADC--% integral
- xde_lp = [xde_lp,0]; % xde_lp-demodulated signal, pad a zero
- A = reshape(xde_lp,R,[]); % every R points, which will be sampled to get a digital value, are arranged in one column;
- xr = mean(A,1); %