Digital Communications: the Past, Current, and Future

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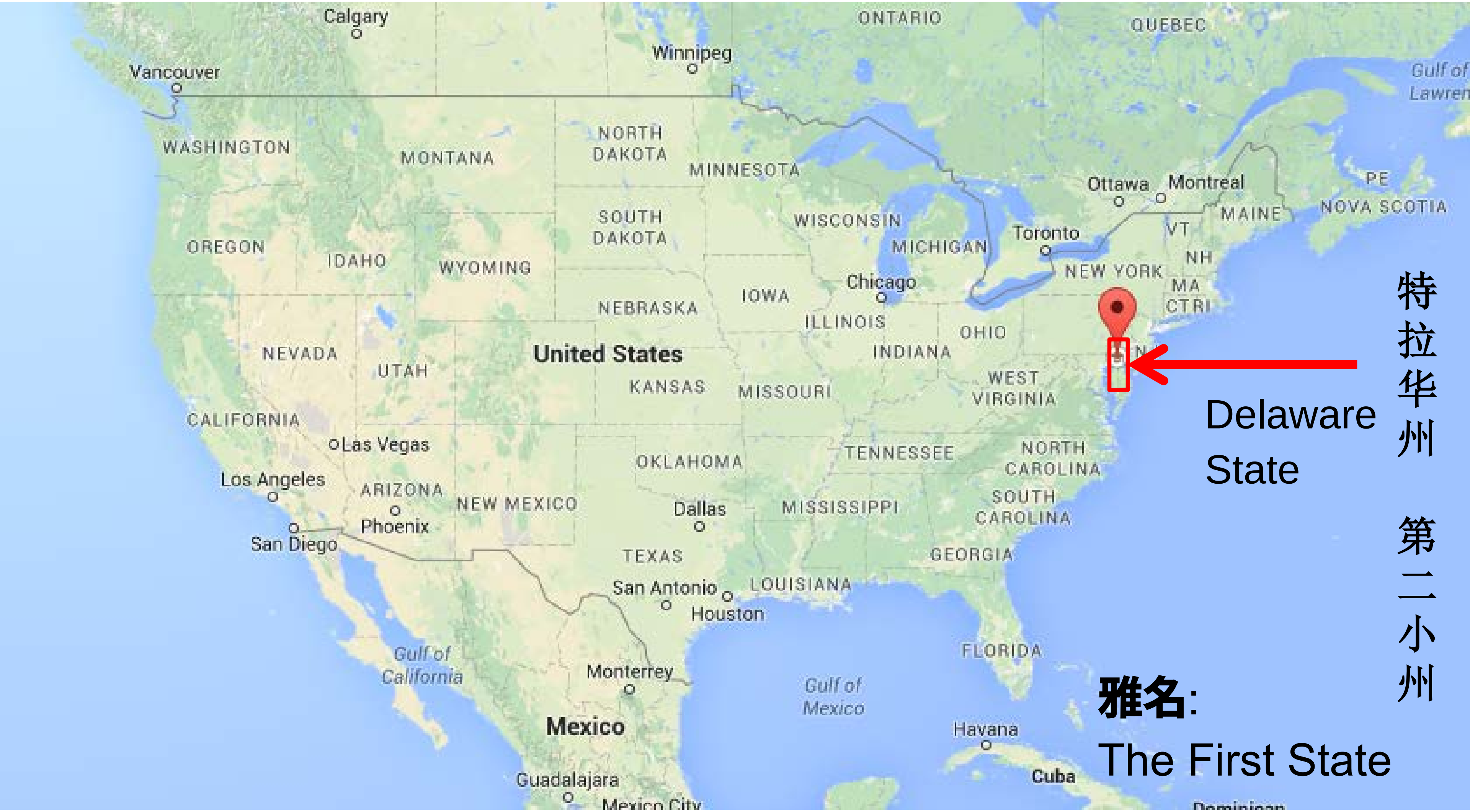
Outline

- Where is University of Delaware
- Brief Review of Past Events of Electronics
- Digital communications have changed our daily life
- Digital Communications: Basics
- Cellular Communications: Standards
- Orthogonal Frequency Division Multiplexing (OFDM) and Vector OFDM Systems
- Conclusions

美国特拉华州 (State of Delaware)

特拉华大学 (University of Delaware)

电子与计算机工程系 (Department of Electrical and Computer Engineering)



Delaware State

特拉华州

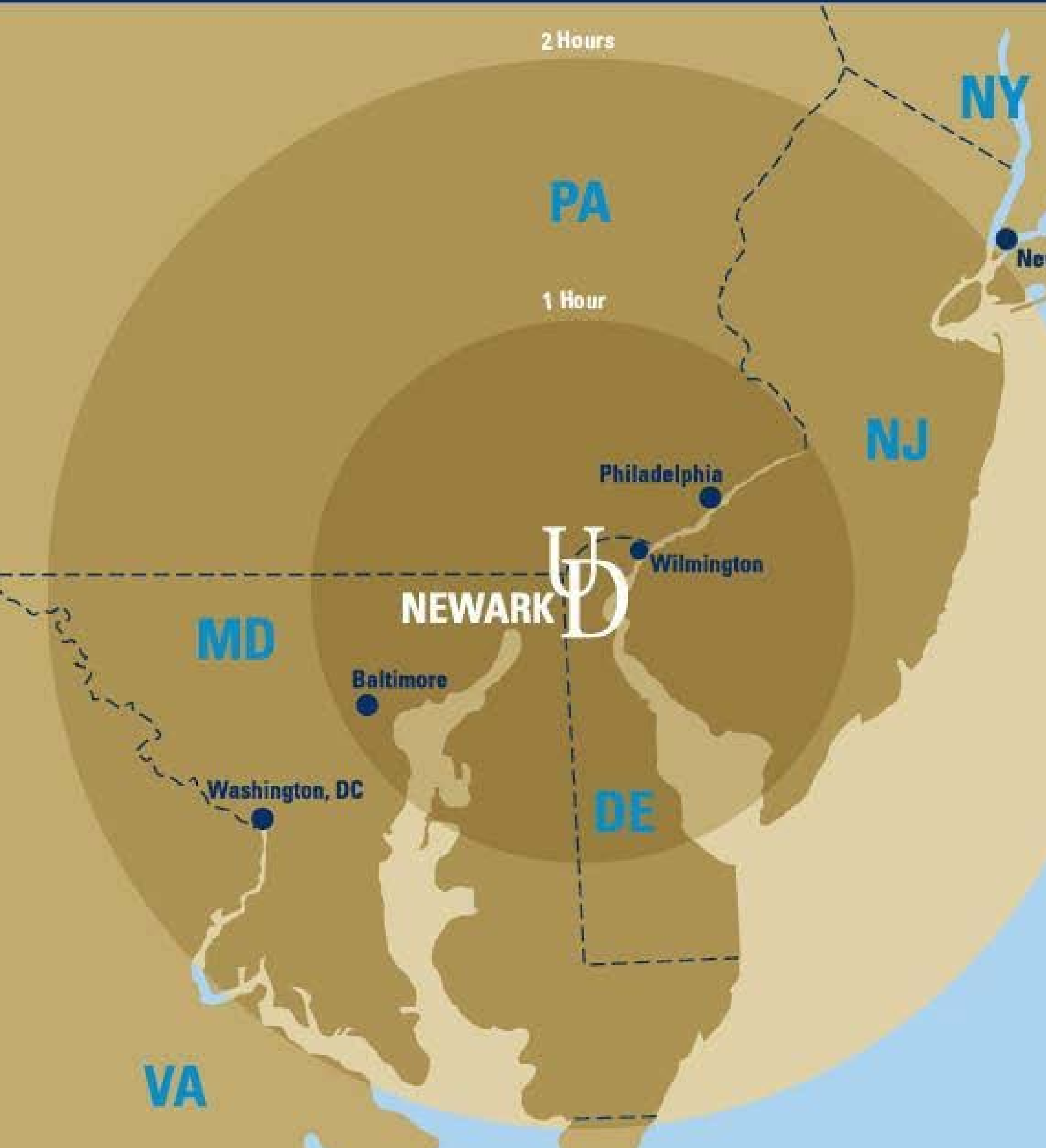
第二小州

雅名:

The First State


Williamsport
Wilkes-Barre
Danbury
New Haven
Milford
Hazleton
Yonkers
PENNSYLVANIA
Pottsville
Bethlehem
New York
Long Island
Levittown
Altoona
Allentown
Edison
Harrisburg
Reading
Trenton
Middletown
Lancaster
Brick
Philadelphia
Toms River
York
University of Delaware
Research-geared school
founded in 1743
Hagerstown
MARYLAND
Atlantic City
Germantown
Baltimore
Dover
Washington
DELAWARE
Manassas
Woodbridge
Stafford
Salisbury
Charlottesville
纽约市
费城
特拉华州
巴尔的摩市
华盛顿DC

Our Location at the Center of the East Coast of the United States



Located near the northern tip of Delaware in Newark, the University is convenient to East Coast cities, including:

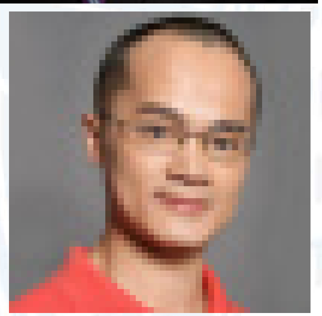
- Wilmington: 20 minutes
- Philadelphia: 50 minutes
- Baltimore: 1 hour
- Washington DC: 2 hours
- New York City: 2½ hrs

University of Delaware 特拉华大学1743年起，是全美最老的大学之一

The 7th oldest university

比普林斯顿大学还老

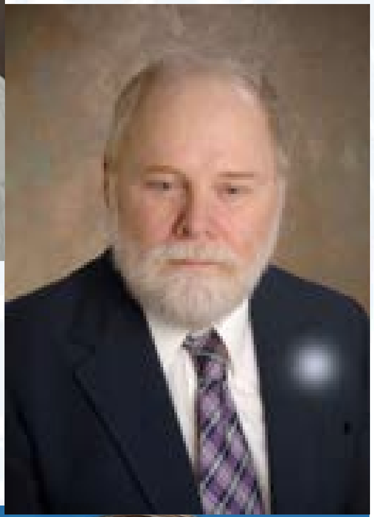

秋天的校园
UNIVERSITY OF DELAWARE

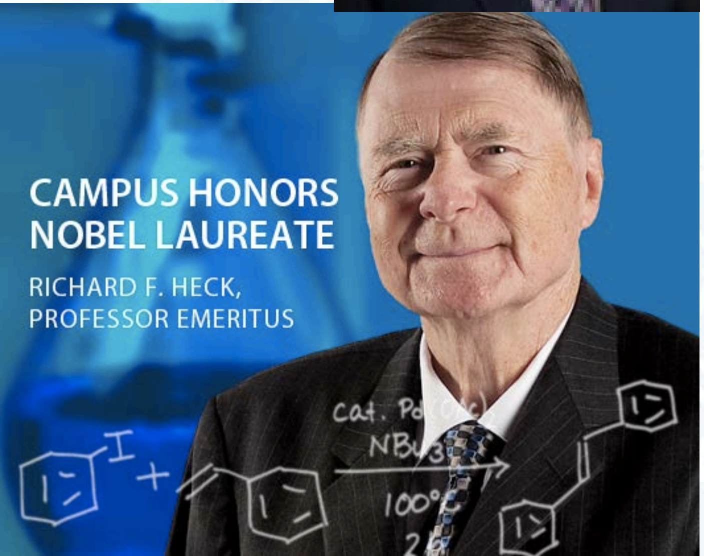


在美国只有5所大学产生过上面两种校友

Famous Alumni

- Joe Biden, the President of USA.
- Chris Christie, Governor of New Jersey and potential presidential candidate.
- Joe Flacco, NFL Super Bowl MVP (most valuable player).
- Xin Wang, builder of RenRen Net (人人网） 美团
- Wayne Westerman, inventor of multi-touch interface.





Famous Faculty

- **Dave Farber, Internet pioneer.**
  Pioneer's Circle of Internet Hall of Fame
  网络先驱者名人墙
- **Dave Mills, Internet pioneer and inventor of the Network Time Protocol.**
  NTP
- **Richard Heck, 2010 Nobel Prize in Chemistry.**

Innovating in leading tech sectors

FingerWorks, a company started by Electrical and Computer Engineering Professor John Elias and UD alumnus Wayne Westerman, developed the key technology in the iPhone's multi-touch interface.

2005年Apple公司买了FingerWorks公司后2007年才有iPhone

***"The iPhone would not have been possible without the engineering solutions of Professors John Elias and Wayne Westerman of the University of Delaware who developed multi-touch sensing capabilities"* --- Steve Jobs' biography**

而真正的智能手机又是从**iPhone**开始的

中文《乔布斯传》：

技术问题解决了，下面摆在乔布斯面前的就是生产出一种支持多点触动技术的触控板。这时候特拉华州一家小企业闯入了乔布斯的视野。这是一家名为 Finger Works 的小公司，公司创始人是美国特拉华大学的学者约翰·埃利亚斯和韦恩·韦斯特曼。当乔布斯将眼光投向这家公司的时候，它已经研发出了具有多点触控功能的平板电脑，并为这项将手指动作转化为有用功能的技术申请了专利。乔布斯发现这家企业后，很快就通过收购获得了该公司及其全部专利，这其中就包括触控缩放和滑动浏览两项专利，两位创始人也转为苹果公司员工，开始为苹果公司的发展出谋划策。

Our daily life has been changed by electronics

- I came to USA in 1988 and I do not feel anything else (clothing, food, housing, transportation) but our electronics, such as computers, phones, internet, are changed/improved over the past 35 years.

- Among all the electronics, due to the chip developments, computers and digital communications have changed the fastest.

我觉得过去40年美国人民的生活没变好，只是每人多了个手机

Microprocessors

- Intel 086, 4.77 MHz – 10 MHz, 1978
- Intel 286, 6 MHz – 12.5 MHz, 1982
- Intel 386, 16 MHz – 33 MHz, 1985
- Intel 486, 25 MHz – 100 MHz, 1989
- Intel Pentium, 60 – 233 MHz, 1993
- Intel Pentium Pro, 150 – 200 MHz, 1995
- Intel Pentium II, 233 – 450 MHz, 1997
- Intel Pentium III, 450 MHz – 1.4 GHz, 1999
- Intel Pentium 4, 1.4 – 3.8 GHz, 2000
- Intel Pentium D, 2.66 – 3.73 GHz, 2005

- Intel Core 2, 1.8 – 3.2 GHz, 2006
- Intel Core i3, 2.93 – 3.33 GHz, 2010
- Intel Core i5, 3 GHz, 2011
- Intel Core i7, 2.5 – 3.6 GHz, 2013
- Intel Core i9, 2.6 – 6 GHz, 2017 +

Historical Events

- 1984: AT&T was split to 8 baby bells
- 1995: AT&T was split again to 3 independent companies: AT&T (communications), Lucent (equipment), another one on computers
- 1989: Berlin Wall fall, cold war was over. Three big US defense companies were changed to commercial companies
  - Hughes, Direct TV, June 1994 (the eariest digital TV broadcast)
  - Rockwell, Computer Modems (shared 80 % market at the time)
  - TRW, automobile products
- Sun Workstations, 1988-2009
- WWW invented in 1989, public use in 1993
- MS Windows, 1995
- Myself
  - My first email was in 1989 without attachment, 1990 with attachment
  - Computer Modems connected to telephone lines 1991

Computer Modems

Telnet (use telephone line to connect to a PC)

Early Modems

1958, 100 bits/s, Bell 101
1962, 300 bits/s, V.21, Bell 103
1976, 1.2 kbs/s, Bell 202
1980, 1.2 kbs/s, Bell 212A, V.22
1984, 2.4 kbs/s, V.22bis
1984, 9.6 kbs/s V.32

Modern Modems

1991, 14.4 kbs/s, V.32bis, Rockwell
1994, 28.8 kbs/s, V.34
1996, 33.6 kbs/s
1998, 56 kbs/s, Rockwell-Lucent

Ethernet

Highspeed Modem, DSL, OFDM

WiFi

Wireless Modems, OFDM

A major chip maker: Broadcom

Cellular Systems/Cellphones

2G 1991

- GSM 1991 (Europe)
- IS-95 (US)

3G 2001

4G 2010

5G 2020

6G coming

Blackberry phones with data

Smartphones starting from iPhone in 2007

A major chip maker: Qualcomm

Digital vs. Analog Communications

家具搬运

工厂

住家

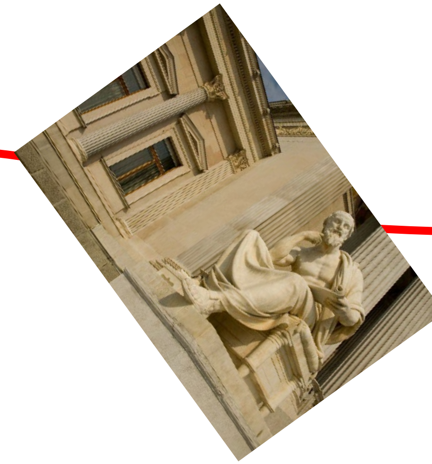
过去：
搬运现存的家具
两边都简单
但：慢！

现代：
把家具拆成最小块
再把小块装箱
只搬运规定好的箱子
两边都不简单，要拆要装
但：快！

Digital vs. Analog Communications

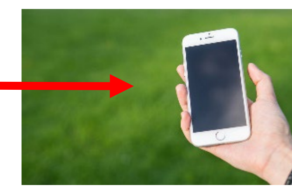
通信：信息的搬运

过去：
模拟通信
发送现存图像
两端方便
但送：慢



现代：
数字通信
把图像拆成最小单元的0和1序列
打包发送
两端不方便，要求高
但送：快

01101001
11001011
10101010



香农数字通信理论

将来：
发送更快，延时更短, 工业制造

频谱是固定的
地球大小是固定的

地球上的人口在增加：现已超过80亿

数字通信：快，但发收两端麻烦

- 正需要两大类人才：两端处理足够快和小体积
  - 一类是芯片等硬件人才
    - 芯片越来小，越来越快：可以小和快到在你的手机上实时地实现FFT等等处理
  - 一类是算法等软件人才
    - 各种调制，编码，压缩等先进算法的发现

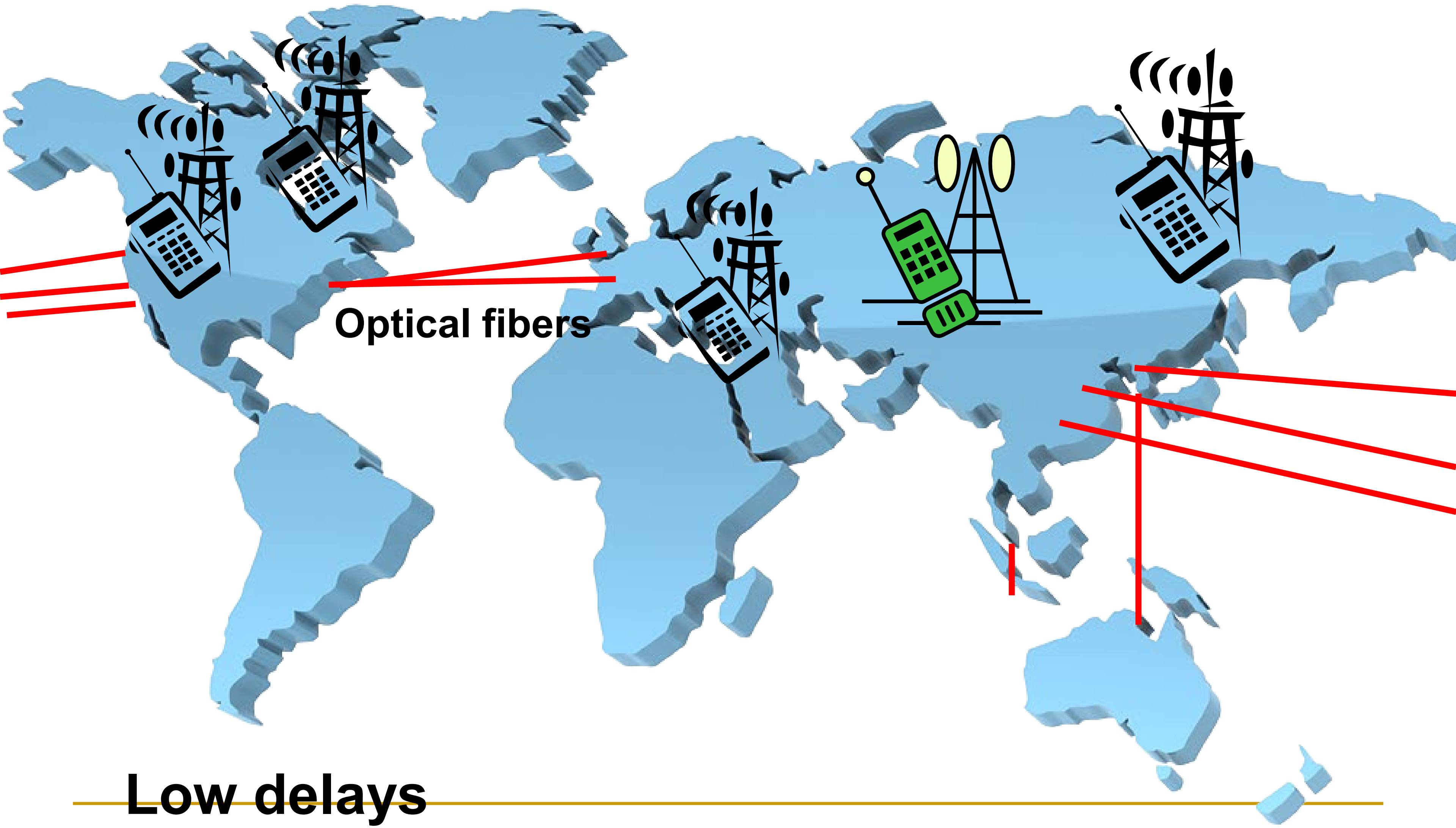
今天的重点

Connectivity: Before 1990's: the world is connected through stationary satellites

现在低轨卫星通信是一个补充
Starlink: 5000 个卫星

Large delays
Slow internet speed across continentals

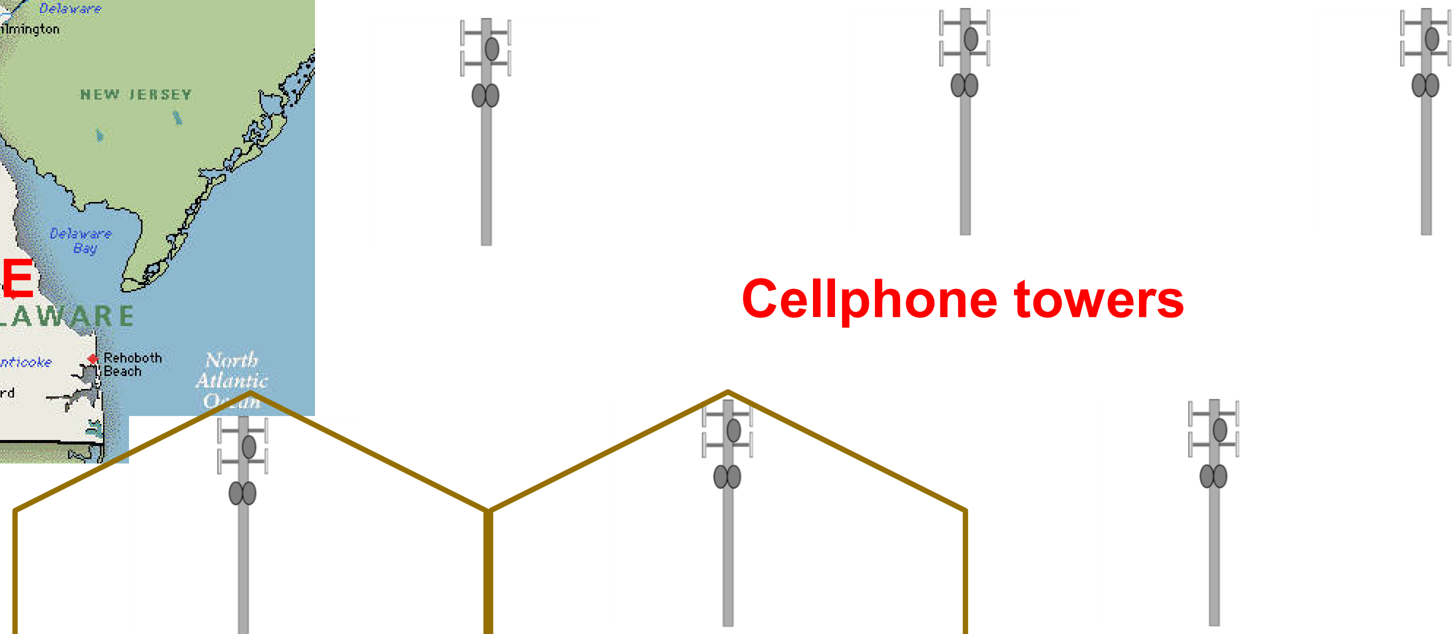
Connectivity: After 1990's: the world is connected through optical fibers and cellphone towers

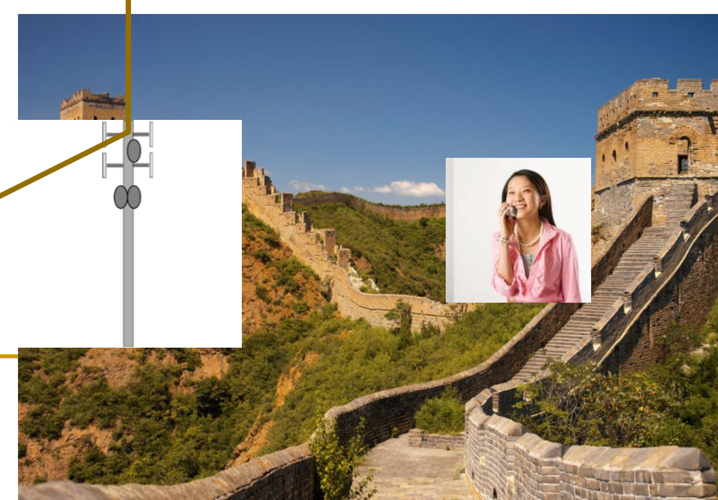


Low delays
Fast internet speed across continentals

Cellular Systems

Thank to the development of digital communications, you can communicate with your friends anywhere anytime now (probably not anything yet)





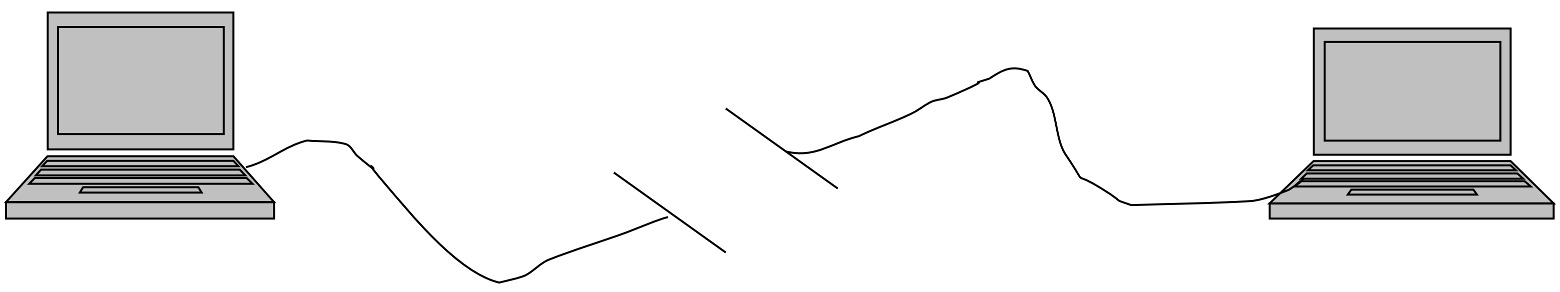
改变了我们每个人的日常生活

RF Communications

wireless

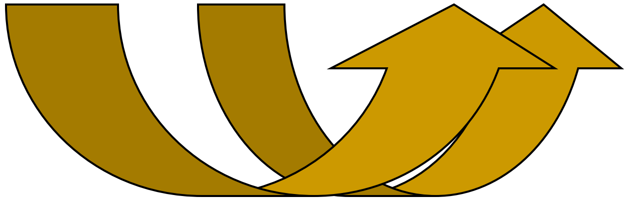
transmission through EM wave propagation

wired



Signal:

A(t) cos(p(t)) carry information

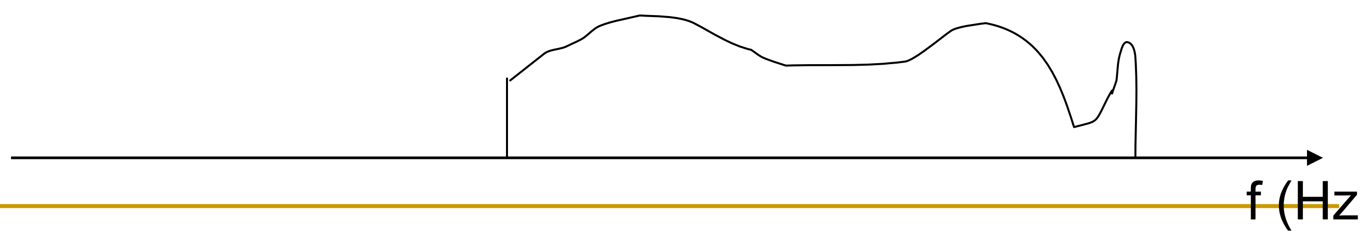


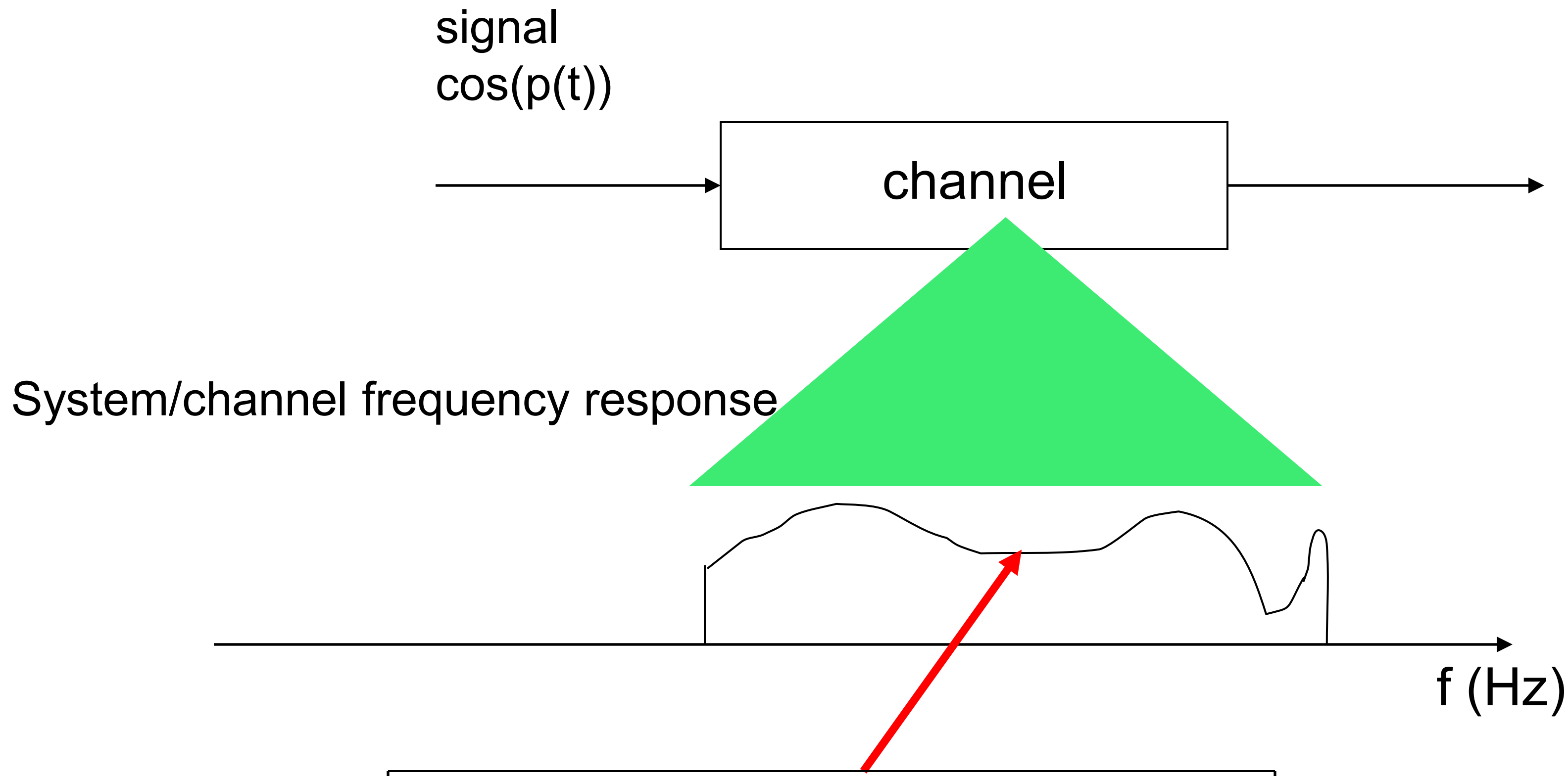
Channel:

a media that wave carrying information propagates through

Approximately a linear system

system frequency response





(approximately) flat

additive white Gaussian (AWGN)

$$y(n) = a\, x(n) + w(n)$$

where a is a constant

none flat

intersymbol interference (ISI)

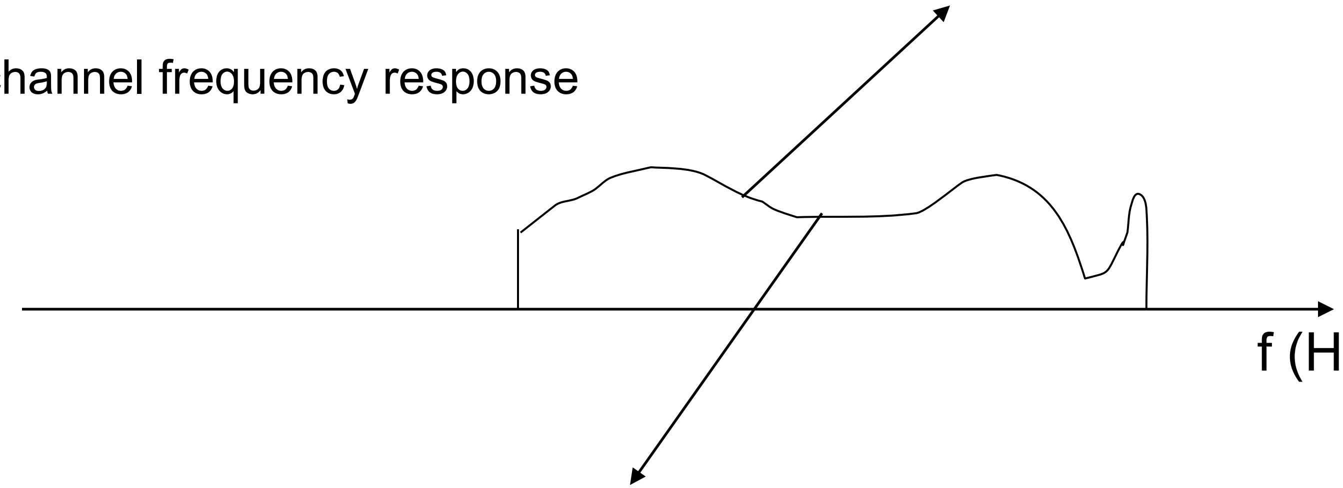
$$y(n) = a\, x(n) + b\, x(n-1) + w(n)$$

where a and b are constants

In broadband systems

this is wide

channel frequency response



f (Hz)

It is not possible to be flat → ISI occurs

More details will follow

Wireless: Multipath

Wired: None flat ISI channel
None ideal

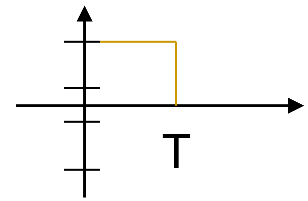
Wired (modem): Channel is fixed and has high SNR

Telnet

< 9.6 kbs/s	equalization (Lucky 60s)
9.6 kbs/s	TCM +equalization (DFE)
14.4 kbs/s	
28.8 kbs/s	TCM + equalization
33.6 kbs/s	
56 kbs/s	TCM/shaping+equalization

Mod/Code Demod/decode

Squeeze more bits to a symbol



time to send one symbol

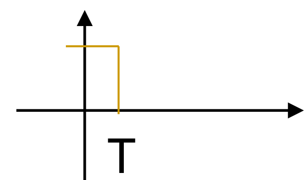
Asymmetric Digital Subscriber Line (ADSL)

Ethernet

6 Mbs/s

orthogonal frequency division multiplexing (OFDM)

or called discrete multi-tone (DMT)



Use more bandwidth

Data Rate	Wire Size	Distance
1.5 or 2 Mbps	0.5 mm	5.5 Km
1.5 or 2 Mbps	0.4 mm	4.6 Km
6.1 Mbps	0.5 mm	3.7 Km
6.1 Mbps	0.4 mm	2.7 Km

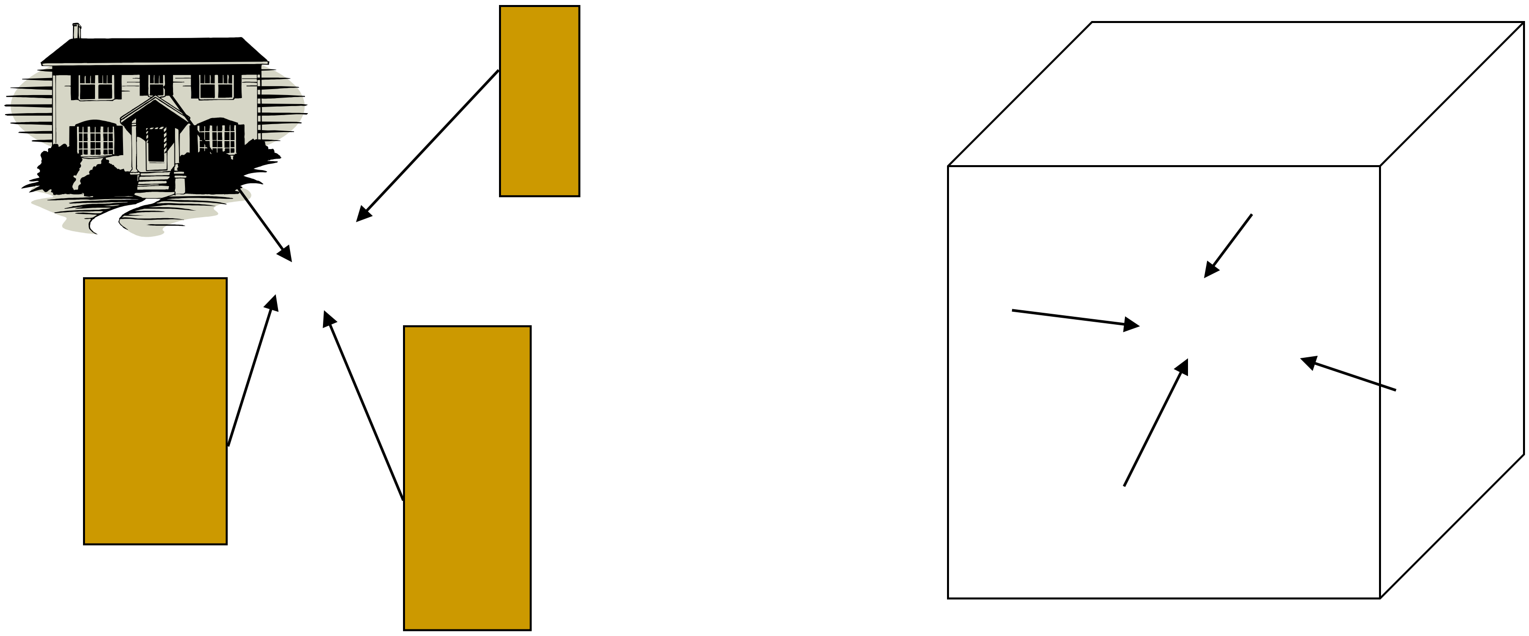
Computer modem was the most important business in communications in the 1990's

Wireless Systems: Channel varies/fades and not high SNR

outdoor

indoor

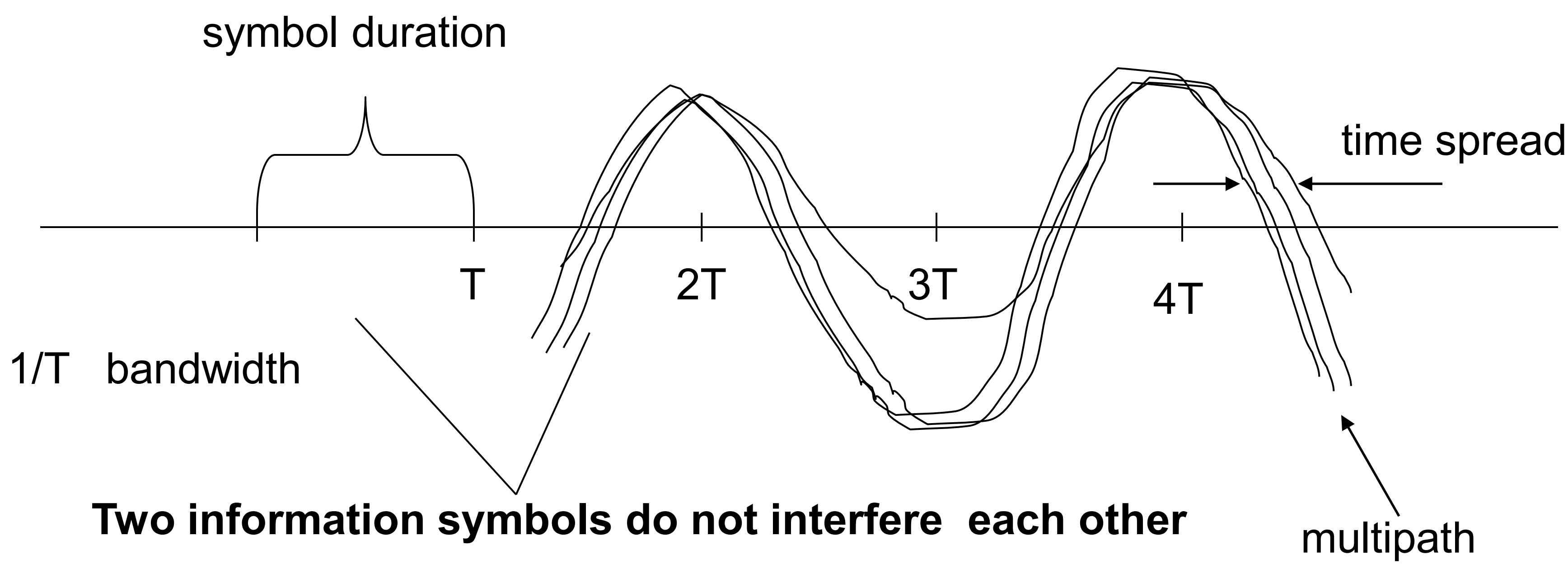
multipaths



multiple reflections

Multipath

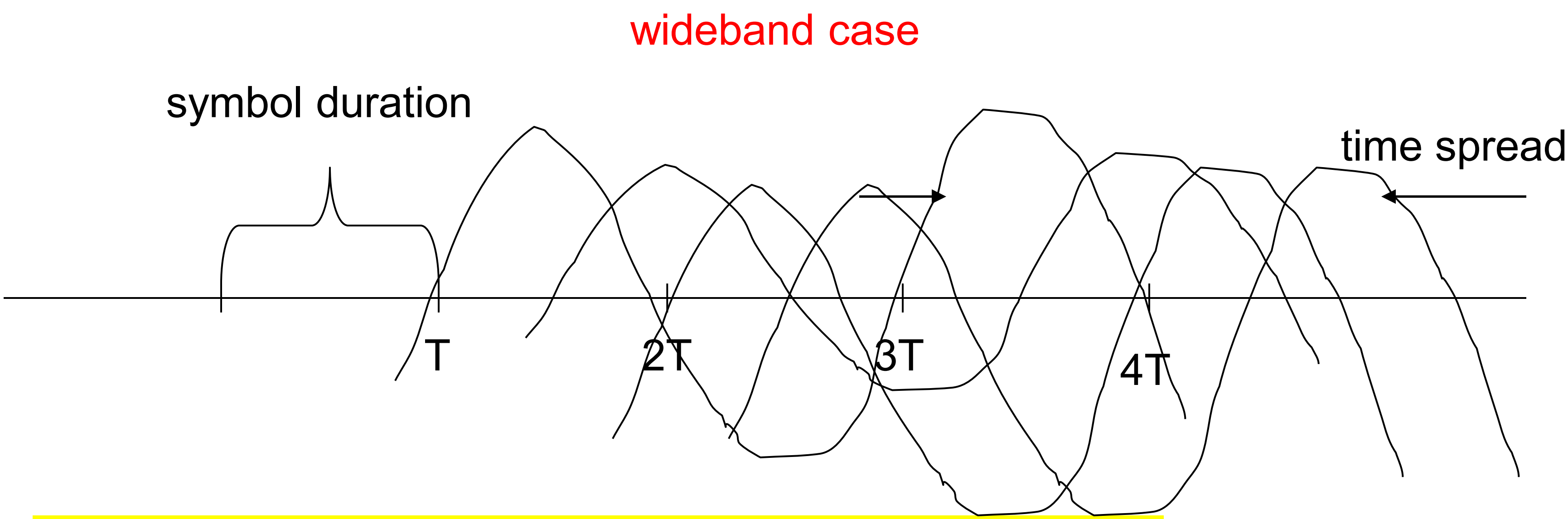
narrowband case



Two information symbols do not interfere each other

No intersymbol interferences

When the bandwidth is too wide or T is too small, the time spread may be across over multiple symbols. In this case, intersymbol interference (ISI) occurs.



x(t): transmitted signal; r(t): received signal

$$r(t) = \sum_{n=0}^{L} h(n)x(t-nT) + W(t)$$

ISI AWGN

Modulation Methods for Multi-users

FDMA: frequency division multiple access

1G

TDMA: time division multiple access

2G

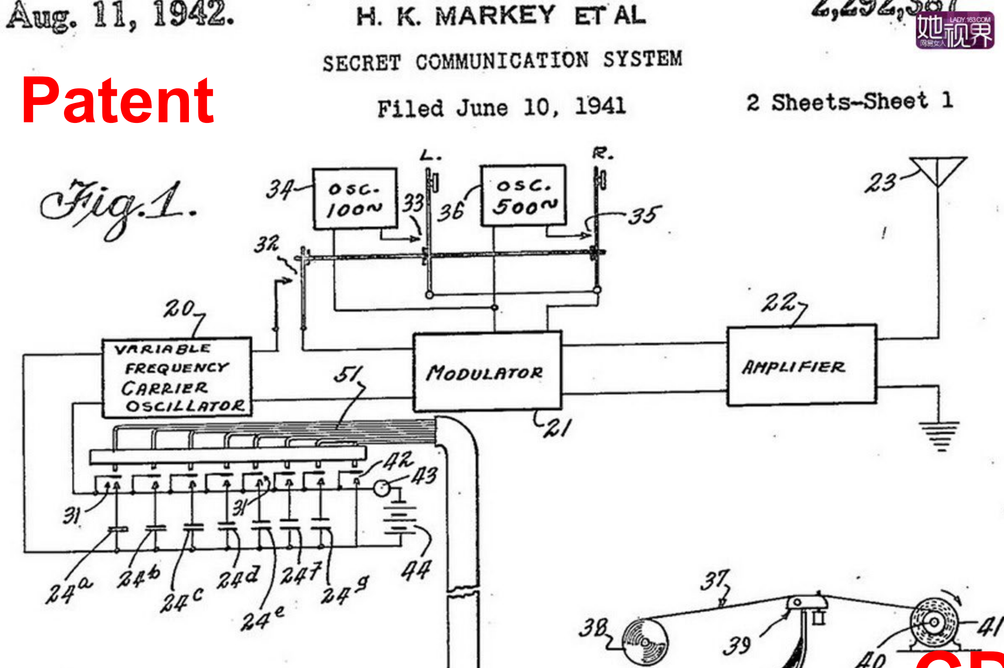
CDMA: code division multiple access

2G and 3G

OFDMA: orthogonal frequency division multiplexing access

4G and 5G

Patent



CDMA is based on the famous star actress Hedy Lamarr's invention of frequency hopping spread spectrum communications (88 frequencies, using piano role unpredictably change the signal, 88 black and white keys on a keyboard) 发明了扩频通信 to protect the allies wireless signals for radio-controlled torpedoes to avoid jamming, thus improve the hitting rate

张益唐

1）2013年还是Univ. of New Hampshire代课老师

2）2013年58岁时做出了著名古老的国际数学难题“孪生素数猜想”的最重大的一步

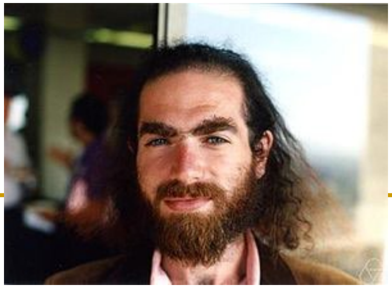
3）博士毕业后没找到合适的工作，在餐馆打工，送外卖等

4）成为最近几十年全世界数学界最传奇的三位人物之一

90年代普林斯顿大学的 Andrew Wiles 证明了费尔马大定理（Fermat‘s Last Theorem)，**消失了7年**

2000年代俄罗斯的 Grigori Perelman证明了庞加莱猜想（Poincare Conjecture）

拒绝领Fields和100万美金的Clay等大奖



国际数学4大期刊之一的《Annals of Mathematics》1945年第4期部分目录

第一篇：
On the General Partial Sums of a Fourier Series (pp. 511-532)
Liang-Pi Chu （西迁的浙江大学**朱良璧**）
第六篇：
A Generalization of the Relativistic Theory of Gravitation (pp. 578-584)
Albert Einstein
第十二篇：
On the Curvatura Integra in a Riemannian Manifold (pp. 674-684)
Shiing-shen Chern（西南联大**陈省身**）

朱先生和陈先生都是在战乱时期做的科研工作，当时都是30多岁

朱先生最近刚刚去世，享年108岁。她是著名数学家陈建功先生的夫人

永远不要低估自己， 真不知道20年后，或许是你自己，或许是你身边的人已做出惊人的成绩

Number of Multipaths vs. Modulation Methods in Wireless Applications

	Bandwidth 带宽	
2G (IS-95)	1.23 MHz	Almost optimal for single path (or equivalent)
3G (WCDMA CDMA2000)	< 11 MHz	6--8 multipaths (or equivalent) almost the break point to use CDMA
IEEE 802.11b (LAN)	similar to 3G	
		past
IEEE 802.11a (LAN) WiFi	20 MHz	16 multipaths (or equivalent) OFDM
IEEE 802.11n (LAN) WiFi	20 & 40MHz	40MHz doubles everything in 20MHz OFDM
4G LTE	20 MHz	16 multipaths (or equivalent) OFDM and SC-FDE **Downlink Uplink**
5G	100 MHz	**current**
6G	??	??? **future**

Digital Wireless Standards vs. Bandwidth (#of Multipaths)

- A standard is determined by a bandwidth (so far)
- 2G: 1.23MHz, almost the highest for non-ISI (or highest for TDMA in cellular systems)
  - Both TDMA and CDMA (DS spread spectrum) work well
- 3G: ~10 MHz, a few multipaths, highest for CDMA
  - Due to the ISI and wireless varying channels, time domain equalization may not work well, TDMA is not used, but CDMA (DS spread spectrum) is used in all standards since it is good to resist a few chip level time delays (RAKE receiver)
- 4G: 20 MHz, more multipaths
  - **Even CDMA RAKE receiver may not work well**
  - **OFDM is adopted (down link)**
    - Due to wireless channel varying, the number of subcarriers, N=64, is used, 25% data overhead for the cyclic prefix (CP) to deal with the multipaths
- 5G: 100 MHz, OFDM

Complexities (for block length N)

- 2G and 3G : N
- 4G and 5G: $N \log N$
- 6G: ??

Some Comments on These Standards

- The modulation schemes for all these standards are determined by the way to deal with ISI.
  - In my opinion, multi-access or multi-cells is NOT the problem to determine which basic modulation is used.
  - Adding more antennas or not is the hardware choice and may not determine a basic modulation (?)
  - A basic modulation has to be simple.
- Dealing with ISI is the key !

The Most Noticeable Things in Digital Communications in the Past

数字通信的里程碑成果

Communication is always one of the most important tasks among any animals.

- Channel Coding (Always the most impacted, 海底捞针)
  - Shannon’s Channel Coding Theorem and Capacity (如来佛)
  - Reed-Solomon Codes (BCH Codes) (孙悟空)
  - Viterbi Decoding
  - Trellis Coded Modulation (TCM)
  - Turbo Codes (LDPC Codes, Iterative Decoding)

The Most Noticeable Things in Communications in the Past

- Source Coding (Compression, 精益求精)
  - Shannon's Source Coding (both lossless and lossy) Theorem
  - Lossless Coding
    - Huffman Coding
    - Lempel-Ziv-Welch Algorithm
  - Lossy Coding
    - DCT, DWT
  - Coded Excited Linear Prediction (CELP) in speech coding

The Most Noticeable Things in Communications in the Past

- Systems: Modulations (排兵布阵)
  - CDMA
  - OFDM
  - MIMO: This is natural and not surprising

The Most Noticeable Things in Communications in the Past

- Systems: Receiver and Signal Processing (画蛇点睛)
  - Matched Filtering
  - Decision Feedback Equalizer (DFE)

The Most Noticeable Things in Communications in the Past

- Techniques/Skills (鲁班在世)
  - Synchronization (Phase Locked Loop)

6G: Bandwidth **>>100** MHz (?)

- To have extreme low latency, large bandwidth is necessary
- Can OFDM Still Work Well?
  - Much more multipaths exist

    → much large CP length to deal with multipaths

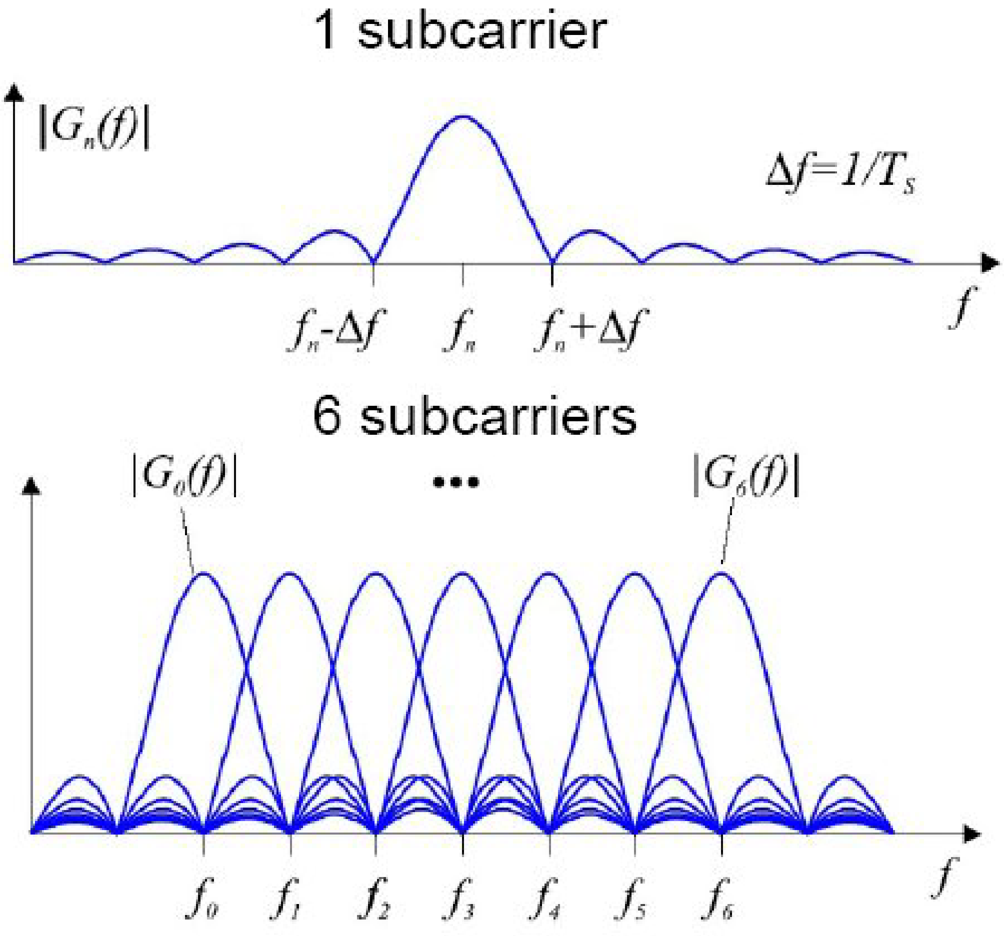
    → much large number *N* of subcarriers/IFFT_size

    → may lead to break down OFDM??
      - High PAPR (?)
      - Time varying channels (?)
- What bandwidth will be the breakpoint for OFDM in **cellular systems**? How large will a bandwidth go?
  - Can we make it work with a **fixed *N*** while it still can deal with the increased # of multipaths? Can we make it ***scalable to a bandwidth***?
    - **Single antenna VOFDM** [Xia, TCOM, August, 2001, also ICC 2000]

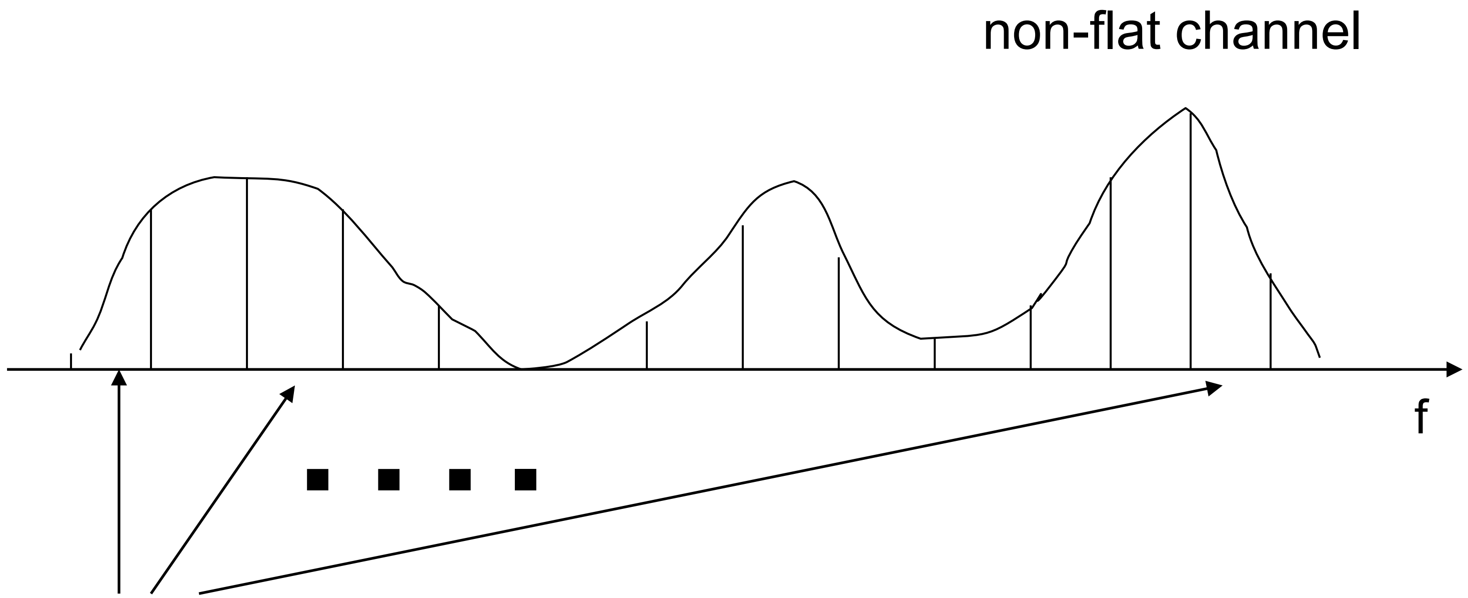
This is also the same as the current OTFS

OFDM

- OFDM: orthogonal frequency division multiplexing



Why OFDM ? -------- Rough Idea



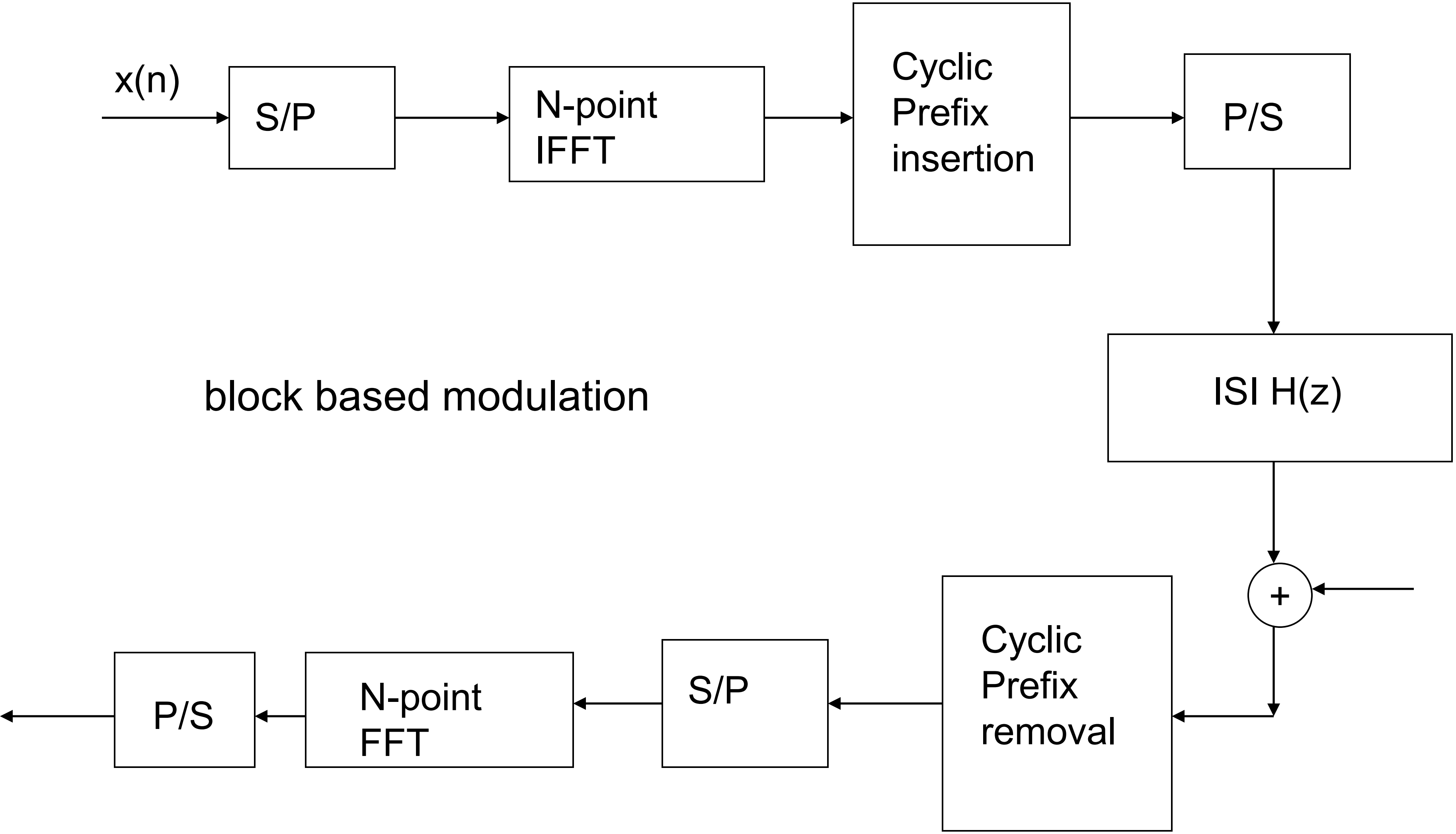
Narrow subchannels using multiple subcarriers

- These subchannels may have overlapped spectrums. So, OFDM is bandwidth efficient
  - The analog signals in these subchannels are not orthogonal each other. Different from FDMA
  - **Their discrete/sampled signals are orthogonal each other.**

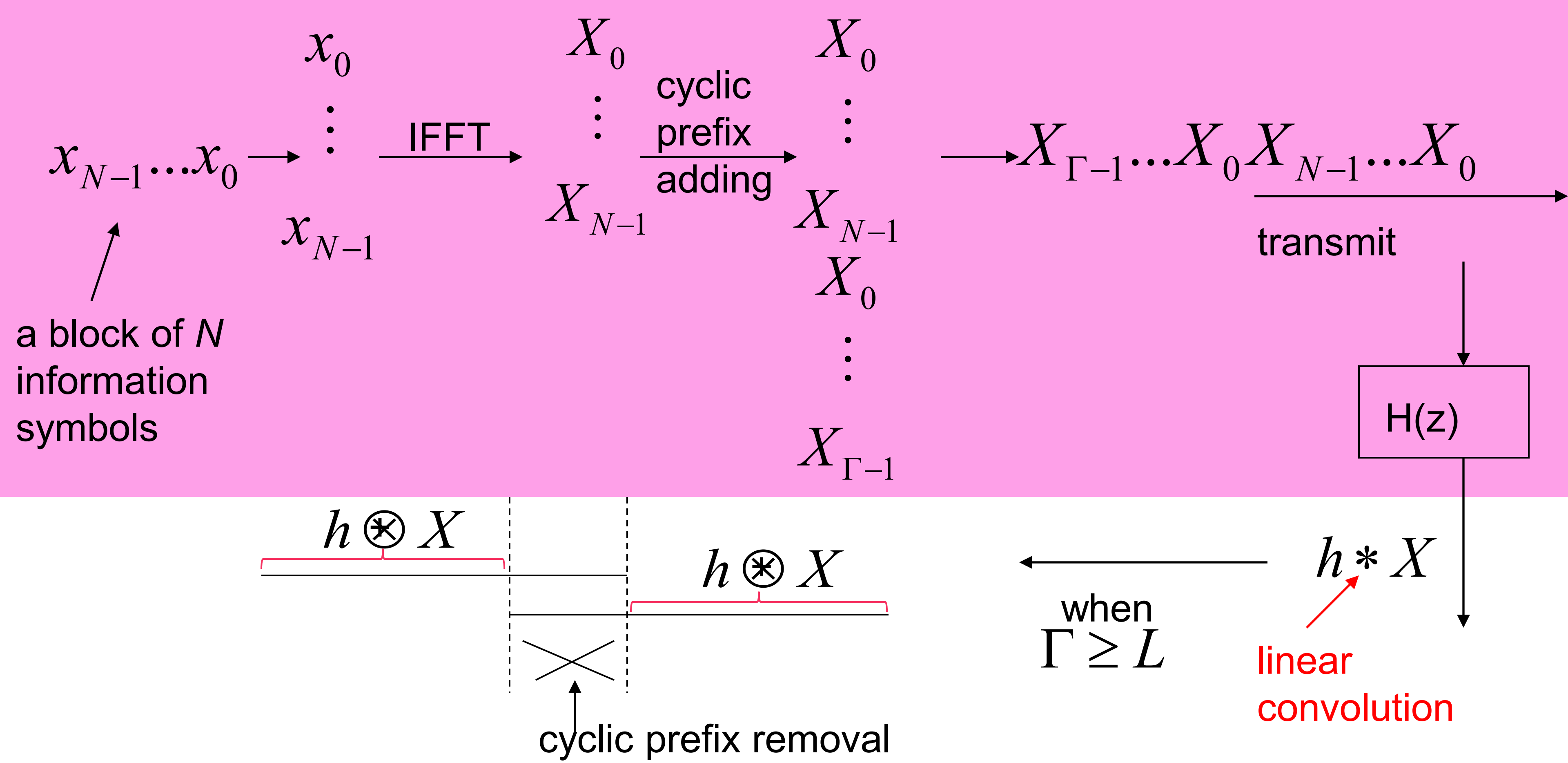
Each subchannel is narrow and therefore more flat

- It does not have ISI.

OFDM



block based modulation



$$Y_k = H_k \cdot x_k,\ k = 0,1,\ldots,N-1 \xleftarrow{\text{FFT}} h \circledast X$$

cyclic
convolution

$$H_k = H(e^{j2\pi\frac{k}{N}}) = \sum_{n=0}^{L} h(n) e^{-j\frac{2\pi nk}{N}}$$

ISI channel

$$y(k) = \sum_{n=0}^{L} h(n)x(k-n) + w(k)$$

adding cyclic prefix as an additional data rate overhead

N ISI-free subchannels

$$Y_k = H_k \cdot x_k + W_k, \quad k = 0,1,\ldots,N-1$$

Each subchannel corresponds to a DFT component H_k of the ISI channel. If the frequency component H_k is small (bad), then this subchannel is bad.

For 20 MHz Channel, OFDM

L <= 16

N=64

Γ=L=16, 25% data rate overhead

Basic Idea for Vector OFDM Single Transmit Antenna System

$x_0, \ldots, x_{N-1} \xrightarrow{\text{N-point IFFT}} X_0, \ldots, X_{N-1} \xrightarrow{\text{cyclic prefix adding}} X_0, \ldots, X_{N-1}, X_0, \ldots, X_{\Gamma-1} \xrightarrow{\text{P/S}}$

scalar

OFDM, when data rate overhead $\Gamma \geq L$

Receiver:

$$Y_k = H_k x_k + W_k$$

N scalar channels/equations

$\underline{x}_0, \ldots, \underline{x}_{N-1} \xrightarrow{\text{N-point IFFT Component wise}} \underline{X}_0, \ldots, \underline{X}_{N-1} \xrightarrow{\text{cyclic prefix adding}} \underline{X}_0, \ldots, \underline{X}_{N-1}, \underline{X}_0, \ldots, \underline{X}_{\tilde{\Gamma}-1} \xrightarrow{\text{P/S}}$

M by 1 vector

VOFDM, when data rate overhead $\tilde{\Gamma} \geq \tilde{L} \approx \dfrac{L}{M}$

Receiver:

$$\underline{Y}_k = \underline{H}_k \underline{x}_k + \underline{W}_k$$

N M by 1 vector channels/equations

VOFDM: Vectorized Channel

- The ISI channel *H(z)* is converted into N vector channels

M symbols in each vector are in ISI

$$\underline{Y}_k = \underline{H}_k \underline{x}_k + \underline{W}_k, \quad k=0,1,\ldots,N-1$$

where $\underline{H}_k$ is the M by M blocked version of the original frequency responses of the ISI *H(z)*:

$$\underline{H}_k = \underline{H}(e^{j2\pi k/N}),$$

$$\underline{H}(z) = \begin{bmatrix} H_0(z) & z^{-1}H_{M-1}(z) & \cdots & z^{-1}H_1(z) \\ H_1(z) & H_0(z) & \cdots & z^{-1}H_2(z) \\ \vdots & \vdots & \vdots & \vdots \\ H_{M-1}(z) & H_{M-2}(z) & \cdots & H_0(z) \end{bmatrix}$$

$$H_m(z) = \sum_{l=0}^{\tilde{L}'} h(Ml+m)z^{-l}, \quad 0 \le m \le M-1.$$

$$\boxed{m\text{th polyphase component of } H(z)}$$

$$\tilde{L}' = \left\lfloor \frac{L}{M} \right\rfloor$$

Vectorized Channel Example

If $H(z) = 1 + 0.9z^{-1} - 0.8z^{-2} + 0.6z^{-3} + 0.5z^{-4} - 0.4z^{-5}$, vector size M=2,

then, its polyphase components are

$$H_0(z) = 1 - 0.8z^{-1} + 0.5z^{-2}, \quad H_1(z) = 0.9 + 0.6z^{-1} - 0.4z^{-2}$$

and the vector channel coefficient matrices are

$$L = 5$$

$$\tilde{L} = \left\lceil \frac{L}{M} \right\rceil = \left\lceil \frac{5}{2} \right\rceil = 3$$

$$\underline{H}(z) = \begin{bmatrix} H_0(z) & z^{-1}H_1(z) \\ H_1(z) & H_0(z) \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 \\ 0.9 & 1 \end{bmatrix} + \begin{bmatrix} -0.8 & 0.9 \\ 0.6 & -0.8 \end{bmatrix} z^{-1} + \begin{bmatrix} 0.5 & 0.6 \\ -0.4 & 0.5 \end{bmatrix} z^{-2} + \begin{bmatrix} 0 & -0.4 \\ 0 & 0 \end{bmatrix} z^{-3}$$

VOFDM, OFDM, SC-FDE

- When M=1, VOFDM=OFDM
- When M=N and the FFT size is 1, VOFDM=SC-FDE:
  - at the transmitter, no IFFT is implemented (so the PAPR is not changed) but just CP of the information symbols is inserted; low PAPR
  - at the receiver, both FFT and IFFT, and frequency domain equalizer are implemented
- VOFDM is a bridge between OFDM and SC-FDE
  - Its ML receiver complexity is also in the middle

VOFDM: Advantages

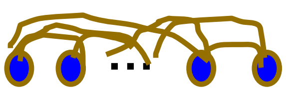
- Cyclic prefix data rate overhead reduction when the FFT/IFFT size is fixed
  - For OFDM, it is $\frac{L}{N}$
  - For VOFDM, it is $\frac{L}{MN}$
- For fixed cyclic data rate overhead, the FFT/IFFT size can be reduced by *M* times
  - The IFFT size reduction reduces the peak-to-average power ratio (PAPR), which is important in cellular communications.
- Good to deal with both time and Doppler spreads.
- Scalable to bandwidth: Increase bandwidth, increase vector size *M*, while IFFT size *N* can be fixed.

Recall Physical Layer Communications Developments in Recent Decades for Both Wireless and Wired Systems

- It has been always on dealing with inter-symbol interference (ISI)

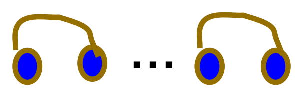
Time domain single carrier vs. equalization

Maximum # symbols in ISI



VOFDM

No, or 2, or 3, …, or Maximum # (**you choose**) symbols in ISI



Frequency domain OFDM

No ISI

Is this VOFDM something to think about after OFDM?

Or what's next???

Conclusion: Modulations

- Wireless Communications Can Be Categorized as
  - Narrowband: both TDMA and CDMA work well
    - 2G complexity *N*
  - Low wideband: CDMA
    - 3G complexity *N*
  - Wideband: OFDM
    - 4G, 5G complexity *N* log *N*
  - High wideband: VOFDM (it is scalable with the bandwidth)
    - 6G? complexity flexible

Conclusion

- More bandwidth will be used in the next 6G cellular systems
- In my opinion, a basic modulation format for a standard is still determined by how to deal with ISI (码间干扰）
- Low latency high speed real-time communications, with applications in autonomous cars, auto factories, VR etc.
  - 20年后，会有居家照顾老人的机器人了么？
- Even if cellphone communications is done/matured, other communications will appear

Thank you!