Mobile Communications

TCS 455

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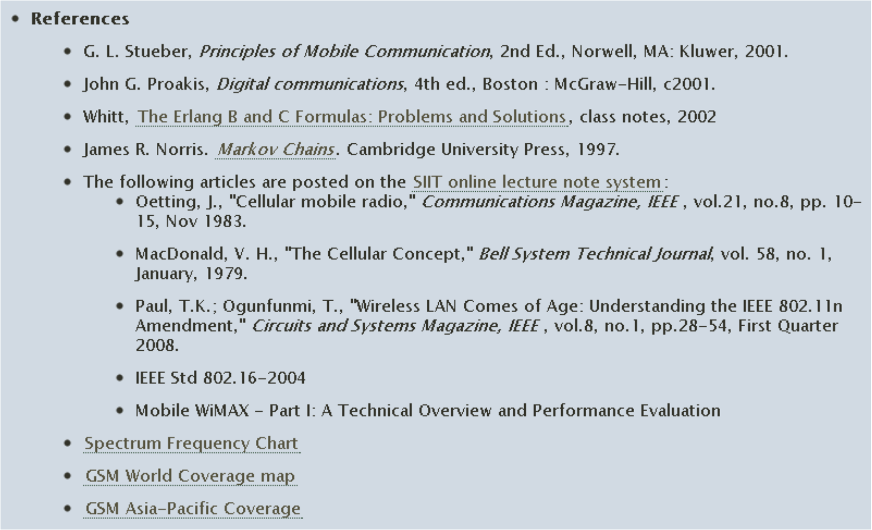
Lecture 23

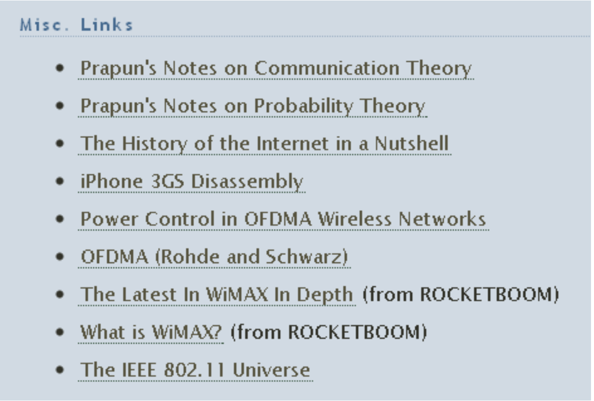
Office Hours:
BKD 3601-7
Tuesday 14:00-16:00
Thursday 9:30-11:30

Announcements

- Read
  - Chapter 9: 9.1 – 9.5
  - Section 1.2 from [Bahai, *Multi-carrier Digital Communications: Theory And Applications Of OFDM*, 2002]
    - Uploaded to the SIIT online lecture note system.
- Check the course web site for some interesting resources and references.



- **References**
  - G. L. Stueber, *Principles of Mobile Communication*, 2nd Ed., Norwell, MA: Kluwer, 2001.
  - John G. Proakis, *Digital communications*, 4th ed., Boston : McGraw-Hill, c2001.
  - Whitt, The Erlang B and C Formulas: Problems and Solutions, class notes, 2002
  - James R. Norris. *Markov Chains*. Cambridge University Press, 1997.
  - The following articles are posted on the SIIT online lecture note system:
    - Oetting, J., "Cellular mobile radio," *Communications Magazine, IEEE* , vol.21, no.8, pp. 10-15, Nov 1983.
    - MacDonald, V. H., "The Cellular Concept," *Bell System Technical Journal*, vol. 58, no. 1, January, 1979.
    - Paul, T.K.; Ogunfunmi, T., "Wireless LAN Comes of Age: Understanding the IEEE 802.11n Amendment," *Circuits and Systems Magazine, IEEE* , vol.8, no.1, pp.28-54, First Quarter 2008.
    - IEEE Std 802.16-2004
    - Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation
  - Spectrum Frequency Chart
  - GSM World Coverage map
  - GSM Asia-Pacific Coverage



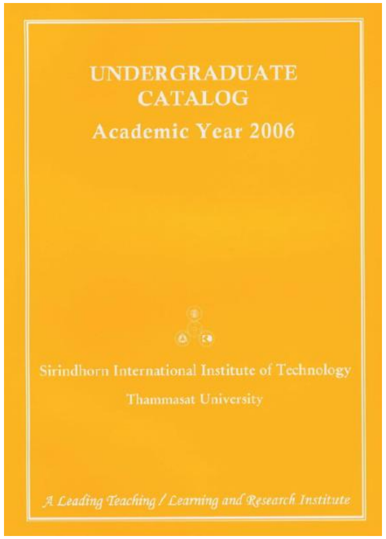
Misc. Links

- Prapun's Notes on Communication Theory
- Prapun's Notes on Probability Theory
- The History of the Internet in a Nutshell
- iPhone 3GS Disassembly
- Power Control in OFDMA Wireless Networks
- OFDMA (Rohde and Schwarz)
- The Latest In WiMAX In Depth (from ROCKETBOOM)
- What is WiMAX? (from ROCKETBOOM)
- The IEEE 802.11 Universe

Where are we?

1. Basic communication systems (review)
2. Cellular communications, Principles of cellular radio
3. Duplexing: TDD vs FDD
4. Multiple access schemes: FDMA, TDMA, CDMA
5. Application: Spread Spectrum Communications (DSSS) and GPS
6. Multi-carrier and OFDM systems
7. Application: GSM, UMTS (W-CDMA)
8. Application: WiMAX and 802.11n
9. Mobile radio propagation and channel modelling, Diversity, Equalization, Channel coding
10. MIMO/SDMA

TCS 455 Mobile Communications 3(3-0-6)
Prerequisite: TCS 332 or consent of Head of School
Principles of cellular radio, mobile radio propagation and channel modeling, multiple access methods, physical and logical channels, digital mobile communication systems: TDMA, GSM, CDMA, WCDMA, multi-carrier and OFDM systems.



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Academic Year 2006

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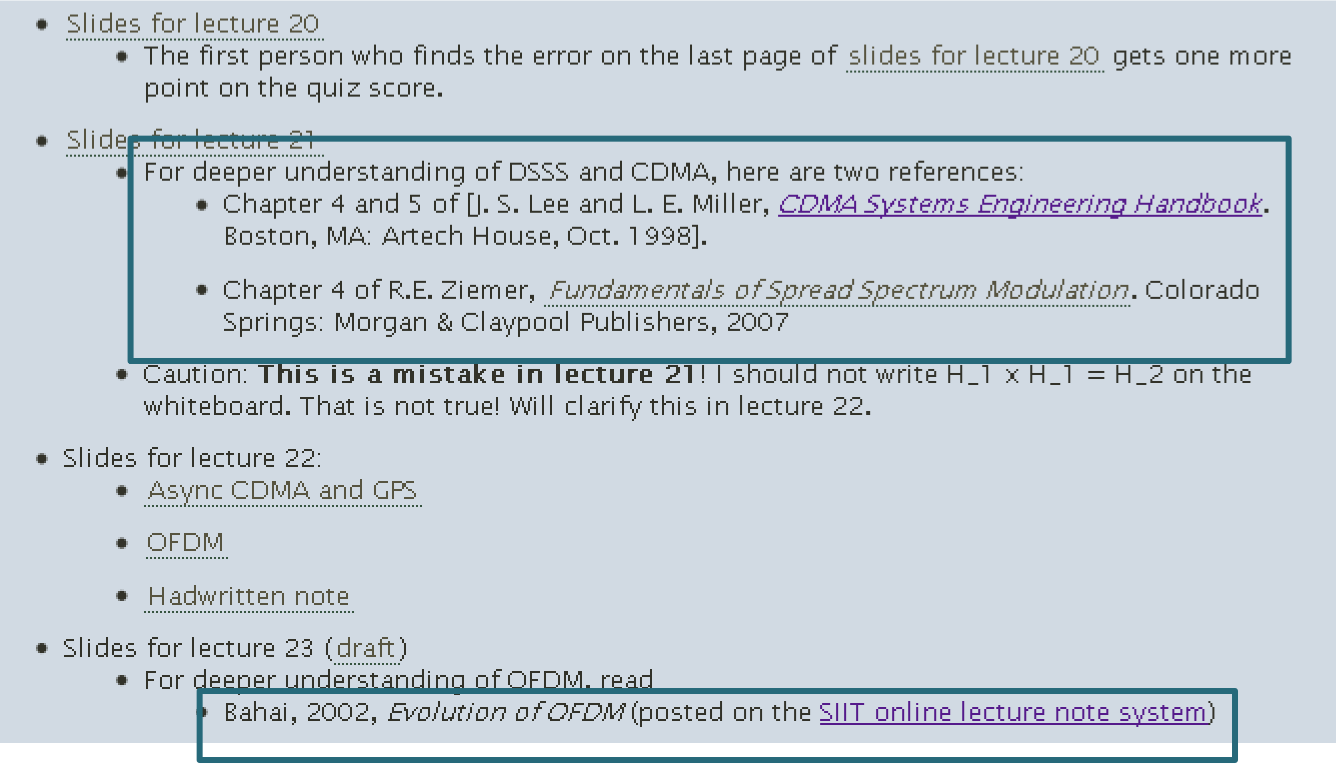
Assignments	5%
Class Participation (10%) and Quizzes (5%)	15%
Midterm Examination	40%
Final Examination (comprehensive)	40%

Final Exam: 9-12PM, March 9 BKD 3506

More reading.....



- Slides for lecture 20
  - The first person who finds the error on the last page of slides for lecture 20 gets one more point on the quiz score.
- Slides for lecture 21
  - For deeper understanding of DSSS and CDMA, here are two references:
    - Chapter 4 and 5 of [J. S. Lee and L. E. Miller, *CDMA Systems Engineering Handbook*. Boston, MA: Artech House, Oct. 1998].
    - Chapter 4 of R.E. Ziemer, *Fundamentals of Spread Spectrum Modulation*. Colorado Springs: Morgan & Claypool Publishers, 2007
  - Caution: **This is a mistake in lecture 21**! I should not write H_1 x H_1 = H_2 on the whiteboard. That is not true! Will clarify this in lecture 22.
- Slides for lecture 22:
  - Async CDMA and GPS
  - OFDM
  - Hadwritten note
- Slides for lecture 23 (draft)
  - For deeper understanding of OFDM, read
    - Bahai, 2002, *Evolution of OFDM* (posted on the SIIT online lecture note system)

Chapter 5

OFDM

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OFDM

- Let S_1, S_2, …, S_N be the information symbol.
- The discrete baseband OFDM modulated symbol can be expressed as

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k \exp\left(j \frac{2\pi kt}{T_s} \right), \quad 0 \le t \le T_s$$

$$= \sum_{k=0}^{N-1} S_k \underbrace{\frac{1}{\sqrt{N}} 1_{[0,T_s]}(t) \exp\left(j \frac{2\pi kt}{T_s} \right)}_{c_k(t)}$$

Some references may use different constant in the front

Some references may start with different time interval, e.g. [-T$_s$/2, +T$_s$/2]

Note that:

$$\mathrm{Re}\{s(t)\} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \left(\mathrm{Re}\{S_k\} \cos\left(\frac{2\pi kt}{T_s} \right) - \mathrm{Im}\{S_k\} \sin\left(\frac{2\pi kt}{T_s} \right) \right)$$

OFDM Application

- 802.11 Wi-Fi: a and g versions
- DVB-T (the terrestrial digital TV broadcast system used in most of the world outside North America)
- DMT (the standard form of ADSL)
- WiMAX

We shall focus on the **single user** case of OFDM.

Motivation

Why do ne need OFDM?

- First, we study the wireless channel.
- There are a couple of difficult problems in communication system over wireless channel.
- Also want to achieve high data rate (throughput)

Chapter 5

OFDM

Wireless Channel

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Single Carrier Transmission

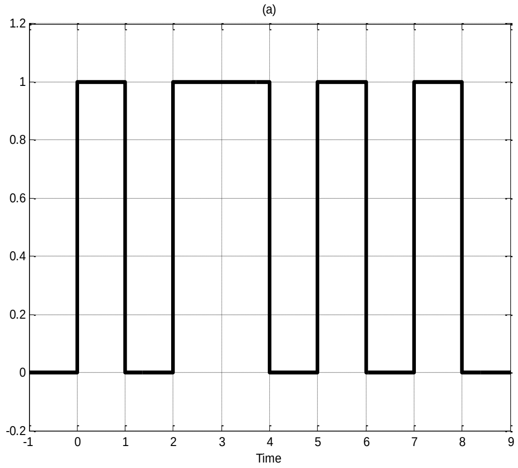
- Baseband:

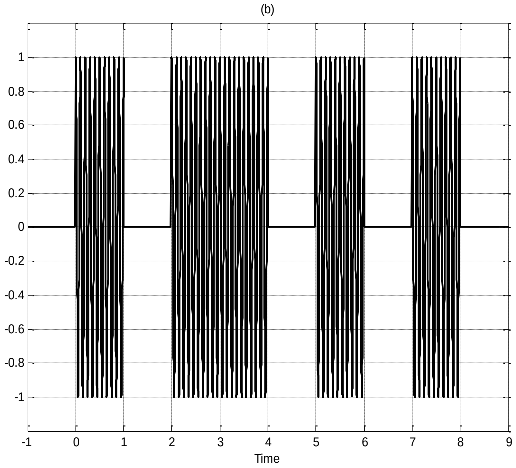
$$s(t)=\sum_{k=0}^{N-1} s_k\, p(t-kT_s)$$

$$p(t)=1_{[0,T_s)}(t)=\begin{cases}1, & t\in[0,T_s)\\ 0, & \text{otherwise.}\end{cases}$$

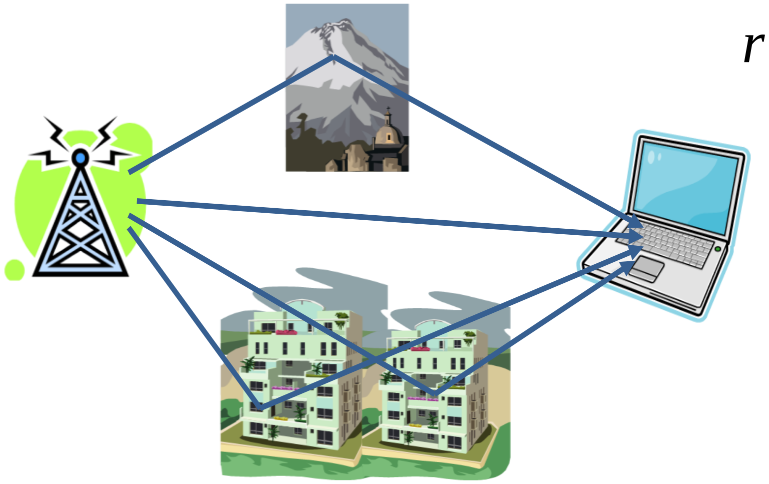
- Passband:

$$x(t)=\mathrm{Re}\left\{s(t)e^{j2\pi f_c t}\right\}$$





Wireless Comm. and Multipath Fading

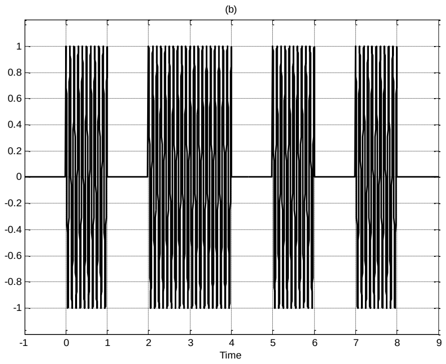


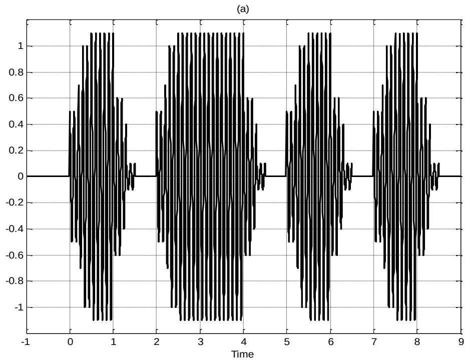
$$r(t)=x(t)*h(t)+n(t)=\sum_{i=0}^{v}\beta_i x(t-\tau_i)+n(t)$$

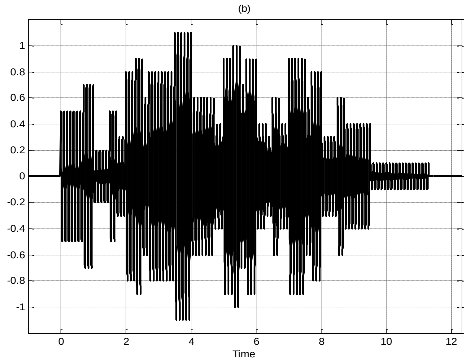
$$\boxed{h(t)=\sum_{i=0}^{v}\beta_i\delta(t-\tau_i)}$$

$$h_1(t)=0.5\delta(t)+0.2\delta(t-0.2T_s)+0.3\delta(t-0.3T_s)+0.1\delta(t-0.5T_s)$$

$$h_2(t)=0.5\delta(t)+0.2\delta(t-0.7T_s)+0.3\delta(t-1.5T_s)+0.1\delta(t-2.3T_s)$$

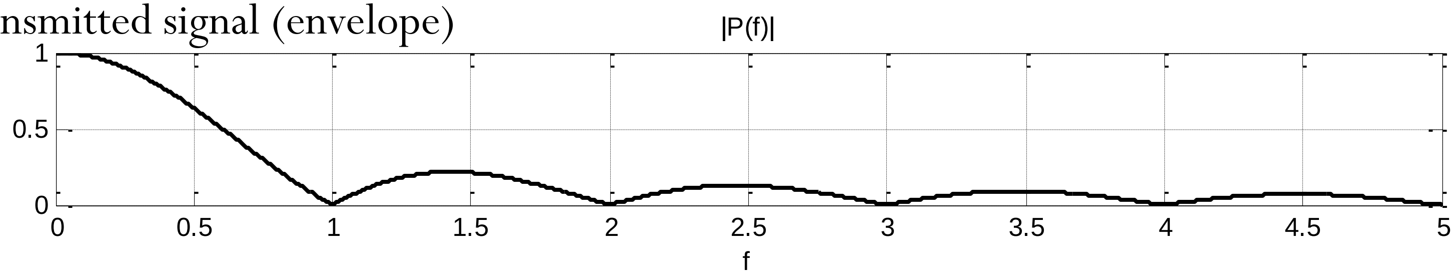




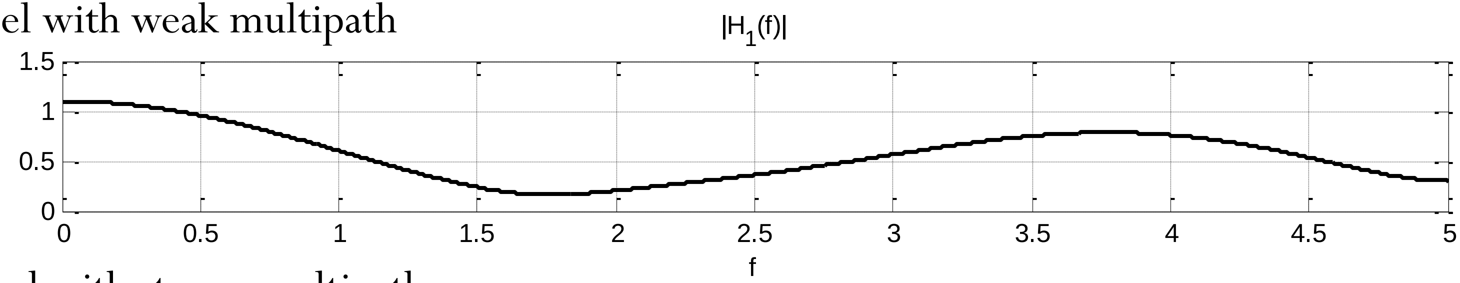


Frequency Domain

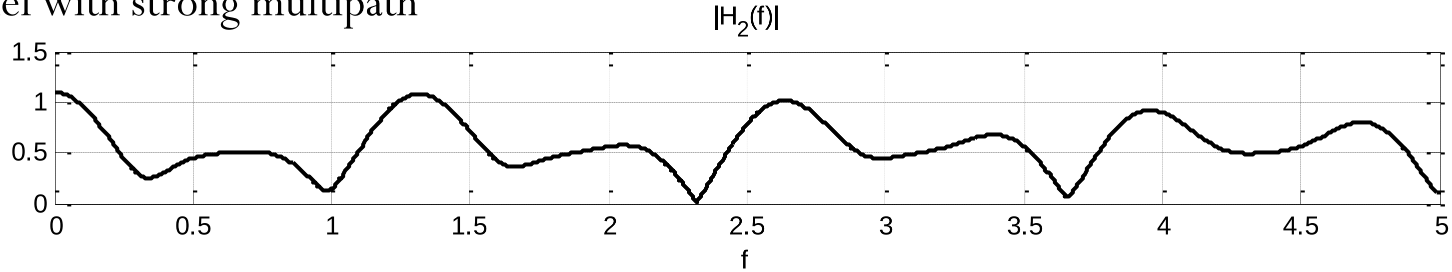
The transmitted signal (envelope)



Channel with weak multipath

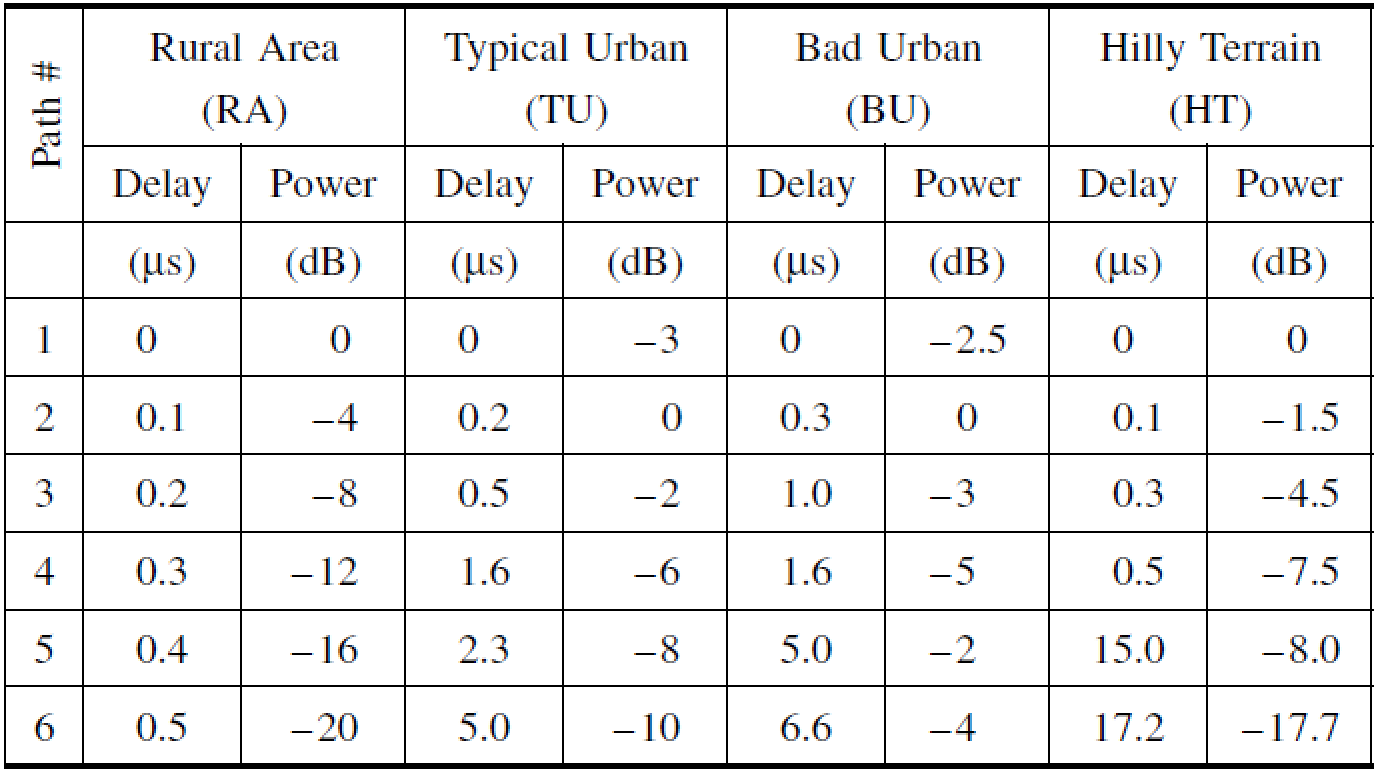


Channel with strong multipath



COST 207 Channel Model

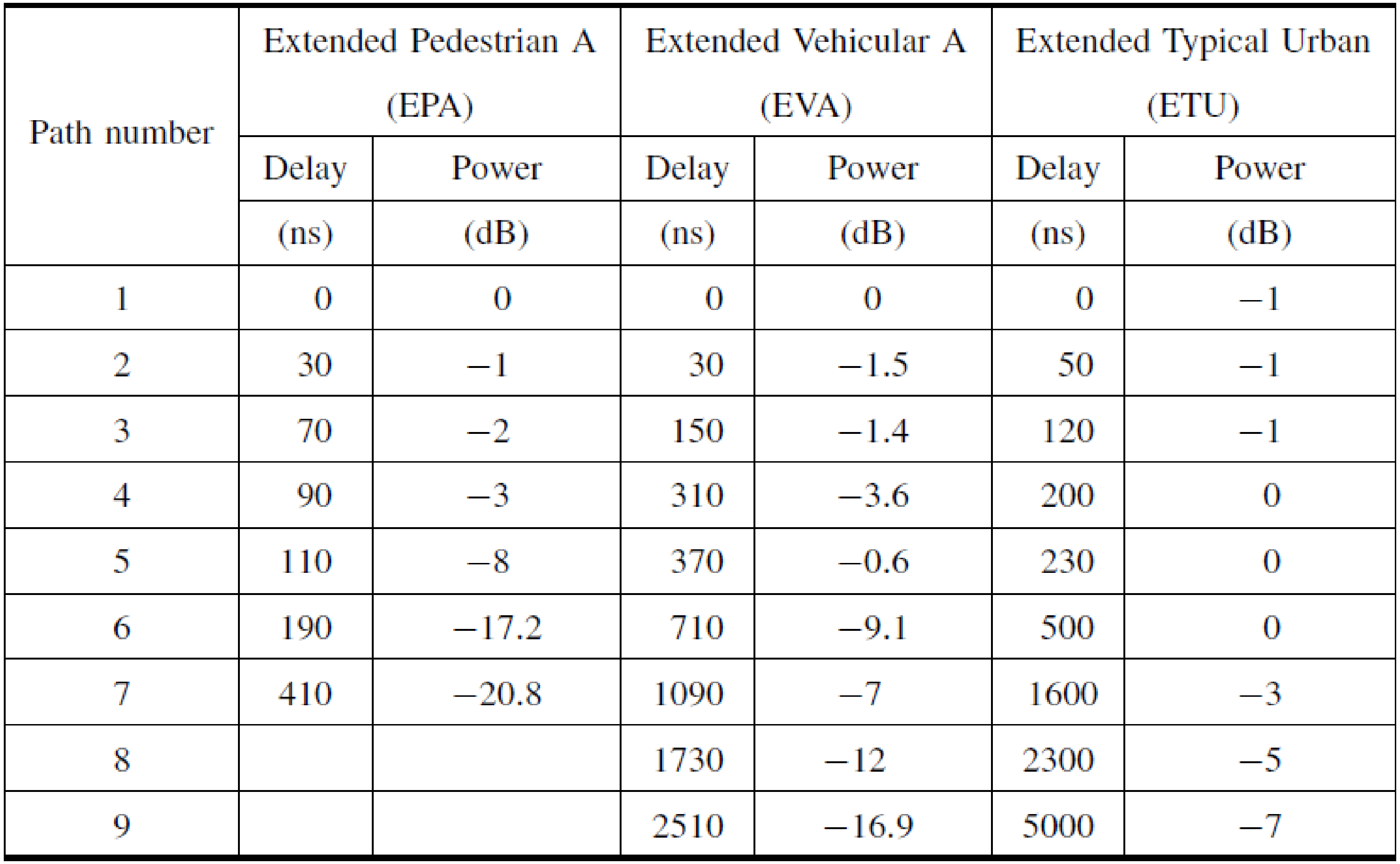
- Based on channel measurements with a bandwidth of 8–10MHz in the 900MHz band used for 2G systems such as GSM.



Path #	Rural Area (RA)		Typical Urban (TU)		Bad Urban (BU)		Hilly Terrain (HT)	
	Delay (µs)	Power (dB)	Delay (µs)	Power (dB)	Delay (µs)	Power (dB)	Delay (µs)	Power (dB)
1	0	0	0	−3	0	−2.5	0	0
2	0.1	−4	0.2	0	0.3	0	0.1	−1.5
3	0.2	−8	0.5	−2	1.0	−3	0.3	−4.5
4	0.3	−12	1.6	−6	1.6	−5	0.5	−7.5
5	0.4	−16	2.3	−8	5.0	−2	15.0	−8.0
6	0.5	−20	5.0	−10	6.6	−4	17.2	−17.7

[Fazel and Kaiser, 2008, Table 1-1]

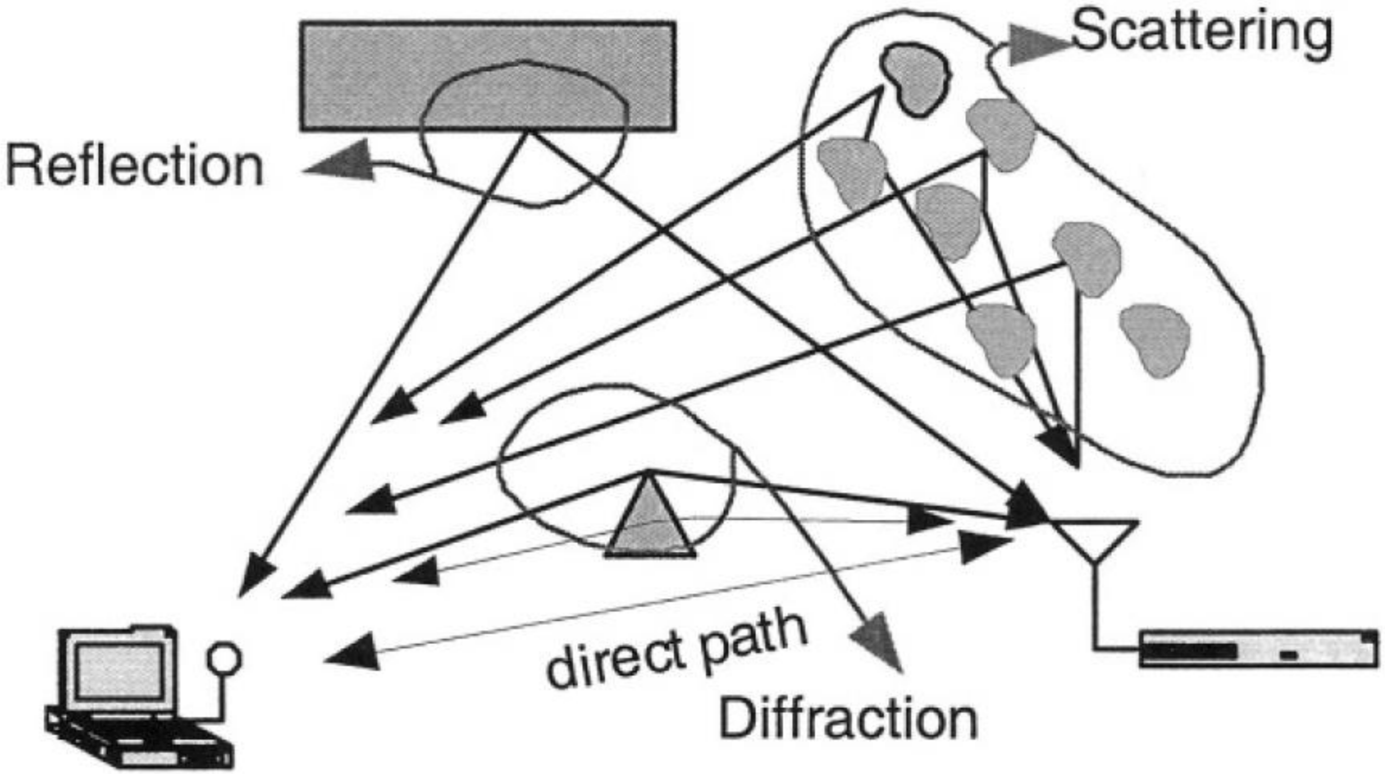
3GPP LTE Channel Modelss



Path number	Extended Pedestrian A (EPA)		Extended Vehicular A (EVA)		Extended Typical Urban (ETU)	
	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)	Delay (ns)	Power (dB)
1	0	0	0	0	0	−1
2	30	−1	30	−1.5	50	−1
3	70	−2	150	−1.4	120	−1
4	90	−3	310	−3.6	200	0
5	110	−8	370	−0.6	230	0
6	190	−17.2	710	−9.1	500	0
7	410	−20.8	1090	−7	1600	−3
8			1730	−12	2300	−5
9			2510	−16.9	5000	−7

[Fazel and Kaiser, 2008, Table 1-3]

Wireless Propagation



[Bahai, 2002, Fig. 2.1]

Three steps towards OFDM

1. Solve Multipath → Multicarrier modulation (FDM)
2. Gain Spectral Efficiency → Orthogonality of the carriers
3. Achieve Efficient Implementation → FFT and IFFT

Chapter 5

OFDM

Multi-Carrier Transmission

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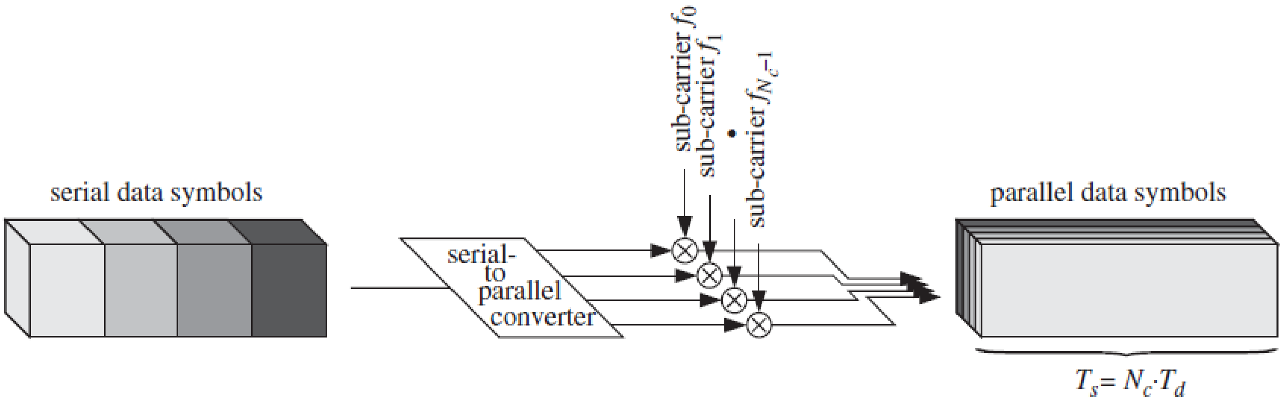
Multi-Carrier Transmission

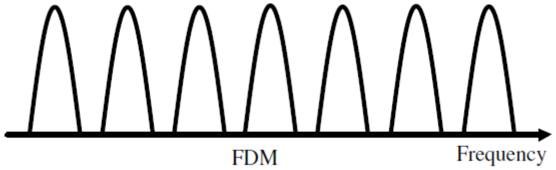
- Convert a serial high rate data stream on to multiple parallel low rate sub-streams.
- Each sub-stream is modulated on its own sub-carrier.
- Since the symbol rate on each sub-carrier is much less than the initial serial data symbol rate, the effects of delay spread, i.e. ISI, significantly decrease, reducing the complexity of the equalizer.



[Fazel and Kaiser, 2008, Fig 1-4]

Frequency Division Multiplexing

- To facilitate separation of the signals at the receiver, the carrier frequencies were spaced sufficiently far apart so that the signal spectra did not overlap. Empty spectral regions between the signals assured that they could be separated with readily realizable filters.
- The resulting spectral efficiency was therefore quite low.



FDM: Better or Worse?

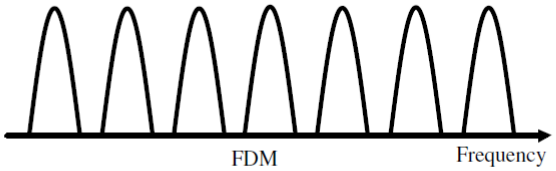
- Comparison with a single higher rate serial scheme
  - The parallel system, if built straightforwardly as several transmitters and receivers, will certainly be more costly to implement.
  - Each of the parallel subchannels can carry a low signalling rate, proportional to its bandwidth.
    - The sum of these signalling rates is less than can be carried by a single serial channel of that combined bandwidth because of the unused guard space between the parallel sub-carriers.
  - The single channel will be far more susceptible to inter-symbol interference.
    - This is because of the short duration of its signal elements and the higher distortion produced by its wider frequency band, as compared with the long duration signal elements and narrow bandwidth in sub-channels in the parallel system.

FDM (3)

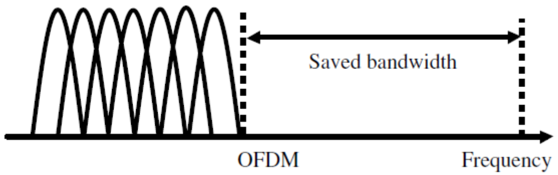
- Before the development of equalization, the parallel technique was the preferred means of achieving high rates over a dispersive channel, in spite of its high cost and relative bandwidth inefficiency.

OFDM

- OFDM = Orthogonal frequency division multiplexing
- One of multi-carrier modulation (MCM) techniques
  - Parallel data transmission (of many sequential streams)
  - A broadband is divided into many narrow sub-channels
  - Frequency division multiplexing (FDM)



- High spectral efficiency
  - The sub-channels are made orthogonal to each other over the OFDM symbol duration T_s.
    - Spacing is carefully selected.
  - Allow the sub-channels to overlap in the frequency domain.
  - Allow sub-carriers to be spaced as close as theoretically possible.



Orthogonality

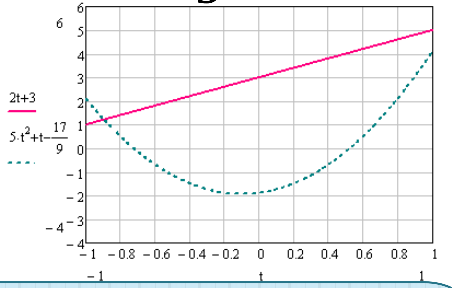
- Two vectors/functions are **orthogonal** if their **inner product** is zero.
- The symbol $\perp$ is used to denote orthogonality.

Vector:

$$\langle \vec{a}, \vec{b} \rangle = \vec{a} \cdot \vec{b}^* = \begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix} \cdot \begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix} = \sum_{k=1}^{n} a_k b_k = 0$$

Example:

$$2t + 3 \text{ and } 5t^2 + t - \frac{17}{9} \text{ on } [-1,1]$$



Time-domain:

$$\langle a, b \rangle = \int_{-\infty}^{\infty} a(t) b^*(t) dt = 0$$

Complex conjugate

Frequency domain:

$$\langle A, B \rangle = \int_{-\infty}^{\infty} A(f) B^*(f) df = 0$$

Example:

$$\sin\left(2\pi k_1 \frac{t}{T}\right) \text{ and } \cos\left(2\pi k_2 \frac{t}{T}\right) \text{ on } [0,T]$$

$$e^{j2\pi n \frac{t}{T}} \text{ on } [0,T]$$

Orthogonality in Communication

CDMA

$$\boxed{s(t)=\sum_{k=0}^{\ell-1} S_k c_k(t)} \xrightarrow{\mathcal{F}} S(f)=\sum_{k=0}^{\ell-1} S_k C_k(f) \quad \text{where} \quad c_{k_1} \perp c_{k_2}$$

TDMA

$$\boxed{s(t)=\sum_{k=0}^{\ell-1} S_k c(t-kT_s)} \xrightarrow{\mathcal{F}} S(f)=C(f)\sum_{k=0}^{\ell-1} S_k e^{-j2\pi fkT_s}$$

where $c(t)$ is time-limited to $[0,T]$.

This is a special case of CDMA with $c_k(t)=c(t-kT_s)$

The c_k are non-overlapping in time domain.

FDMA

$$\boxed{S(f)=\sum_{k=0}^{\ell-1} S_k C(f-k\Delta f)}$$

where $C(f)$ is frequency-limited to $[0,\Delta f]$.

This is a special case of CDMA with $C_k(f)=C(f-k\Delta f)$

The C_k are non-overlapping in freq. domain.

OFDM: Orthogonality

$$\int c_{k_1}(t)c_{k_2}^*(t)dt = \int_0^{T_s} \exp\left(j\frac{2\pi k_1 t}{T_s}\right)\exp\left(-j\frac{2\pi k_2 t}{T_s}\right)dt$$

$$= \int_0^{T_s} \exp\left(j\frac{2\pi (k_1-k_2) t}{T_s}\right)dt = \begin{cases} T_s, & k_1 = k_2 \\ 0, & k_1 \neq k_2 \end{cases}$$

When $k_1 = k_2$,

$$\int c_{k_1}(t)c_{k_2}^*(t)dt = \int_0^{T_s} 1dt = T_s$$

When $k_1 \neq k_2$,

$$\int c_{k_1}(t)c_{k_2}^*(t)dt = \frac{T_s}{j2\pi(k_1-k_2)}\exp\left(j\frac{2\pi(k_1-k_2)t}{T_s}\right)\Bigg|_0^{T_s}$$

$$= \frac{T_s}{j2\pi(k_1-k_2)}(1-1) = 0$$

Frequency Spectrum

$$s(t) = \sum_{k=0}^{N-1} S_k \underbrace{\frac{1}{\sqrt{N}} 1_{[0,T_s]}(t) \exp\left(j \frac{2\pi k t}{T_s} \right)}_{c_k(t)}$$

$$\Delta f = \frac{1}{T_s}$$

This is the term that makes the technique FDM.

$$1_{\left[-\frac{T_s}{2}, \frac{T_s}{2}\right]}(t) \xrightarrow{\mathcal{F}} T_s \sin c\left(\pi T_s f \right)$$

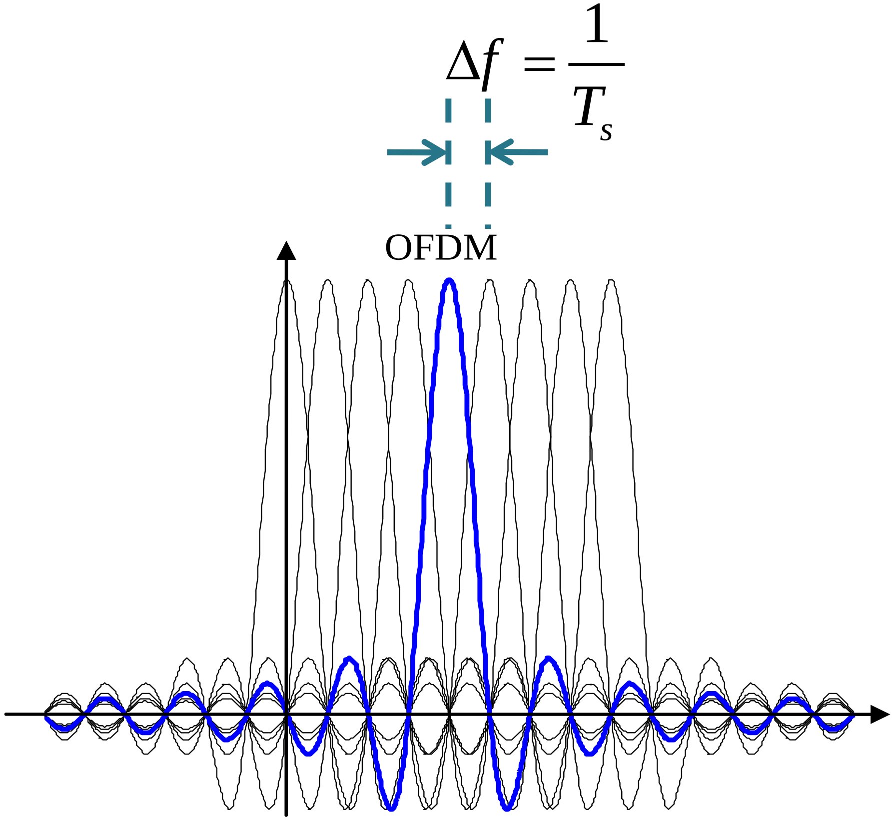
$$c(t) = \frac{1}{\sqrt{N}} 1_{[0,T_s]}(t) \xrightarrow{\mathcal{F}} C(f) = \frac{1}{\sqrt{N}} T_s e^{-j 2\pi f \frac{T_s}{2}} \sin c\left(\pi T_s f \right)$$

$$c_k(t) = c(t) \exp\left(j \frac{2\pi k t}{T_s} \right) \xrightarrow{\mathcal{F}} C_k(f) = C\left(f - \frac{k}{T_s} \right) = C\left(f - k\Delta f \right)$$

$$s(t) = \sum_{k=0}^{N-1} S_k c_k(t) \xrightarrow{\mathcal{F}} S(f) = \sum_{k=0}^{N-1} S_k C_k(f)$$

$$= \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{-j 2\pi (f - k\Delta f) \frac{T_s}{2}} T_s \sin c\left(\pi T_s \left(f - k\Delta f \right) \right)$$

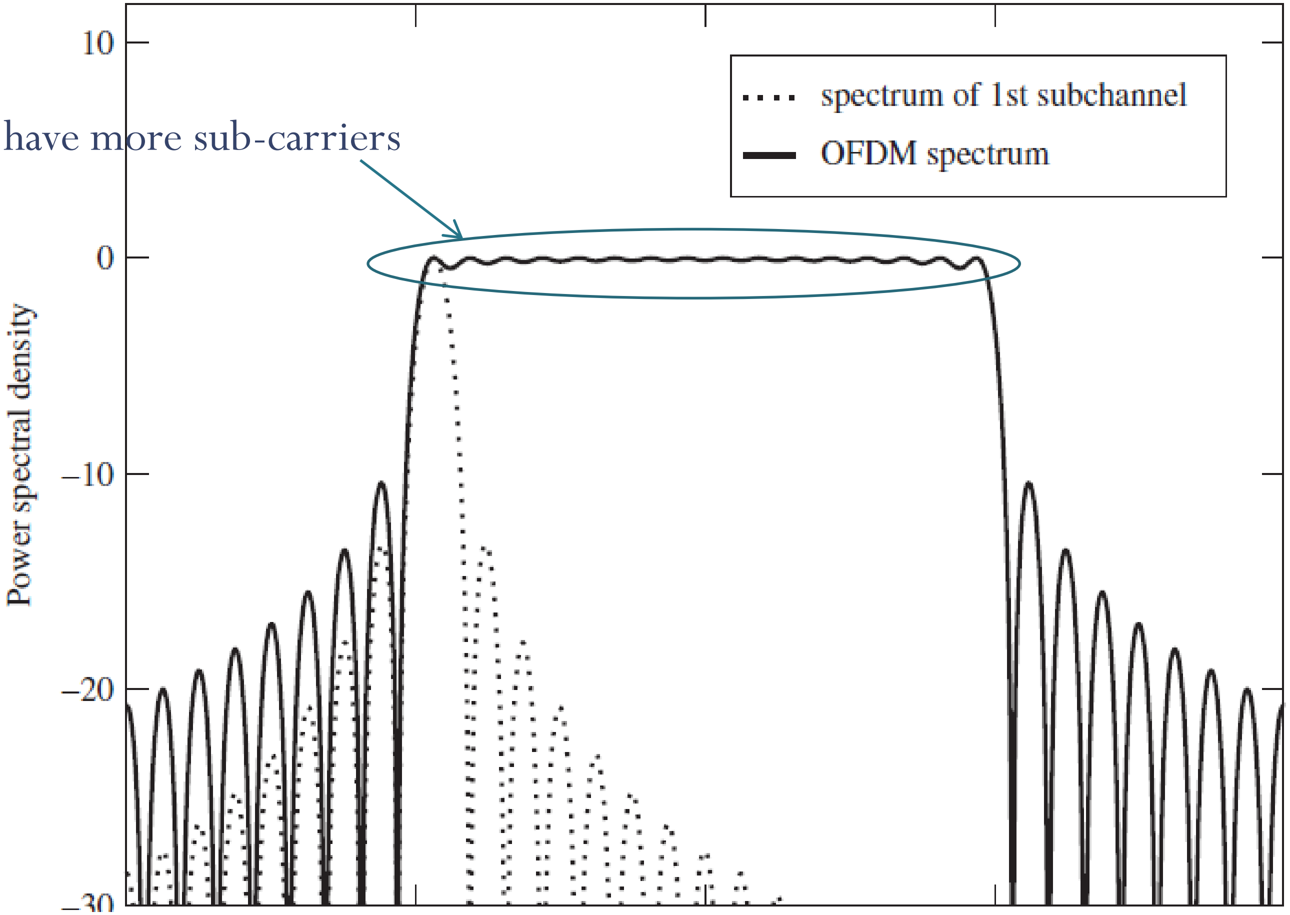
Subcarrier Spacing



$$\Delta f = \frac{1}{T_s}$$

Spectrum Overlap in OFDM

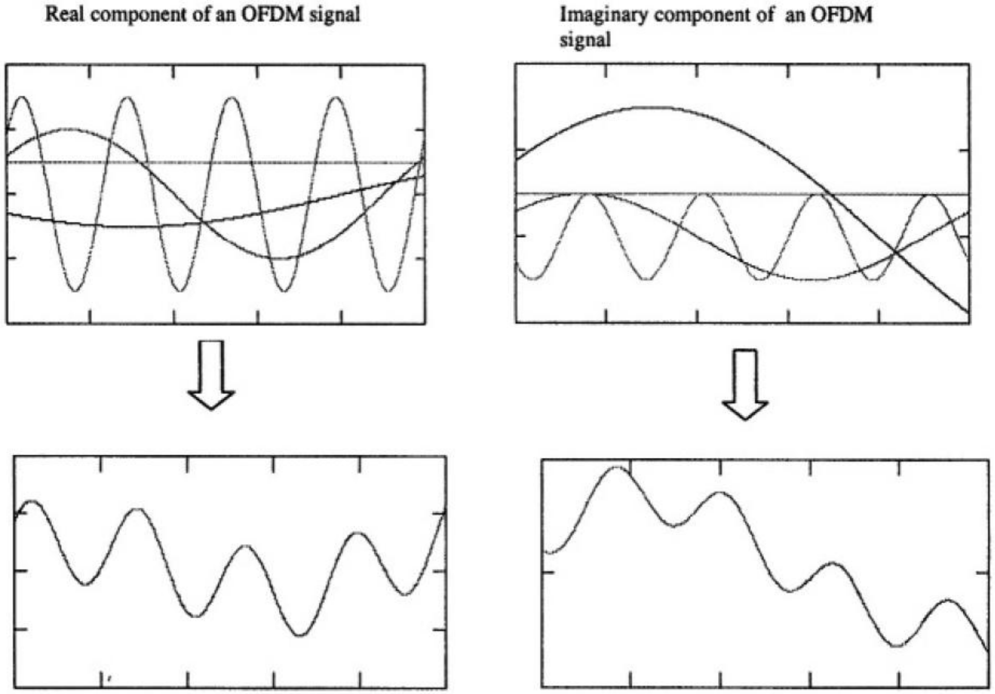
Normalized Power Density Spectrum



Flatter when have more sub-carriers

[Fazel and Kaiser, 2008, Fig 1-5]

Time-Domain Signal



Real component of an OFDM signal

Imaginary component of an OFDM signal

[Bahai, 2002, Fig 1.7]

Real and Imaginary components
of an OFDM symbol is the
superposition of several harmonics
modulated by data symbols

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k \exp\left(j \frac{2\pi kt}{T_s} \right), \quad 0 \le t \le T_s$$

$$\mathrm{Re}\{s(t)\} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \left(\mathrm{Re}\{S_k\} \cos\left(\frac{2\pi kt}{T_s} \right) - \mathrm{Im}\{S_k\} \sin\left(\frac{2\pi kt}{T_s} \right) \right)$$

Summary

- So, we have a scheme which achieve
  - Large symbol duration (T_s) and hence less multipath problem
  - Good spectral efficiency
- One more problem:
  - There are so many carriers!