Introduction to Wireless Local Area Network

Po-Ning Chen, Professor
Depart. Of Communications Engineering
National Chiao-Tung University

Subject: OFDM in WLAN

Selective Materials from OFDM Wireless LANs: A Theoretical and Practical Guide by Juha Heiskala and John Terry

Historical Notes on OFDM

- Research on multicarrier modulation can be dated back to 1950s and early 1960s.
- Perhaps, R. W. Chang (1966) is the first one who demonstrates the concept we today call orthogonal frequency division multiplexing (OFDM).
  - He demonstrated the principle of transmission of multiple messages simultaneously through a linear band-limited channel without interchannel interference (ICI) and intersymbol interference (ISI).
  - *R. W. Chang, "Synthesis of band-limited orthogonal signals for multichannel data transmission," Bell System Tech. Journal, 45:1775-1796, Dec. 1966.*

Historical Notes on OFDM

- Shortly after, Saltzberg (1967) performs a performance analysis on OFDM, and concludes that the dominate impairment in OFDM is ICI.
  - *B. R. Saltzberg, "Performance of an efficient parallel data transmission system," IEEE Trans. Commun., COM-15(6), Dec., 1967, pp. 805-811.*
- Weinsten and Ebert (1971) were the first to suggest using the Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT) to perform baseband modulation and demodulation in 1971.

Historical Notes on OFDM

- To combat ICI and ISI, Peled and Ruiz introduced the concept of a cyclic prefix (i.e., a cyclic extension of the OFDM symbol), rather than using an empty guard space.
  - Circular convolution is performed as long as the cyclic prefix is longer than the impulse response of the channel.
  - Penalty: Loss of signal energy proportional to the length of CP.
  - Benefit: Less ICI.
  - *A. Peled and A. Ruiz, "Frequency domain data transmission using reduced computational complexity algorithms," In Proc. IEEE Int. Conf. Acoust., Speech, Signal Processing, pp. 964-967, 1980.*

Historical Notes on OFDM

- Presently, OFDM becomes (part of) the standard (candidates) of:
  - Digital Audio Broadcasting (DAB)
  - Digital Video Broadcasting (DVB-T)
  - IEEE 802.11a
  - High Performance Local Area Network Type 2 (HiperLAN2)
  - Mobile Multimedia Access Communication (MMAC) System (Japan)
  - … etc.

Mathematical Background on OFDM (Notations following Slide 6-224)

☐ **Multi-Carrier Modulation (MCM)**

– **To transmit $2K+1$ informative messages simultaneously at $2K+1$ frequencies**

$$S(t) = \mathrm{Re}\left\{ \sum_{k=-K}^{K} S(k) \exp\{j2\pi f_k t\} \right\} \Pi\left(\frac{t}{T}\right), \; f_k = f_c + k \cdot \Delta f$$

$$\text{where } \Pi(t) = \begin{cases} 1, & -\frac{1}{2} \le t < \frac{1}{2}. \\ 0, & \text{otherwise} \end{cases}$$

– **What is the smallest Δf such that these $2K+1$ informative messages are "orthogonal" (i.e., no "inter-carrier interference") through sampling at the frequency domain?**

Mathematical Background on OFDM

– **The $2K+1$ informative messages are:**

$$S(t) = \mathrm{Re}\left\{ \sum_{k=-K}^{K} \left(S(k) \exp\{j2\pi f_k t\} \Pi\left(\frac{t}{T}\right) \right) \right\}, \; f_k = f_c + k \cdot \Delta f$$

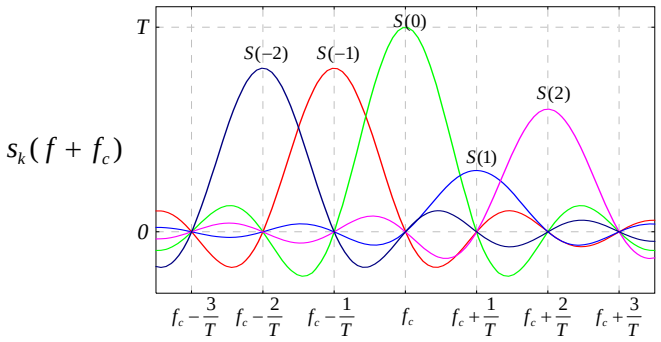
$$= \mathrm{Re}\left\{ \sum_{k=-K}^{K} S_k(t) \right\}, \text{ where } S_k(t) = S(k) \exp\{j2\pi f_k t\} \Pi\left(\frac{t}{T}\right)$$

$$\Rightarrow s_k(f) = S(k) \frac{\sin(\pi(f - f_k)T)}{\pi(f - f_k)}$$

$$\Rightarrow s_k(f + f_c) = S(k) \frac{\sin(\pi(f - k \cdot \Delta f)T)}{\pi(f - k \cdot \Delta f)}$$

– **Note: *As $S_k(t)$ is time-limited to $T/2$, $s_k(f)$ can be distortionlessly represented by its samples with sampling period $P \le 1/T$ by sampling theorem. Here, we take $P = 1/T$ for theoretical convenience.***

Mathematical Background on OFDM



- **So if we wish that the samples of $s_k(f+f_c)$ are interference-free to samples of $s_{k'}(f+f_c)$, where $k \neq k'$, then Δf must be a multiple of $1/T$.**
- **Back to the Question: What is the smallest Δf such that these $2K+1$ informative messages are inter-carrier-interference-free through sampling at the frequency domain? Answer: $1/T$.**

Mathematical Background on OFDM

- **As a result,**

$$S(t) = \mathrm{Re}\left\{\left(\sum_{k=-K}^{K} S(k)\exp\left\{j\frac{2\pi kt}{T}\right\}\Pi\left(\frac{t}{T}\right)\right)\exp\{j2\pi f_c t\}\right\}$$

$$= \mathrm{Re}\{s(t)\exp\{j2\pi f_c t\}\}$$

$$\Rightarrow s(t) = \sum_{k=-K}^{K} S(k)\exp\left\{j\frac{2\pi kt}{T}\right\}\Pi\left(\frac{t}{T}\right)$$

$$\Rightarrow \text{For } -N/2 \le n < N/2 \ \ (N \text{ even}),$$

$$s\left(n\frac{T}{N}\right) = \sum_{k=-N/2}^{N/2-1} [S(k)\cdot \mathbf{1}(|n| \le K)]\exp\left\{j\frac{2\pi kn}{N}\right\}$$

$$= \sqrt{N}\cdot \mathrm{IDFT}[S(n)\cdot \mathbf{1}(|n| \le K)],$$

where $N \ge 2K$; otherwise some x's will be excluded in IDFT.

Mathematical Background on OFDM

☐ **Exercise**

- **What is the minimum A/D sampling rate in principle at the demodulator for IEEE 802.11a?**
- **Answer:** $K = 26$ **for IEEE 802.11a**

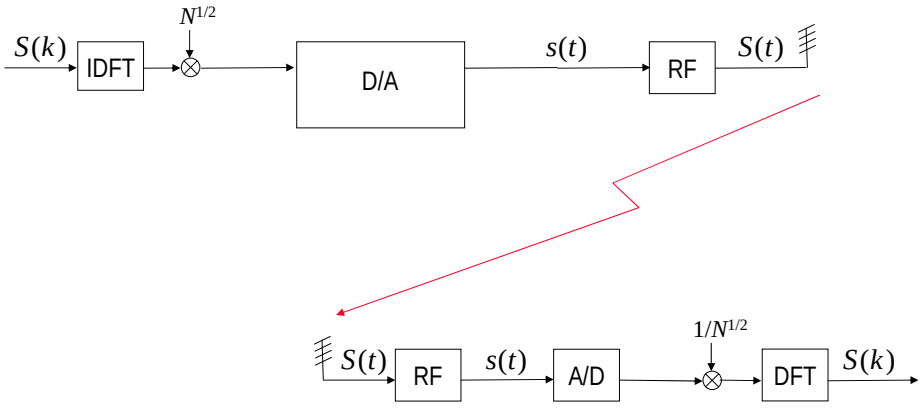
$$f_s = \frac{N}{T} \geq \frac{52}{3.2u\,\text{sec}} = 16.25\,\text{MHz}.$$

Considering two extra 0.5 at both ends (in freq domain),

take $\dfrac{53}{3.2u\,\text{sec}} = 16.5625\,\text{MHz}.$

A quantity matches the displayed 16.6MHz baseband bandwidth in Table 86 of IEEE Sttd 802.11a-2000.

Mathematical Background on OFDM



OFDM Re-Visited – Cyclic Prefix

- Question: Do we need cyclic prefix if the channel is memoryless? (i.e., v=0 on Slide 6-220)