EE 443/CS 543 Optical Fiber Communications
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Fall Semester

Lecture 24

http://www.wiretechworld.com/the-future-of-optical-fibres/
What Do We Mean By “Bandwidth”?  

Two filter responses (same bandwidth)  

BW measure: -3 dB bandwidth, Full-Wide-Half-Maximum Bandwidth
What is Bandwidth?

Bandwidth is the highest sine wave frequency component that is significant in a signal. Because of the vagueness of the term “significant,” unless detailed qualifiers are added, the concept of bandwidth is only approximate.

-- Eric Bogatin (2013)

How much bandwidth do I need for that signal?

-3 dB Bandwidth versus FWHM Bandwidth

Bandwidth of a communication channel is the difference between the highest and lowest frequencies that a channel will allow to pass.

https://www.testandmeasurementtips.com/bandwidth-basics-and-fundamentals/

https://en.wikipedia.org/wiki/Full_width_at_half_maximum
Time-Domain and Frequency-Domain Relationship

Rise Time Bandwidth Relationship

\[ \tau_{r}^{10\text{–}90} = \frac{0.35}{\text{Bandwidth}} \]

This equation is exact for a system with a single-pole low-pass response (e.g., “low-pass RC circuit”) and it's reasonably close for many well-behaved systems. Depending upon the circumstances the constant can range from 0.32 to 0.45.

https://www.edn.com/whats-that-signals-bandwidth/
The 10-90 rise time plotted for each waveform, compared to the bandwidth of the waveform.

• Information to be communicated is the baseband signal with bandwidth $W$
• Modulation adds frequency components (sidebands) to carrier for both analog and digital communication
• Sidebands must be within the allotted communication channel
• Bandwidth of the communication channel must be equal or greater than the bandwidth $W$ of the information (identical to the baseband)

This is illustrated on the next slide.
Baseband Spectrum, Carrier & Modulated Carrier Spectrum

W = baseband bandwidth

Carrier with double sideband

This is true for all RF, microwave and optical communication systems.
Optical Fiber Signals are Digital Bit Sequences

Baseband Signal Driving Modulator

Amplitude Modulated Optical Signal

Received Signal After Demodulation

## Data Rates By Communication Technology

<table>
<thead>
<tr>
<th>Technology</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modem / Dialup</td>
<td>56 kbit/s</td>
</tr>
<tr>
<td>ADSL Lite</td>
<td>1.5 Mbit/s</td>
</tr>
<tr>
<td>T1/DS1</td>
<td>1.544 Mbit/s</td>
</tr>
<tr>
<td>E1 / E-carrier</td>
<td>2.048 Mbit/s</td>
</tr>
<tr>
<td>ADSL1</td>
<td>8 Mbit/s</td>
</tr>
<tr>
<td>Ethernet</td>
<td>10 Mbit/s</td>
</tr>
<tr>
<td>Wireless 802.11b</td>
<td>11 Mbit/s</td>
</tr>
<tr>
<td>ADSL2+</td>
<td>24 Mbit/s</td>
</tr>
<tr>
<td>T3/DS3</td>
<td>44.736 Mbit/s</td>
</tr>
<tr>
<td>Wireless 802.11g</td>
<td>54 Mbit/s</td>
</tr>
<tr>
<td>Fast Ethernet</td>
<td>100 Mbit/s</td>
</tr>
<tr>
<td>OC3</td>
<td>155 Mbit/s</td>
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<tr>
<td>Wireless 802.11n</td>
<td>600 Mbit/s</td>
</tr>
<tr>
<td>OC12</td>
<td>622 Mbit/s</td>
</tr>
<tr>
<td>Gigabit Ethernet</td>
<td>1 Gbit/s</td>
</tr>
<tr>
<td>OC48</td>
<td>2.5 Gbit/s</td>
</tr>
<tr>
<td>USB 3.0</td>
<td>5 Gbit/s</td>
</tr>
<tr>
<td>OC192</td>
<td>9.6 Gbit/s</td>
</tr>
<tr>
<td>10 Gigabit Ethernet, USB 3.1</td>
<td>10 Gbit/s</td>
</tr>
<tr>
<td>100 Gigabit Ethernet</td>
<td>100 Gbit/s</td>
</tr>
</tbody>
</table>
Fourier Series versus Fourier Transform

Fourier series for continuous-time periodic signals → discrete spectra
Fourier transform for continuous aperiodic signals → continuous spectra
Fourier Transform of a Single Rectangular Pulse

\[
F(\omega) = A\tau \cdot \left[ \frac{\sin(\omega\tau/2)}{\omega\tau/2} \right] = A\tau \cdot \text{sinc}(\pi f \tau)
\]

Note the pulse is time centered.
Fourier Series To Transform For a Rectangular Pulse Train

Fourier Series of period $T_0$

Frequency resolution inversely proportional to the period $T_0$.

Fourier Transform in the limit $T_0 \to \infty$

Figure 4.3: Take the pulse train in (a), as we increase its period, i.e., allow more time between the pulses, the fundamental frequency gets smaller, which makes the spectral lines move closer together as in (c). In the limiting case, where the period goes to $\infty$, the spectrum would become continuous.

Sinc Function and Sinc Squared Function

The sinc function

\[ \text{sinc} \beta \]

The sinc squared function

\[ \text{sinc}^2 \beta \]

https://www.slideserve.com/argyle/diffraction-and-fresnel-zones
Single Digital Pulse and Its Frequency Spectrum

A single pulse over an infinite timeframe

\[ f_b = \frac{1}{\tau_b} \]

Fundamental plus all harmonics

Rectified sinc function

All frequencies within envelope

Presented by Daniel Chow (EDN -- 2013)

Single Digital Pulse and Its Frequency Spectrum

NRZ coded

\[ f_b = \frac{1}{2\tau_b} \]

Fundamental plus only the odd harmonics which diminish as \( 1/f \)

Infinite “pulse train” over infinite timeframe

Only a countably infinite number of discrete frequencies

Fourier Series

\[ \frac{1}{2} f_b, \frac{3}{2} f_b, \frac{5}{2} f_b \]

Discrete spectrum over infinite frequency range

What Happens With a Pseudo-Random Bit Pattern?

Example:
A k28.5 Data Pattern and Its Frequency Spectrum

The lowest spectral line is \( f_{\text{PATTERN}} = \frac{f_b}{20} \) since 20 bits defines the repetitive bit pattern. All other spectral lines are odd harmonics due to odd symmetry.

The bit pattern determines the magnitude of the other spectral lines.

A Longer Data Pattern and Its Frequency Spectrum

The lowest spectral line is $f_{\text{PATTERN}} = f_b/127$ since 127 bits defines the repetitive bit pattern. PRBS has no symmetry, so all harmonics appear.

What Happens With Cross-Talk and Interference?

Cross-talk occurs from capacitive coupling and inductive coupling with adjacent signals (electrical pickup). In this case the coupled signals are proportional to

\[ \frac{dV}{dt} \quad \text{and} \quad \frac{dI}{dt} \]

Thus, the fast edges of the adjacent waveforms produce the unwanted cross-talk.

We start by considering adjacent pulses for which the derivatives generate a pair of delta functions (+ for rising edge and – for falling edge).
Frequency Content in a Pair of Delta Functions

\[ f_b = \frac{1}{\tau_b} \]

Rectified sine function with zeros at multiples of \( f_b \).

This is a continuous spectrum of frequencies

Chain of Delta Functions Has Only Odd Harmonics of $\frac{1}{2}f_0$

This is now a periodic waveform

Corresponding spectra of only odd harmonics of $\frac{1}{2}f_b$. Similar to the square wave case.

Spectral lines are aligned with the peaks of the rectified sine function.

Spectral Pattern For the Twenty-Bit Pattern

The lowest spectral line is $f_{\text{PATTERN}} = f_b/20$ since 20 bits defines the repetitive bit pattern. All other spectral lines are odd harmonics due to odd symmetry.

Note: The major difference with the delta functions is stronger signal content at higher frequencies.

Spectral Pattern For a 127-Bit Pattern

The lowest spectral line is $f_{\text{PATTERN}} = f_b/127$. More of the same.

Frequency Content in a Pair of Decaying Exponentials

The Lorentzian is an analytical function.

This waveform is more realistic for cross-coupled signals.

This shape is a Lorentzian (Gray curve)

This is a continuous spectrum of frequencies. But there is no DC.

Comparing Gaussian and Lorentzian Standardized Line Shapes

Natural, collisional, and power broadening are homogeneous mechanisms and produce Lorentzian line shapes.

https://www.chemicool.com/definition/lorentzian_spectral_lineshape.html
Frequency Content in a Train of Decaying Exponentials

Corresponding spectra of only odd harmonics of $1/2f_b$. Fits the Lorentzian envelope.

Discrete spectrum

Frequency Content in 20-Bit Pattern of Decaying Exponentials

The lowest spectral line is $f_{\text{PATTERN}} = f_b/20$.

Frequency Content in 127-Bit Pattern of Decaying Exponentials

Yes, as you would expect.

Dependence of Waveform Shape Upon Filtering Bandwidth

Bandwidth = 1 GHz (Main lobe only)

Bandwidth = 2 GHz (Main + 1st lobe)

Bandwidth = 3 GHz (Main + 1st & 2nd lobes)

https://www.advantest.com/documents/11348/3e95df23-22f5-441e-8598-f1d99c2382cb
Pulse Shaping: Raised-Cosine Pulse

QUESTIONS
https://www.semanticscholar.org/paper/Analysis-of-Crosstalk-Effects-on-Jitter-in-Chow/65804e9c3dc6022bd33d769d4639a3f69d2f1528