High Dynamic Range, 100km

RADIO OVER FIBER LINKS

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Optical fiber is now ubiquitous

- High Capacity (Pb/s)
- Low Loss (0.2 dB/km [opt])
- Long Haul (Digital)
  *Transatlantic, Internet Backbone*
- ✔️ Last Mile (RF/ Radio Over Fiber [RoF])
  *FiOs, CATV, Fiber-to-the-Home*
Fiber delivers LOW-LOSS RF transmission over large distances

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wireless (isotropic)</th>
<th>Coax (LMR-400)</th>
<th>Radio over Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss@ 1km (5.8 GHz)</td>
<td>107 dB</td>
<td>354 dB</td>
<td>0.6 dB</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>~10%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Main Issues</td>
<td>Regulatory Issues, Wireless Channel Impairments</td>
<td>Extremely High Loss</td>
<td>Cost/Complexity, Dynamic Range</td>
</tr>
</tbody>
</table>
1550 nm is an optimal wavelength

SMF28 Fiber Attenuation

- **1550 nm - Minimum Loss Window**
  - ✔️ 0.18 dBo/km attenuation
  - ✔️ Compatible with erbium doped fiber amplifiers
  - ❌ Optical dispersion present

- **1310 nm - Minimum Dispersion Window**
  - ❌ 0.32 dBo/km attenuation
  - ✔️ Negligible dispersion

Source: nutsvolts.com

Note: dBo connotes optical gain/loss
dB connotes traditional RF gain/loss
PRINCIPLE: Optical interferometer

- Small differences in phase ($\Delta \Phi$) between the two paths cause constructive or destructive interference.
- Interferometer converts phase shifts into intensity changes.
PRINCIPLE: The Mach Zehnder Modulator (MZM)

- The Mach Zehnder Modulator (MZM) is an interferometer made with optical waveguides.
- The MZM encodes changes in input voltage onto the optical intensity.
  - Step 1: Applied (RF) voltages modulate the index of refraction in the lower arm path via the electro-optic effect.
  - Step 2: Changes in index of refraction modulate the optical phase in the lower arm.
  - Step 3: When we recombine the top and bottom arms, constructive/destructive interference between the paths causes the optical intensity to change with applied voltage.
- When optical and electrical velocities are well matched, modulation bandwidth >40 GHz.

\[
\text{Input Optical power: } P_o
\]
\[
\text{Input RF power (RMS): } P_{\text{rf-in}} = \frac{V_{\text{rf-in}}^2}{2Z} \quad (2)
\]

Source: Patent US6501867
Signal Distortion depends on MZM bias setting

- Response is periodic in voltage, not linear
- Quadrature DC bias (50%) as shown above ⇒ linear portion of the response.
- Green areas excursions cause odd order distortion products
- The $n$th order (rms) OPTICAL INTENSITY products follow a Bessel series (just like for PM and FM in radio communications).

\[ P_{\text{mzm}} (\text{DC}) = \frac{P_o}{2} \quad (3) \]
\[ P_{\text{mzm}} (f1) = P_o J_1(\pi V_{\text{rf}}/V_n) \quad (4) \]
\[ etc. \]
Optical-to-Electrical
PIN InGaAs Photodiode

Optical Intensity $\rightarrow$ RF Current

Using (1) - (4) the RF output power can be now written in terms of just electrical parameters

$$ P_{\text{rf-out}} = \frac{1}{2} I_{\text{DC}}^2 Z \frac{\pi}{\pi} \frac{V_{\text{rf}}}{V_{\pi}} $$

(5)

NOTE: RF power goes as the square of optical power:
RF attenuation is twice the optical attenuation (in dB).
The photodiode is an optical homodyne detector

\[ I \propto P_o \propto \mathbf{E} \cdot \mathbf{E} \]

[1] SIGNAL: Carrier \times Carrier = Optical Intensity


- Optical noise figure, \( NF_{opt} \)
- \( NF_{opt} \) cascades like RF noise figure.
- \( NF_{opt} \) & \( G_{opt} \) = 0 dB \rightarrow quantum shot noise limit.

\[ N_{sig-sp}[dBm/Hz] = -169 + 10 \log (\Re I_{DC}[mA]) + G_{opt}[dB] + NF_{opt}[dB] \]

(6)

\[ NF_{RF}[dB] = 174 - G_{RF}[dB] + N_{sig-sp}[dBm/Hz] \]

(7)

Other sources of noise are typically negligible

Thermal Noise in the diode is negligible compared to these other products.
A typical link is just slightly lossy without added RF amplification.

\[
G_{RF} = \frac{P_{rf-out}}{P_{rf-in}} = \left( \frac{I_{DC} Z\pi}{V_\pi} \right)^2
\]  \hspace{1cm} (8)

\[
G_{RF}[dB] = -16 - 20 \log (V_\pi [V]) + 20 \log (I_{DC} [mA])
\]  \hspace{1cm} (9)
PRINCIPLE: Distortion & Dynamic Range

- 3rd-order distortion of multiple large signals produces adjacent spurious signals in all practical RF systems.
- +1dB in fundamentals $\rightarrow$ +3dB in 3rd order distortion.
- Our OIP3 can be determined from the MZM’s Bessel Series.

Terminology
- Spur-free-dynamic range = range over which distortion is “lost in the noise.”
- Output Third order intercept (OIP3) is the output power where the fundamental and distortion lines intersect.

$$OIP3[\text{dBm}] = -7 + 20\log(I_{dc}[\text{mA}])$$ (10)
We can now write down the **KEY RF SYSTEM PARAMETERS**

---

**Gain**

\[ G_{RF}[dB] = -16 - 20 \log(V_\pi[V]) + 20 \log(I_{DC}[mA]) \]  \hspace{1cm} (9)

**Noise Figure**

\[ NF[dB] = 21 + 20 \log(V_\pi[V]) - 10 \log(\Re I_{dc}[mA]) + G_{opt}[dB] + NF_{opt}[dB] \]  \hspace{1cm} (11)

**Linearity**

\[ OIP3[dBm] = -7 + 20 \log(I_{dc}[mA]) \]  \hspace{1cm} (10)

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**TAKEAWAYS**

- Maximize photocurrent.
- Minimize the optical noise figure.
- Minimize \( V_\pi \).
Managing Dispersion

- Upper and lower sidebands travel at slightly different velocities.
- The heterodyned output from LSB and USB may get out of phase and cancel at certain frequencies.

**SOLUTION:** Dispersion Compensating Fiber (DCF)

Measured (solid) and calculated (dashed) dispersion response for a ROF channel through 50 km of SMF-28 fiber.

$$RF_{out} = (\text{carrier} \times \text{LSB}) + (\text{carrier} \times \text{USB})$$

SMF-28®
+18 ps/nm•km

Fujikura - DCF
-155 ps/nm•km
Extending the reach to 10 km and beyond with *Erbium Doped Fiber Amplifiers*

- In-fiber amplification at 1550 nm
- Inject PUMP photons at 980nm to produce an excited state in atoms
- Excited atoms produce stimulated emission at 1550nm
- 1550nm signal is amplified.
- Like a laser without end mirrors (no feedback)
- No oscillation, just amplification

Thorlabs.us
>20dB gain, 5 dB Noise Figure
Optical Power Limit
Stimulated Brillouin Scattering (SBS)

- Incident high power photons in PUMP scatter exciting vibrations in the glass.
- Acoustic waves cause ripple in refractive index (photo-elastic effect).
- Refractive index ripple forms a grating and scatters the optical signal backwards in a (red shifted) STOKES wave.
- Red shifted by resonant acoustic (phonon) frequency of ~10.8 GHz.
- Scattered forward again by (elastic) Rayleigh scattering.

Noise spectrum at the photodiode caused by Stokes wave heterodyning with Pump wave.

\[ P_{th} \approx \frac{A_{eff}}{g_B L_{eff}} \]  \hspace{1cm} \text{(12)}

\[ L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \]  \hspace{1cm} \text{(13)}

SBS: 1551 nm DFB semiconductor laser through 20 km of SMF-28, having an SBS threshold of approximately 7 dBm.
Long Haul Link Design

Optical Noise Figure and SBS depends on optical amplifier placement

- EDFA at launch
  - ✓ Min. $NF_{opt}$
  - ✗ Max. $P_{opt}$ and SBS
- EDFA at end
  - ✓ Reduced SBS
  - ✗ Poor $NF_{opt}$
- Distributed amplification
  - ✓ Reasonable compromise
  - ✓ Spacing to keep $P_{opt}$ below SBS threshold

Remember, SBS = Stimulated Brillouin Scattering
RESULTS: Excellent Dynamic Range performance over 110 km!

- \( \checkmark \) SFDR: 103 dBHz\(^{2/3} \)
- Dynamic Range is critical for multi-carrier RF applications & AM-based modulation formats
- Sufficient for 256-QAM signal with \( \sim \)30dB MER

**Measured Constellations**
Typical of digital TV (CATV) and cable modem signal constellations.
16-QAM encodes 4 bits/symbol & 256-QAM encodes 8 bits/symbol

- SFDR measured at 18 GHz
- 5 MSymb/s @ 2 GHz
Radio over Fiber can provide **low-loss & high dynamic range** RF links over 110 km or more!

- Simple RF link equations: Gain, Noise Figure, Dynamic Range.
- Distributed optical amplification enables long-haul links.
- Dynamic Range is limited primarily by **modulator linearity**, **Brillouin scattering**, and **optical noise** from spontaneous emission.

**Learn More Here...**

**Download this talk:** RedMountainRadio.com
