EE 233. LIGHTWAVE SYSTEMS
Chapter 8B. Multichannel Systems [subcarrier mux]

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SUBCARRIER MULTIPLEXING; HYBRID FIBER COAX (HFC)
HFC

• Hybrid Fiber-Coax Network: Comcast
• MSO = multiple service operator = cable service provider
• CATV = community antenna TV = cable
Coax to HFC

X-LU

HE

4/11/06
Coax to HFC

- Increase transport capability
- Improve quality and reliability

→ Challenge for linear lightwave
CABLE SPECTRUM

- 5 - 42 MHz: upstream applications
- 50 - 500 MHz: downstream analog apps
- 550 - 1000+ MHz: emerging digital apps
- 6 MHz subcarrier channel spacing
Figure 8.29: Schematic illustration of subcarrier multiplexing. Multiple microwave subcarriers (SC) are modulated, and the composite electrical signal is used to modulate an optical carrier in the transmitter (Tx).
Fig. 14.1 Single-channel amplitude-modulated vestigial-sideband (AM-VSB) video spectrum showing a video carrier, color and audio subcarriers, and time-averaged modulation sidebands at low levels relative to the video carrier.

Fig. 14.2 Multichannel AM-VSB spectrum as transmitted on a typical cable television system. The variation in the video carrier level results from instantaneous differences in amplitude modulation (AM) depth. The features resolved in the spectrum are the video carriers and the frequency-modulated (FM) audio subcarriers.
Fig. 14.2 Multichannel AM-VSB spectrum as transmitted on a typical cable television system. The variation in the video carrier level results from instantaneous differences in amplitude modulation (AM) depth. The features resolved in the spectrum are the video carriers and the frequency-modulated (FM) audio subcarriers.
Fig. 9.2 Configuration of signal processing and combining equipment in headend.
Fig. 9 Measured light output (solid) and derivative $dL/dI$ (dash-dot) vs. current showing static laser linearity. Vertical dashed line shows bias point with schematic analog current input superimposed, while proportional light output response is plotted on horizontal dashed line.
5.2 LIGHTWAVE TECHNOLOGY

5.2.1 Linear Lightwave

As we discussed previously, linear lightwave technology has been one of the foundations of the modern cable network (HFC). Typical lightwave links used in RF SCM systems consist of transmitters, fiber runs, and receivers. The performance of these links is determined by the performance of both active and passive components, including different phenomena occurring in fiber runs “stimulated” by the light. The lightwave link performance can be quantified by CNR and second- and third-order distortions (CSO and CTB), which directly determine the quality of the analog AM-VSB signals received at the customer premise equipment (e.g., TV set) [18, 39–60].

Excluding fiber effects, the CNR at the receiver is given by

\[ \text{CNR} = \frac{\frac{1}{2} (m I_0)^2}{B_c (2eI_0 + n^2_{th} + RIN \times I_0^2)}, \]  
(9.1)

The signal power per channel is \((m I_0)^2/2\), where \(m\) is the Optical Modulation Depth (OMD) per channel, and \(I_0\) is the average received photocurrent. The denominator consists of several noise factors and the \(B_c\) is the noise bandwidth (4 MHz for NTSC channels). The thermal noise of the receiver is \(B_c n^2_{th}\), and the shot noise is \(2B_c eI_0\), where \(e\) is the electron charge. The laser’s relative intensity noise is \(RIN\) (dB/Hz).

The noise and quantum efficiency of the receiver determines the necessary received optical power to satisfy the CNR requirement. The received optical power is related to the photocurrent by:

\[ P_0 = \frac{h \nu}{\eta e} I_0, \]  
(9.2)

where \(h \nu\) is the photon energy and \(\eta\) is the quantum efficiency of the photodiode. From Eqs 9.1 and 9.2, one can determine the necessary optical power to achieve the desired CNR.

Besides noise, when multiple RF signals are multiplexed (FDM), the second-order and third-order distortion products that are generated within the multichannel multiplexing band will affect the signal quality. For a simple (memoryless) nonlinear characteristic, the optical power can be expressed as a Taylor-series expansion of the electrical signal:

\[ P \propto X_0 (1 + x + ax^2 + bx^3 + \ldots), \]  
(9.3)

where \(X_0\) is the DC bias and \(x\) is the modulation signal:

\[ x(t) = \sum_i N_{ch} m_i(t) \cos (2\pi f_i t + \phi_i), \]  
(9.4)

where \(m_i(t)\) is the normalized modulation signal for channel \(i\), \(f_i\) is the channel \(i\) frequency, and \(N_{ch}\) is the number of channels. A general practice is to simulate the AM channels with RF tones of certain modulation depth \(m = m_i(t)\). The CTB and CSO can then be given by:

\[ \text{CTB} = 10 \log \left[ N_{\text{CTB}} \left( \frac{3}{2} \frac{b m^2}{\eta e I_0} \right)^2 \right], \]  
(9.5)

\[ \text{CSO} = 10 \log \left[ N_{\text{CSO}} (am)^2 \right], \]  
(9.6)

where \(N_{\text{CTB}}\) and \(N_{\text{CSO}}\) are third-order and second-order product counts.

In a RF lightwave system, transmitters, receivers, and optical fibers contribute to the CNR, CTB, and CSO performance in many different ways. The system (end-to-end) performance is then the balance among those variables. Over the past decades, tremendous efforts have been given to increasing the effective signal-to-noise/distortion ratio through many different techniques on laser structure, system optimization, etc. Table 9.3 shows the effect of different sources on the system performance and a choice of available technologies and solutions to meet the end-to-end system performance requirements under different network conditions.
5.3 1310 nm ANALOG LASER DESIGN

Typical fiberoptic CATV systems use 1310 nm DFB laser-based transmitters broadcasting over 100 downstream channels through a fiber plus splitting total attenuation of over 10 dB. Interharmonic modulation products contribute distortion (IMD) to each channel band. Under testing, during which carrier tones are substituted for video signals, aggregate harmonic distortion is distinguishable from the carrier in each channel. Composite second-order (CSO) distortion measures the maximum aggregate second-order IMD product in a given channel relative to the carrier tone in that channel. Composite triple-beat (CTB) distortion measures the corresponding quantity for third-order IMD products. Typical specifications for an 80 to 110 channel system with an 8 to 11 dB link loss budget are CNR > 53 to 54 dB (measured in a 4 MHz band), CSO < −63 to −65 dBc, CTB < −67 to −70 dB (both measured in a 30 kHz band) at a CW fiber-coupled power of 2 to ~30 mW (Blauvelt, 2001). These specifications might also include QAM channels loaded at the high frequency end of the band.
\begin{table}
\centering
\caption{Two-Tone Product Count, $N_{\text{CSO}}$}
\begin{tabular}{lrrrr}
\hline
\multicolumn{1}{c}{Channel Load} & \multicolumn{4}{c}{\textit{N}_{\text{CSO}}} \\
\hline
& 42 & 50 & 60 & 80 \\
\hline
Ch 2 (max.) & \text{55.25 MHz} & 31 & 39 & 49 & 69 \\
Ch 11 & \text{139.25} & 7 & 15 & 25 & 45 \\
Ch 40 & \text{313.25} & 12 & 12 & 12 & 25 \\
Ch 50 & \text{373.25} & 16 & 16 & 16 & 16 \\
Ch 60 & \text{433.25} & 21 & 21 & 21 & 21 \\
Ch 80 & \text{553.25} & & & & \\
\hline
\end{tabular}
\end{table}

\begin{table}
\centering
\caption{Three-Tone Product Count, $N_{\text{CTB}}$}
\begin{tabular}{lrrrr}
\hline
\multicolumn{1}{c}{Channel Load} & \multicolumn{4}{c}{\textit{N}_{\text{CTB}}} \\
\hline
& 42 & 50 & 60 & 80 \\
\hline
Ch 3 & \text{61.25 MHz} & 289 & 438 & 669 & 1282 \\
Ch 11 & \text{139.25} & 530 & 771 & 1117 & 1960 \\
Ch 40 & \text{313.25} & 377 & 681 & 1127 & 2170 \\
Ch 50 & \text{373.25} & 527 & 1001 & & 2134 \\
Ch 60 & \text{433.25} & & 783 & & 1998 \\
Ch 80 & \text{553.25} & & & & 1446 \\
\hline
\text{Maximum count} & 531 & 786 & 1172 & 2170 & \\
\hline
\end{tabular}
\end{table}
Fig. 14.5 Hybrid fiber coax (HFC) broadband access system. Broadband analog video, broadband digital video, and switched voice and data services are delivered by analog lightwave to fiber nodes. Fiber nodes convert analog optical signals to electrical and drive coaxial distribution systems that serve between 200 and 2000 subscribers. Various network interface units (NIUs) provide the required digital-to-RF conversion.
CHALLENGES OF AM-VSB TRANSMISSION

Requirements:

\[
\begin{align*}
\text{CNR} & : 52\text{dB} & 47\text{dB} \\
\text{CTB/CSO} & : -65\text{dBc} & -55\text{dBc}
\end{align*}
\]

Challenges:

- Linearity
- Noise
- Chirp
- Dispersion
- Reflection
- Linearity
- Noise
- Others
**M-way Modulation Formats**

Describing

\[ f(t) = A \sin(\omega t + \phi) \quad \text{AM/QAM} \]

\[ \sin(a + b) = \sin a \cos b + \sin b \cos a \]

\[ = A \cos \phi \sin \omega t + A \sin \phi \cos \omega t \]

\[ = a \sin \omega t + b \cos \omega t \quad \text{QAM quadrature} \]

- provide AM of \( \sin + \cos \) independently
- with \( M = 2^k \) levels per modulation period
- or \( k \) bits / period
- there is one symbol per modulation period = baud rate
- bit rate = \( k \cdot \text{baud rate} \)
for \( M = 4 \), stationary QAM
\[ k = 2 \]
\[ 00 \rightarrow (-1,1) \]
\[ 10 \rightarrow (-1,-1) \]
\[ 01 \rightarrow (1,1) \]
\[ 11 \rightarrow (1,-1) \]

constellation

Fig. 1.14

- If on-off keying, gives:
  \( M = 2 \), \( k = 1 \) bit/symbol.
  and spectral bandwidth in \( H_3 \)
equals 8 bits/sec.

- Then Information Spectral Density (ISD)
  \[ 1 \text{ bit/sec/}H_3 \] for 000
  \[ 2 \text{ bit/sec/}H_3 \] for \( Q\text{-QAM} \)
  \( 4 \) bit/sec/\( H_3 \) for \( 16\text{-QAM} \)
  \( 6 \) bit/sec/\( H_3 \) for \( 64\text{-QAM} \).
FIGURE 1.14 Quaternary-QAM bandpass waveform and Gray-code symbol equivalence. The constellation coordinates are shown in parentheses.
FIGURE 1.13  Rectangular constellation diagram for 16-ary QAM and Gray-code symbol equivalence.
SHANNON LIMIT

It is possible to transmit

\[ C \text{ (bits/sec)} = B \left( H_2 \right) \log_2 \left( 1 + \frac{P_s}{P_n} \right) \]

with arbitrarily small probability of error. You figure out how.

For example,

\[ \text{SNR} = \frac{P_s}{P_n} = 2^{10} = 1024 \Rightarrow 30 \text{ dB}. \]

\[ \frac{C}{B} \approx 10 \text{ bits/sec/Hz} \]

Fig. 1.32.
FIGURE 1.32 Bandwidth-efficiency diagram, representing the information spectral density \( \log_{10}[C_{bit/s/Hz}] \) as a function of the bit SNR (dB). The thick line correspond to ISDs bounded by the Shannon–Hartley law. The families of points correspond to ISDs of the M-ary signal modulation formats FSK, PSK and QAM, at constant bit-error rate (\( BER = 10^{-3} - 10^{-11} \)). The two crosses on the \( C = 1 \text{ bits}^{-1} \text{ Hz}^{-1} \) axis correspond to the same BER range for ON/OFF, NRZ signals. [After E. Desurvire et al., 2002. See Bibliography at end of this book.]
The End