Analog Front End Design For ADSL

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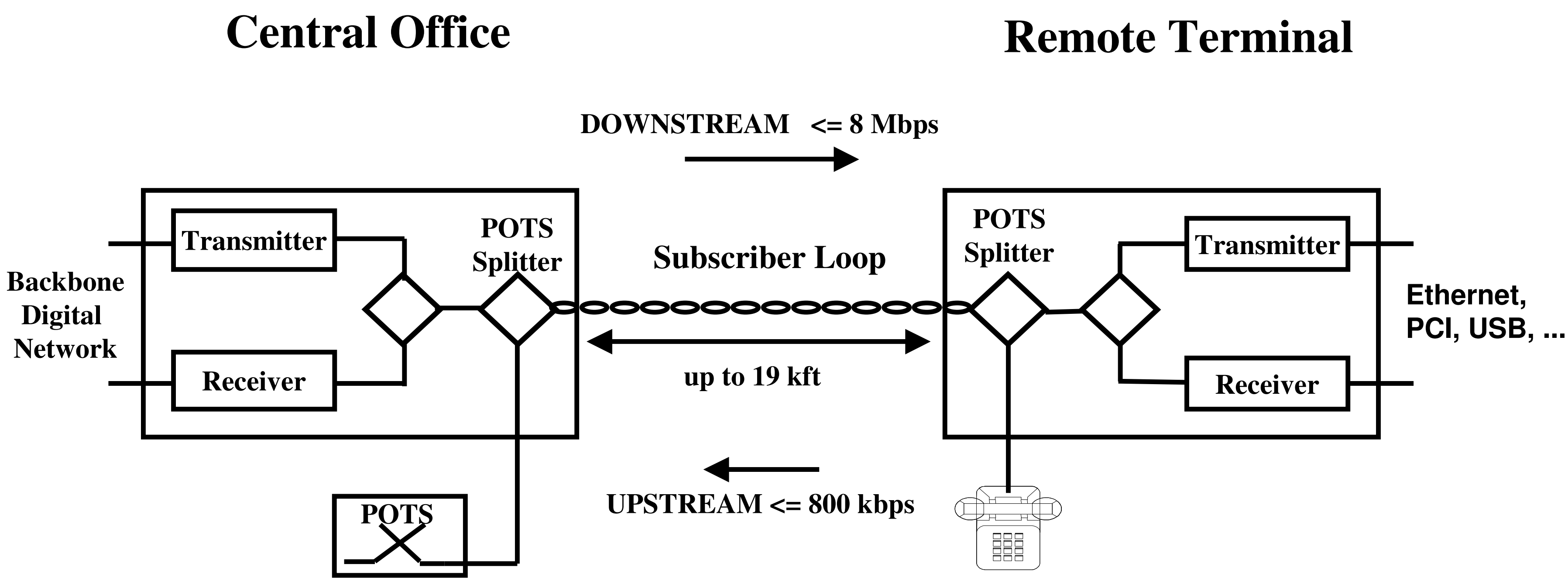
Outline

- **Canonical ADSL System Diagram**
- **Signal Characteristics**
- **Impairments**
- **Line Coupling Circuits**
- **Transmitter Design**
- **Receiver Design**

ADSL System



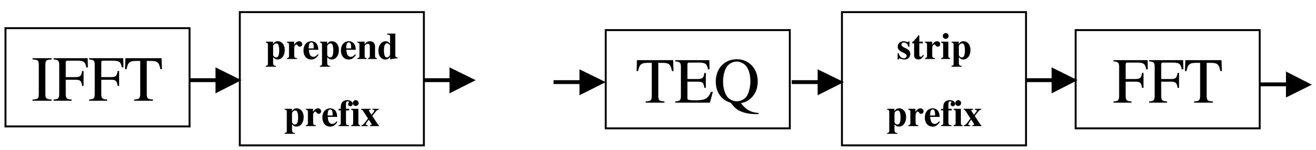
Unlike V.xx dial-up modems, the signal is not terminated by a voice-band line card

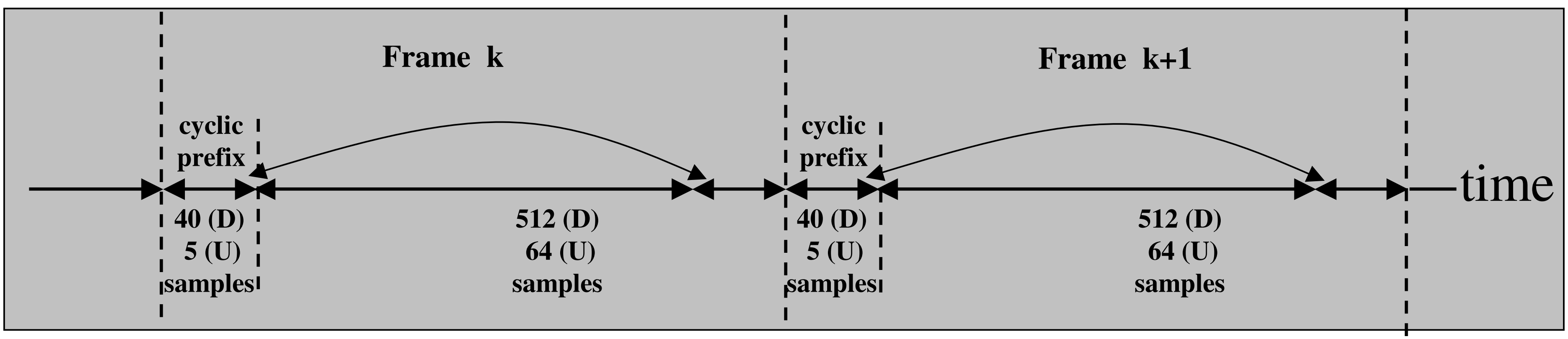
Signal Characteristics

- DMT modulation
- Frequency plan
- Capacity
- Peak-to-Average Ratio and BER
- Continuous-time/Discrete-time PSD

Discrete Multi-Tone Signaling (ODFM)

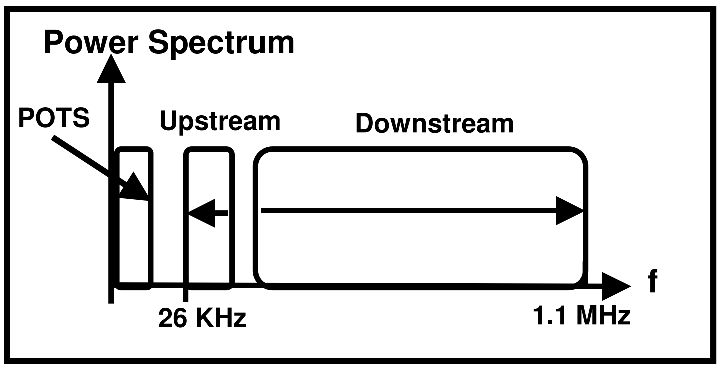
- **Employs many narrow-band (4.3125 kHz) sub-carriers**
- **Low baud frequency (4 kHz)**
- **Data dynamically assigned to sub-carrier according to SNR**
- **IFFT/FFT used to modulate/demodulate in blocks**



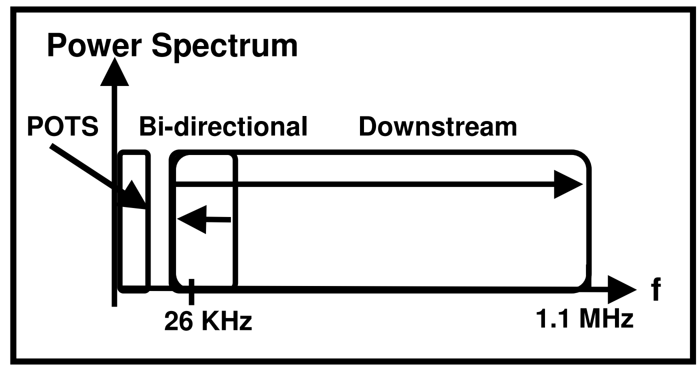


Frequency Plan

Frequency Division Duplexed

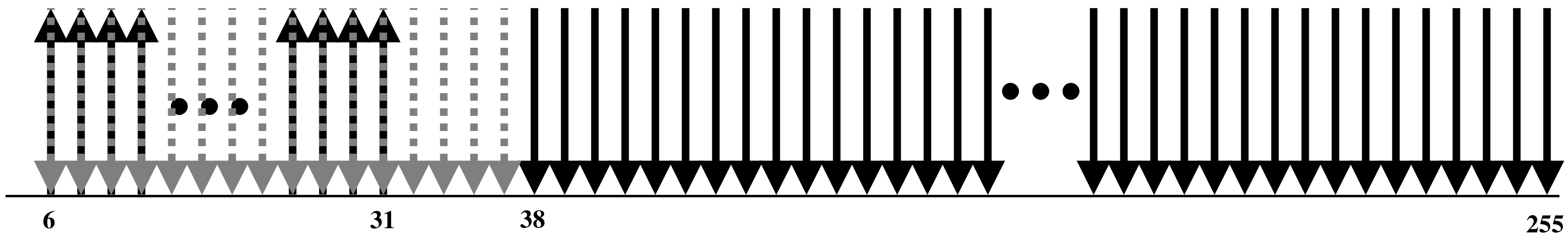


Echo-Cancelled



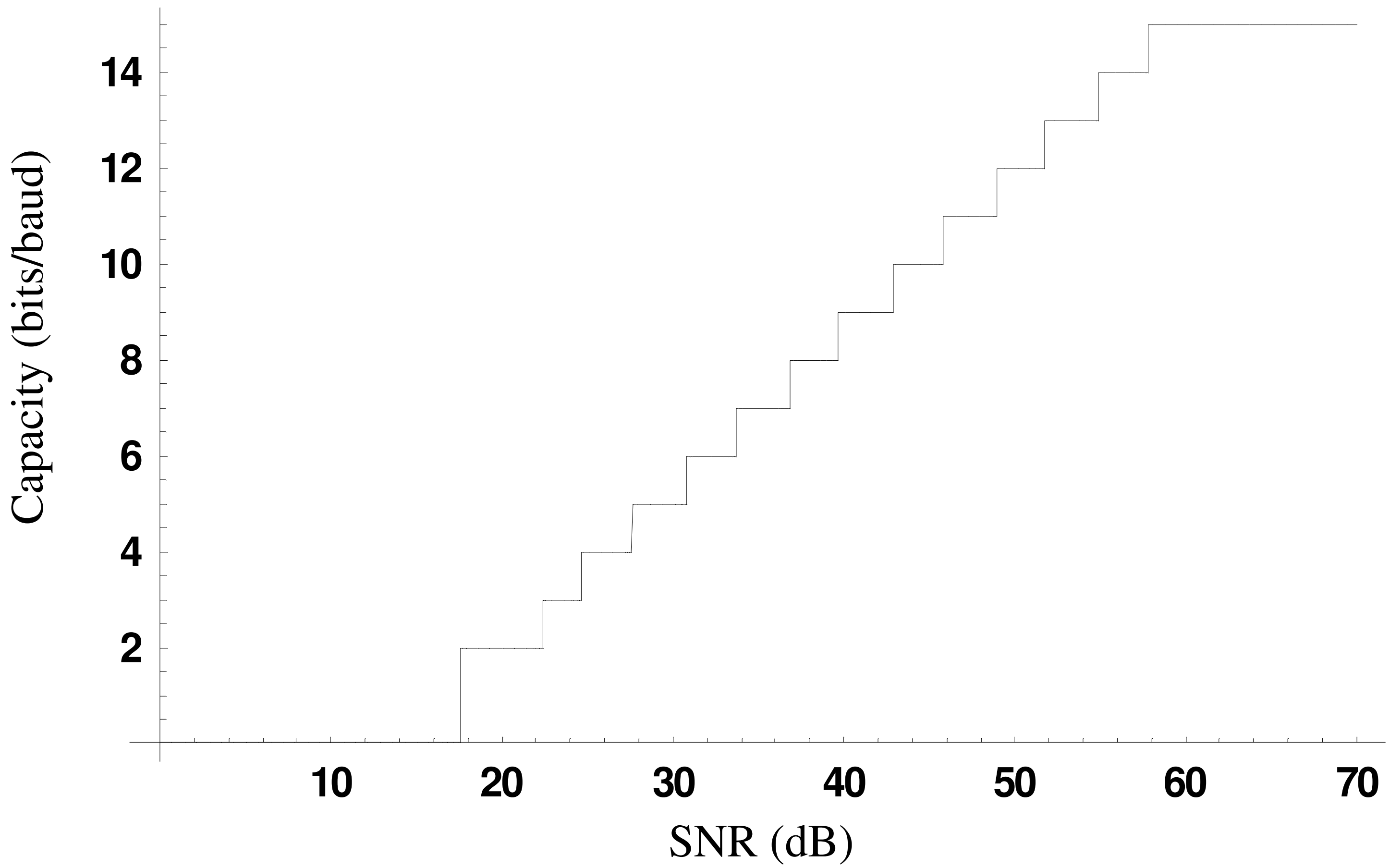
ITU G.hs training protocol guarantees FDD-EC modem interoperability

Annex A Frequency Plan Example

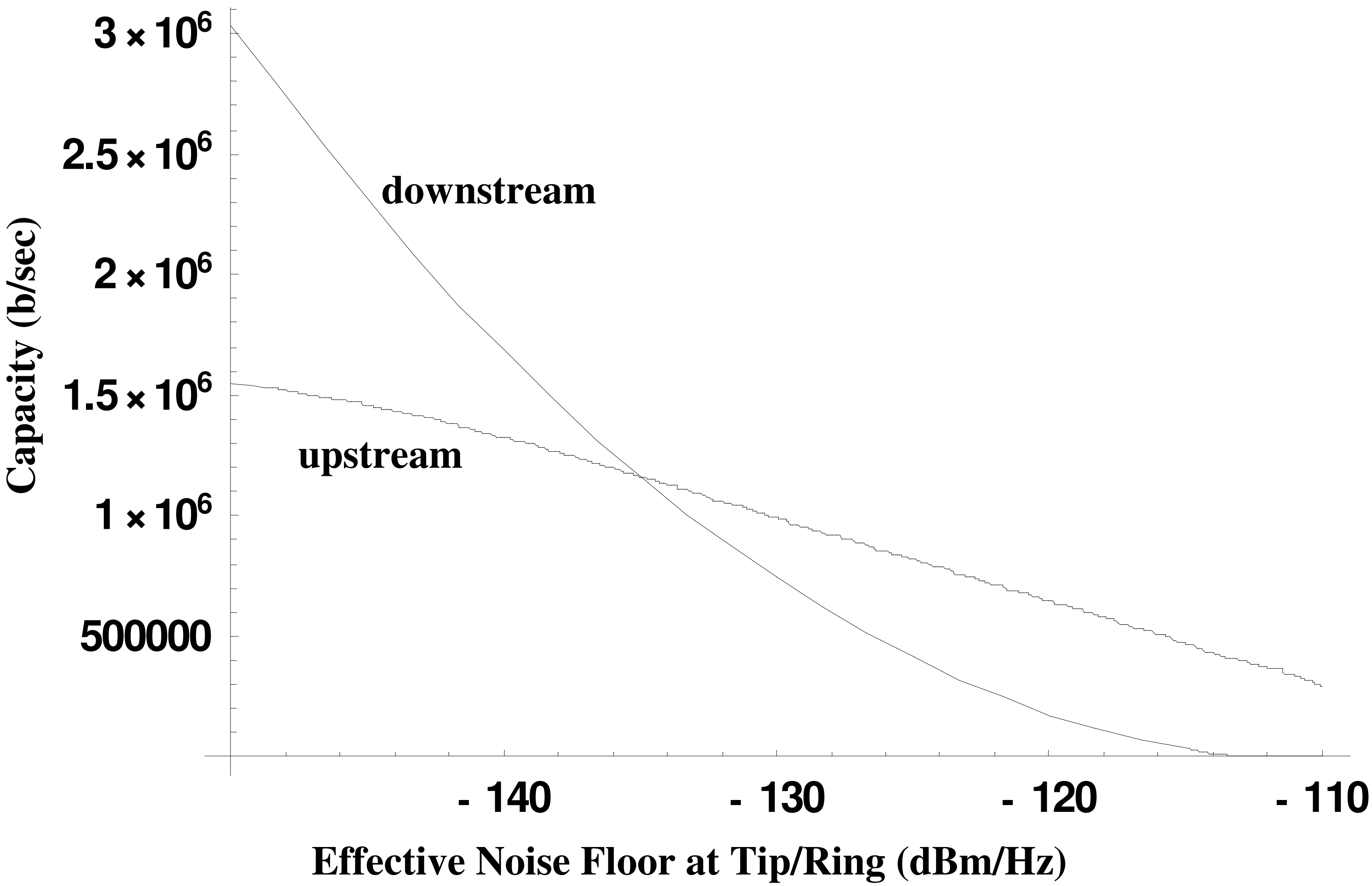


- Sub-carrier frequencies: n*4.3125 kHz
    - Upstream n= 6, …, 31
    - Echo-canceling downstream n= 6, …, 255
    - Frequency division downstream n= 33, …, 255
- Modulation: 4QAM … 32768QAM
- Subcarrier data rate capacity: 2-15 bits per baud period

Subcarrier Capacity versus SNR



Maximum 15kft 26awg Data Rate Capacity



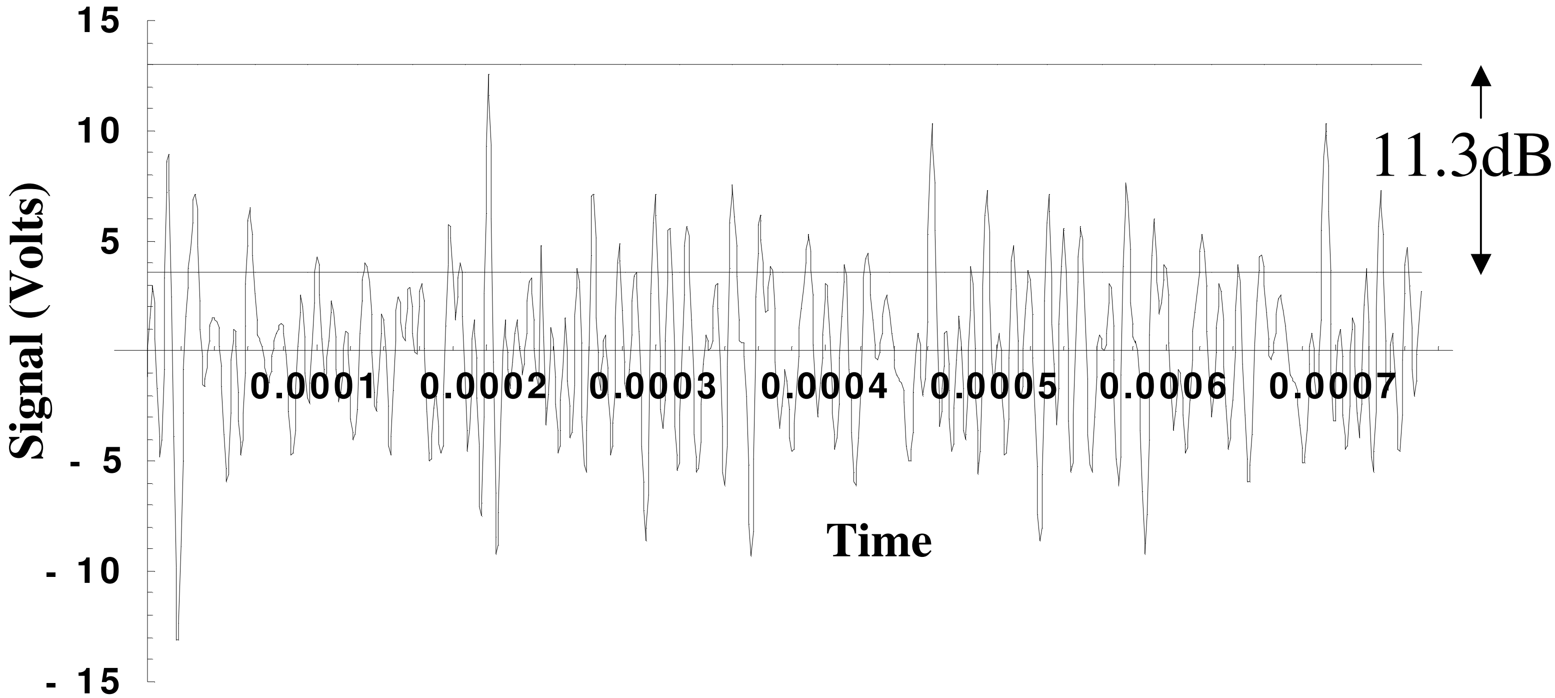
More on Frequency Plan

Annex	Upstream	Downstream
• A (POTS)	6 – 31	6 (33) – 255
• A+	6 – 31	6 (33) – 511
• B (ISDN)	29 – 63	29 (60) – 255
• B+	29 – 63	29 (60) – 511
• C (TCM-ISDN)	33 – 63	33 – 255
• H (TCM-ISDN)	6 – 255	6 – 255
• I	1 – 31	1 – 255
• J	1 – 31 (63)	1 – 255

Peak-to-RMS Ratio

- Subcarriers are statistically independent, so sum of N has Gaussian probability distribution in time-domain, where variance is 0.43152* N volt^2.

- When N=250, the RMS signal is 3.28V, and a 16dB peak-to-RMS ratio corresponds to 41.4 V_{PP}.



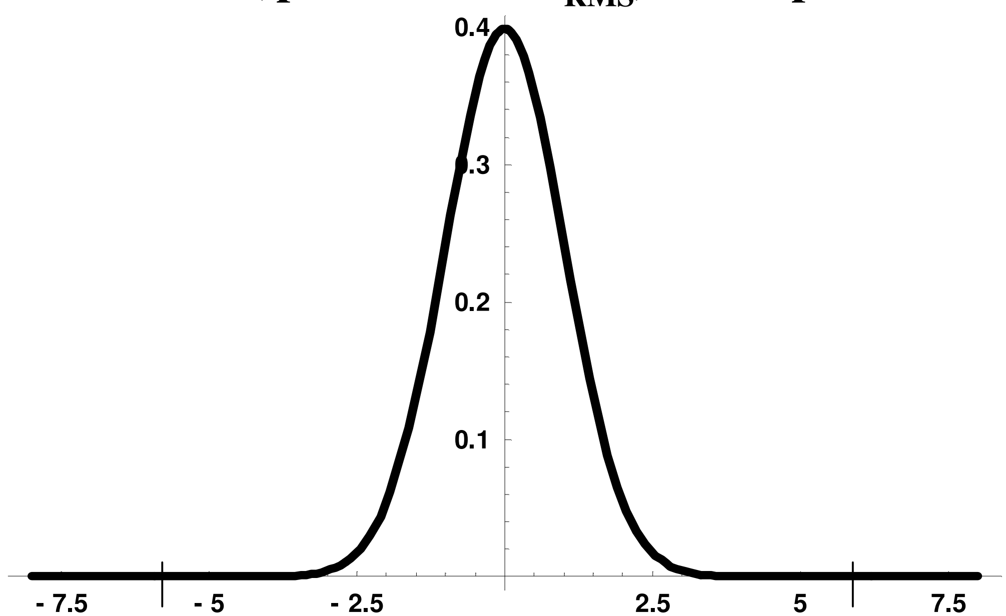
Gaussian Signal Statistics

- Sub-carriers are statistically independent, so sum of N sub-carriers has Gaussian probability (central limits theorem)

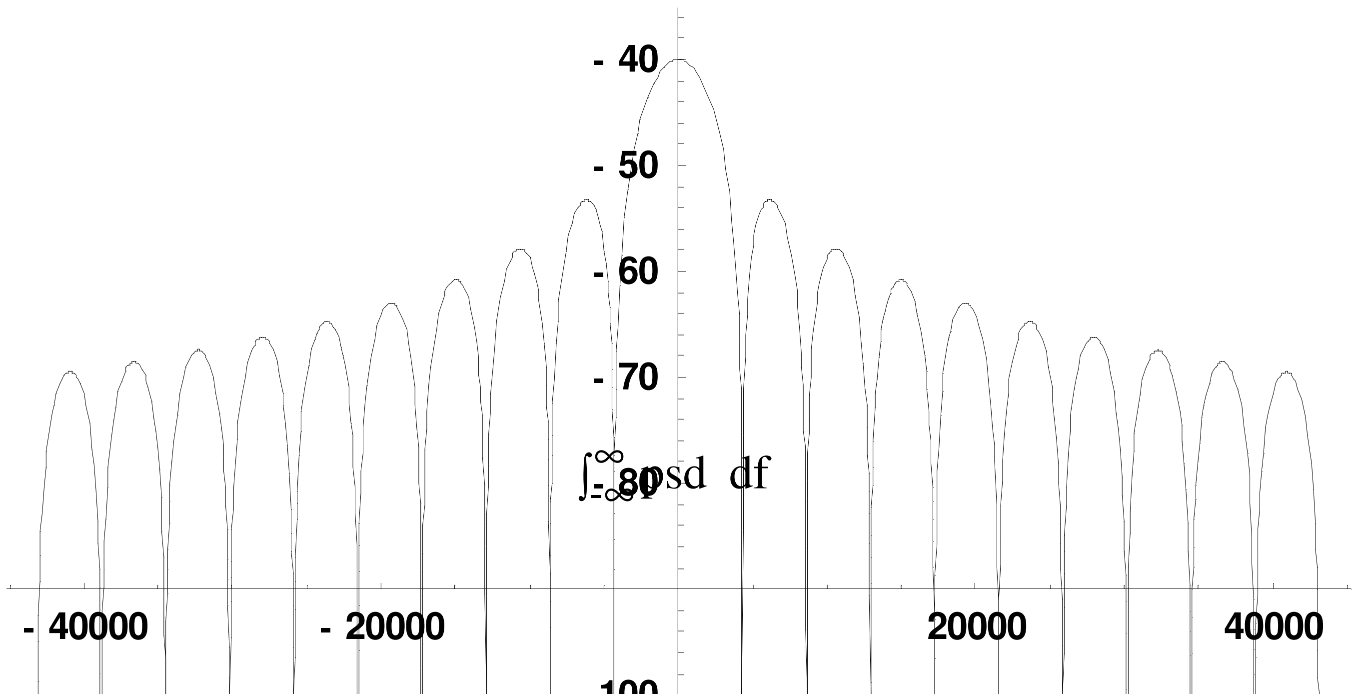
- Signal clipping, either analog or digital, transmitter or receiver, wrecks SNR and creates transmission errors

- Must support signal swing that corresponds to desired bit error rate

- 16dB peak-to-RMS ratio (peaks to 6.3 V_{RMS}) corresponds to a 10^{-7} BER.



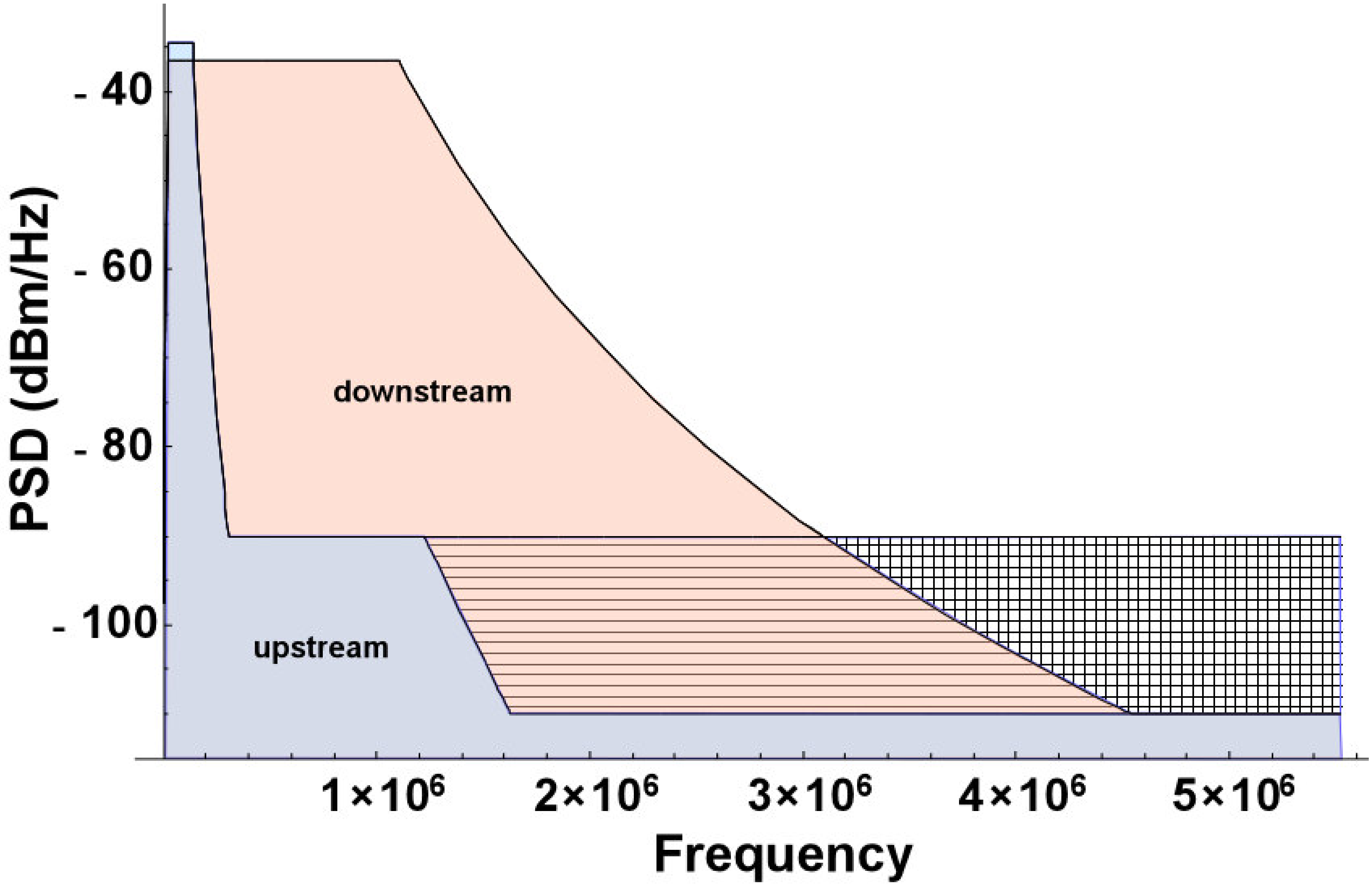
Sub-Carrier Power Spectral Density (dBm/Hz)



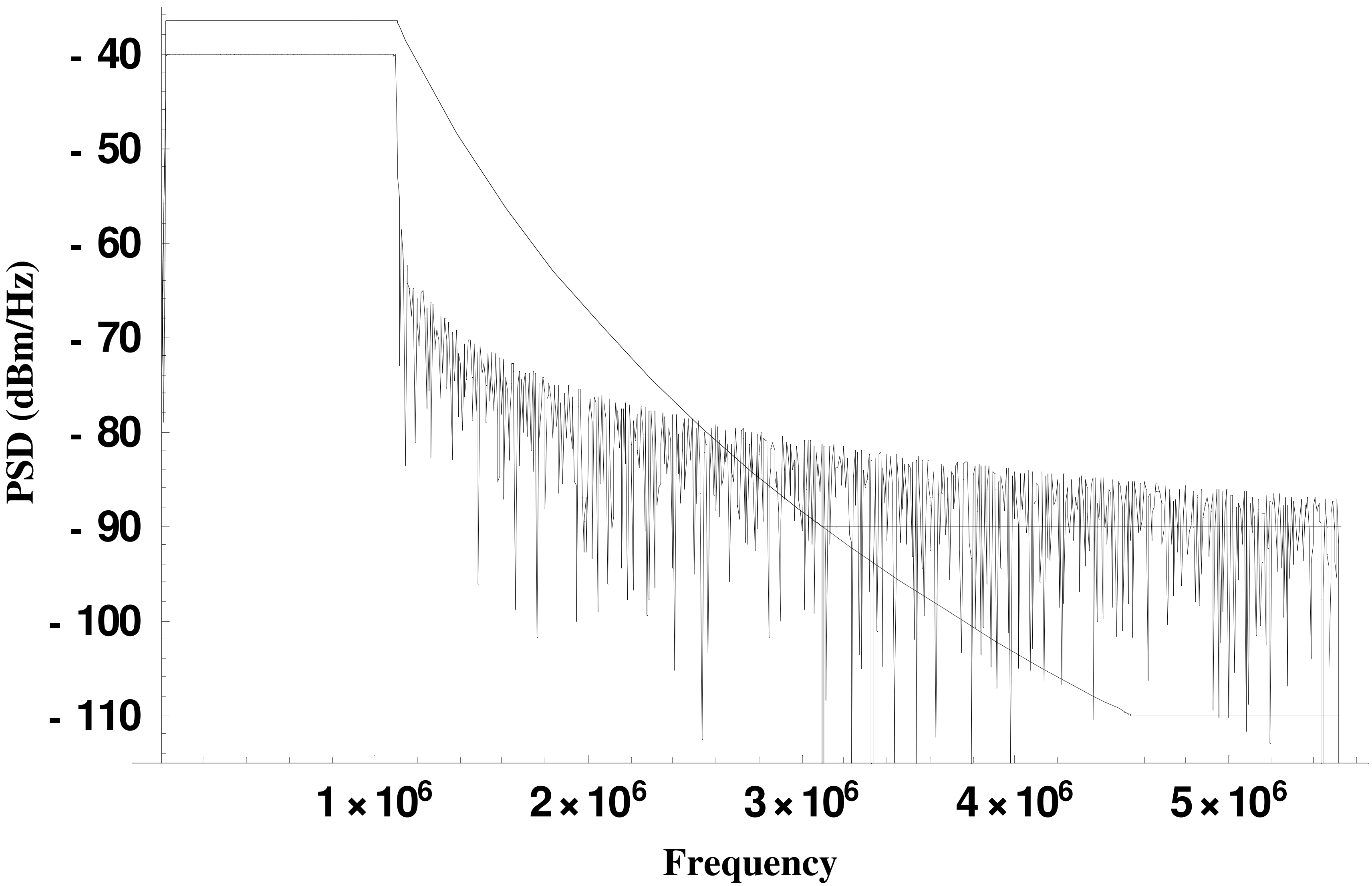
Sub-carrier Power = $\int_{-\infty}^{\infty} \text{psd}\, df$

= -3.65dBm (432μW) downstream and -1.65dBm (544μW) upstream.

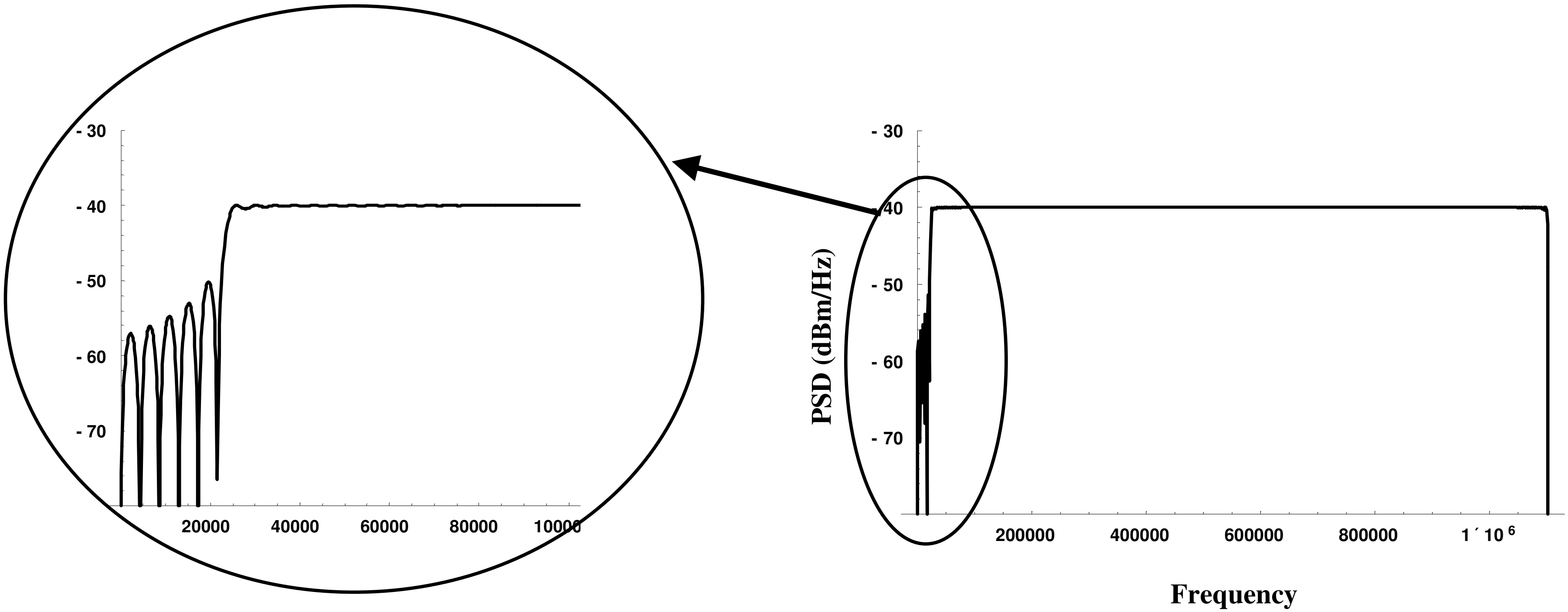
ITU/ANSI PSD Masks



Downstream PSD With Continuous Time Sub-Carrier Generation



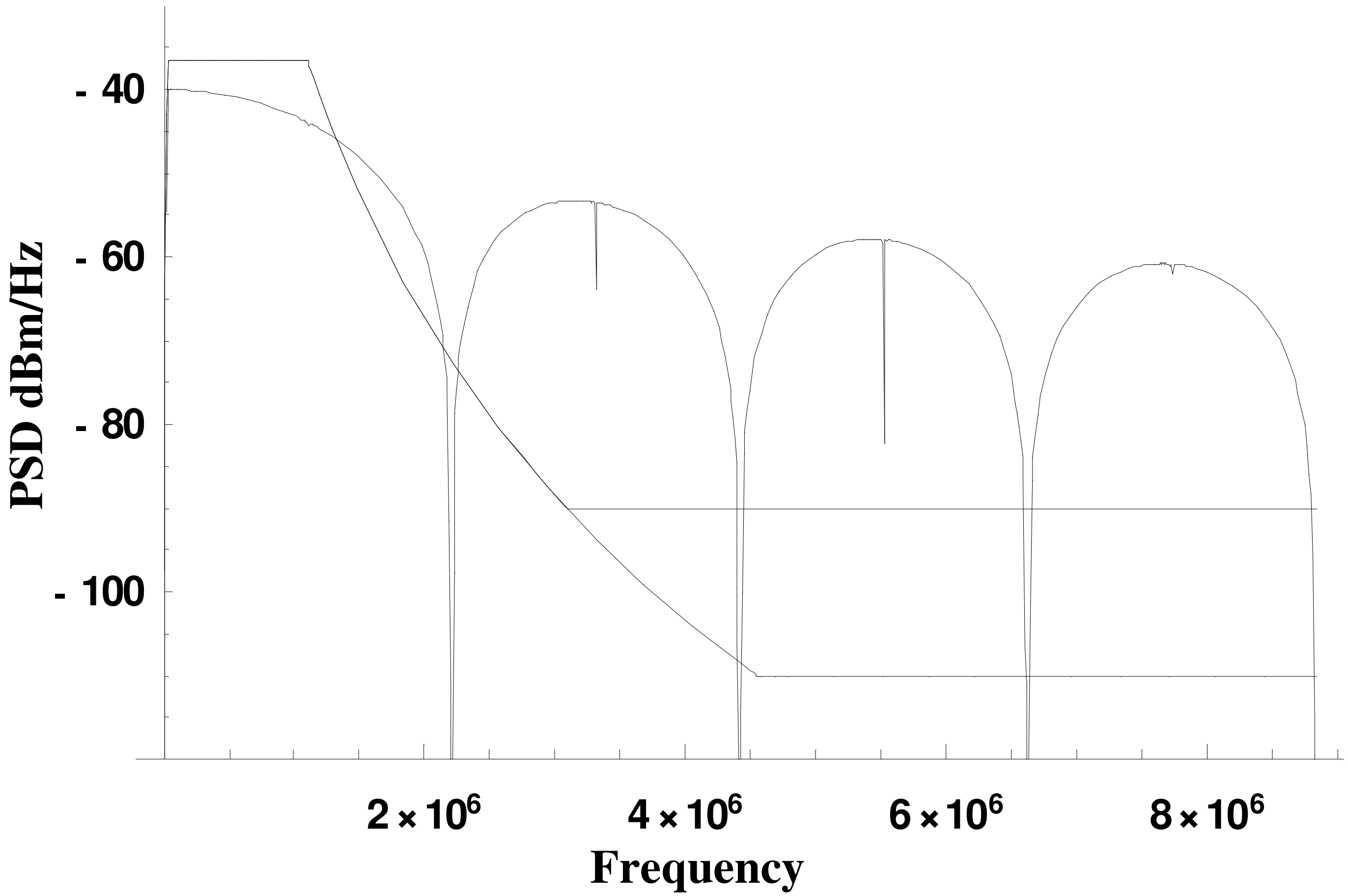
DSP Transmitter Signal (Minimum Sample Rate)



- **Minimum Annex A downstream 256-point IFFT with 4312.5Hz resolution (one bin per subcarrier) produces 2208kS/sec sample rate.**

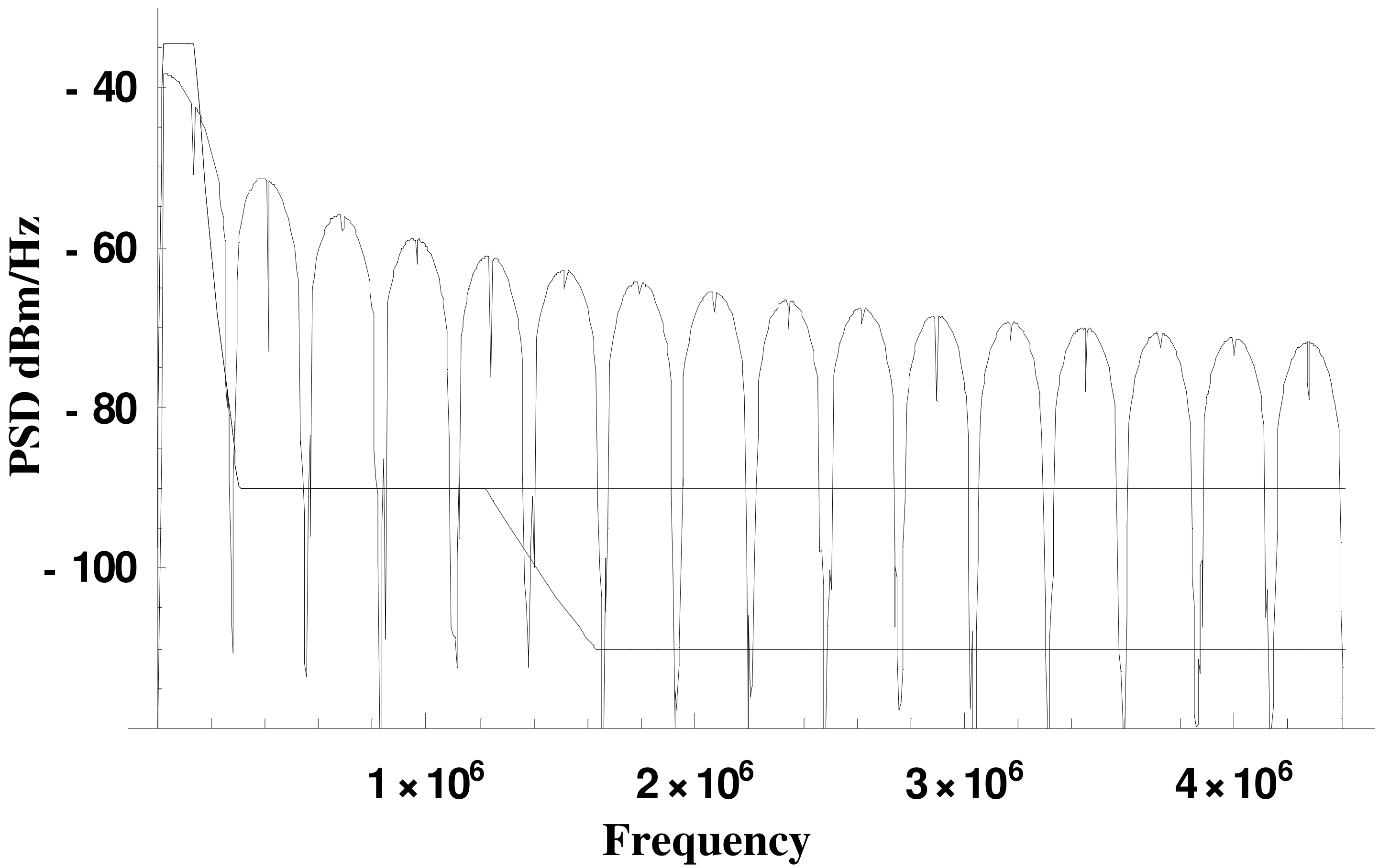
- **Minimum Annex A upstream 32-point IFFT with 4312.5Hz resolution (one bin per subcarrier) produces 276kS/sec sample rate.**

Downstream PSD With Minimum Sample Rate



• Conversion of downstream signal to continuous-time at 2208kS/sec produces in-band droop and significant standard's non-compliance.

Upstream PSD With Minimum Sample Rate (276kS/sec)

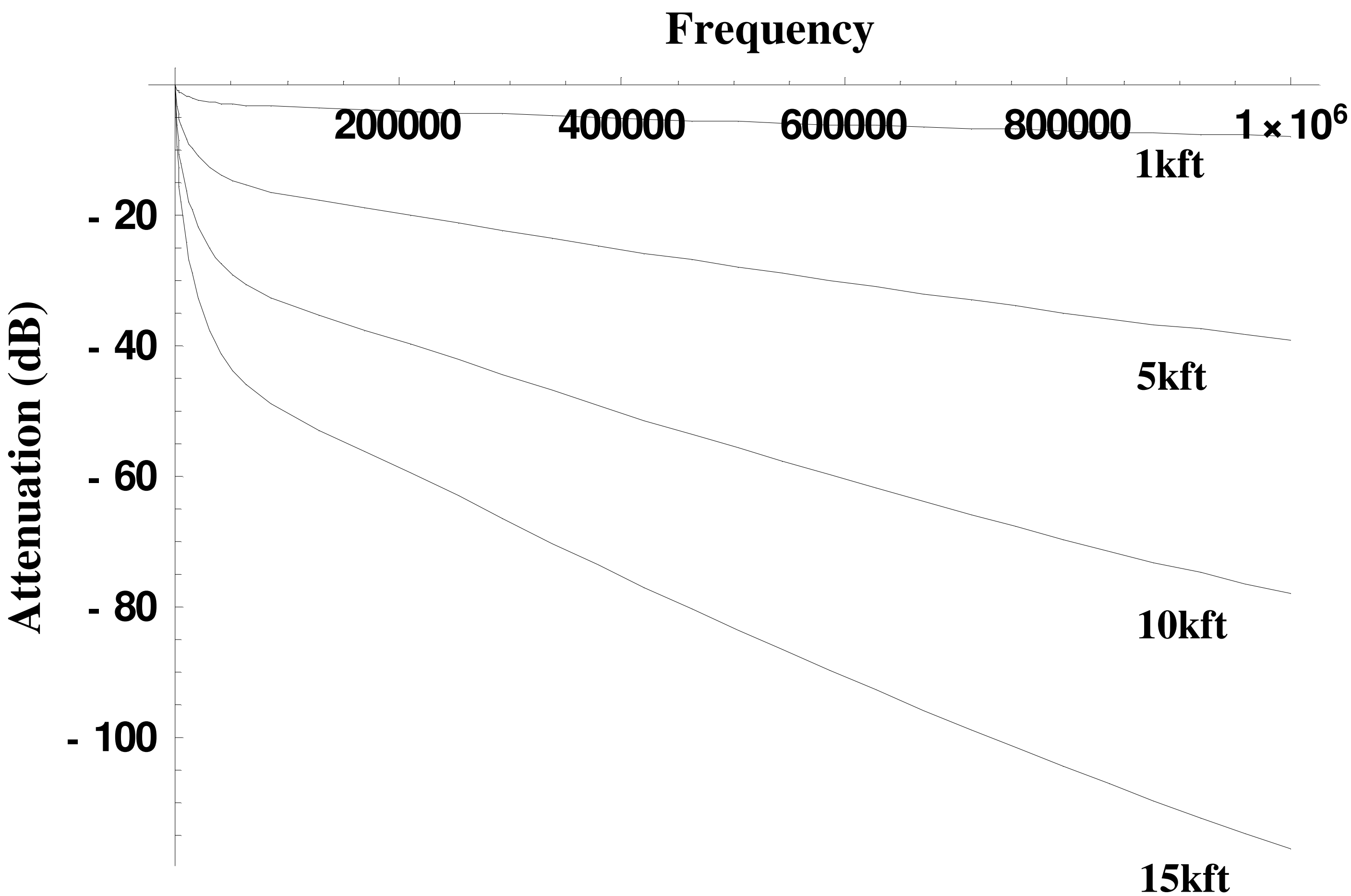


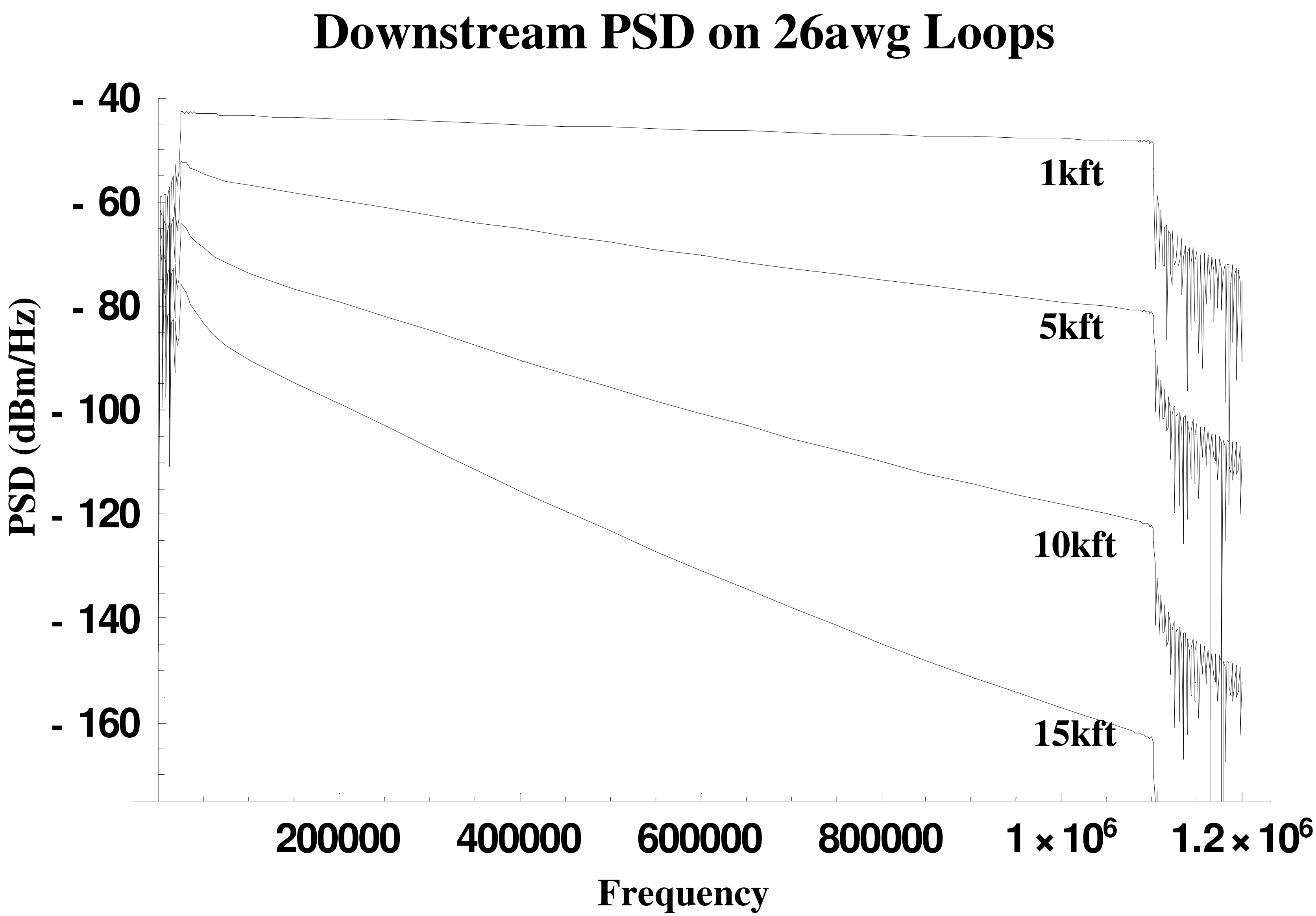
• Conversion of upstream signal to continuous-time at 276kS/sec produces in-band droop and significant standard's non-compliance.

Impairments

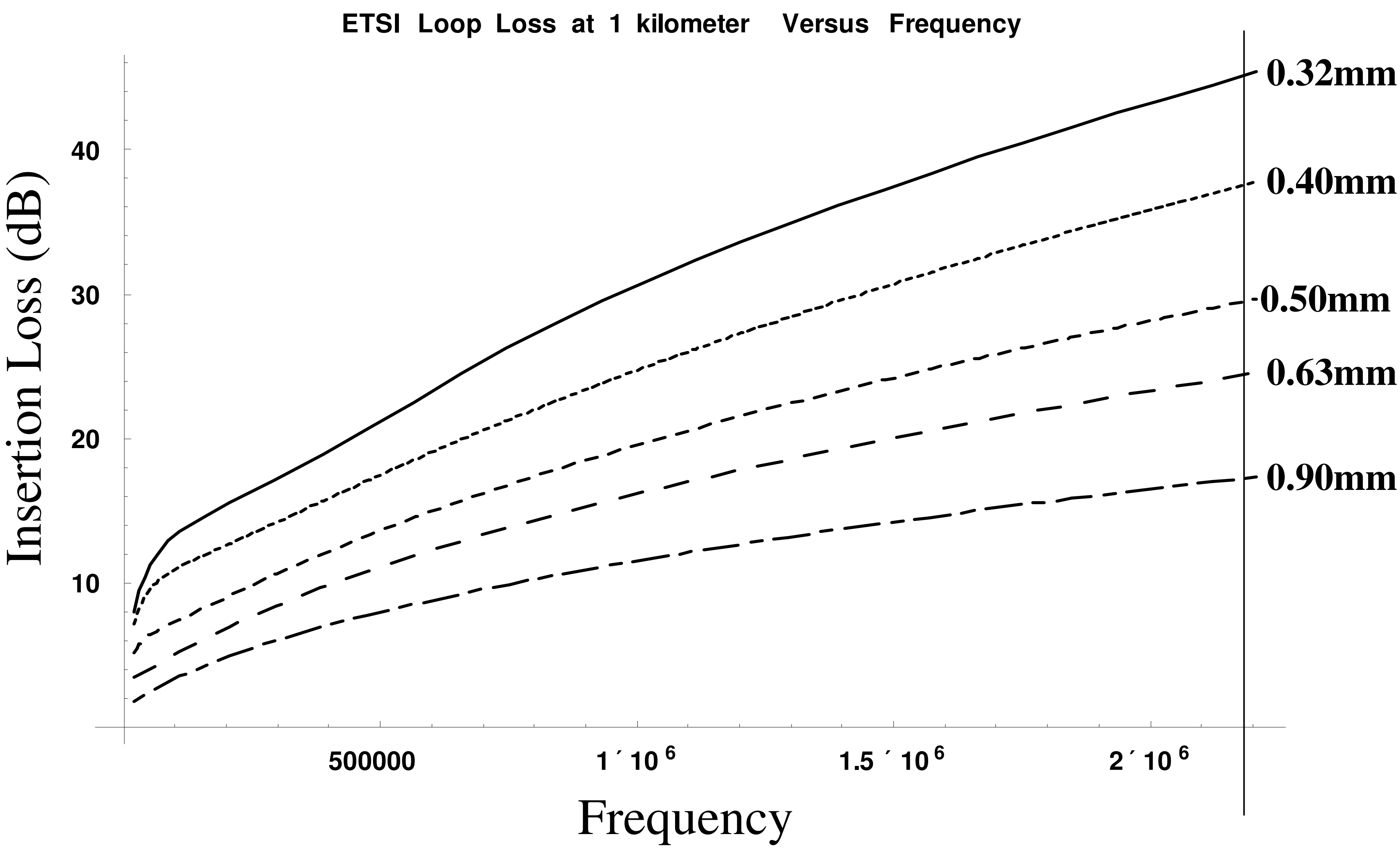
- Loop attenuation
- Loop variability
- Crosstalk

26awg Loop Attenuation

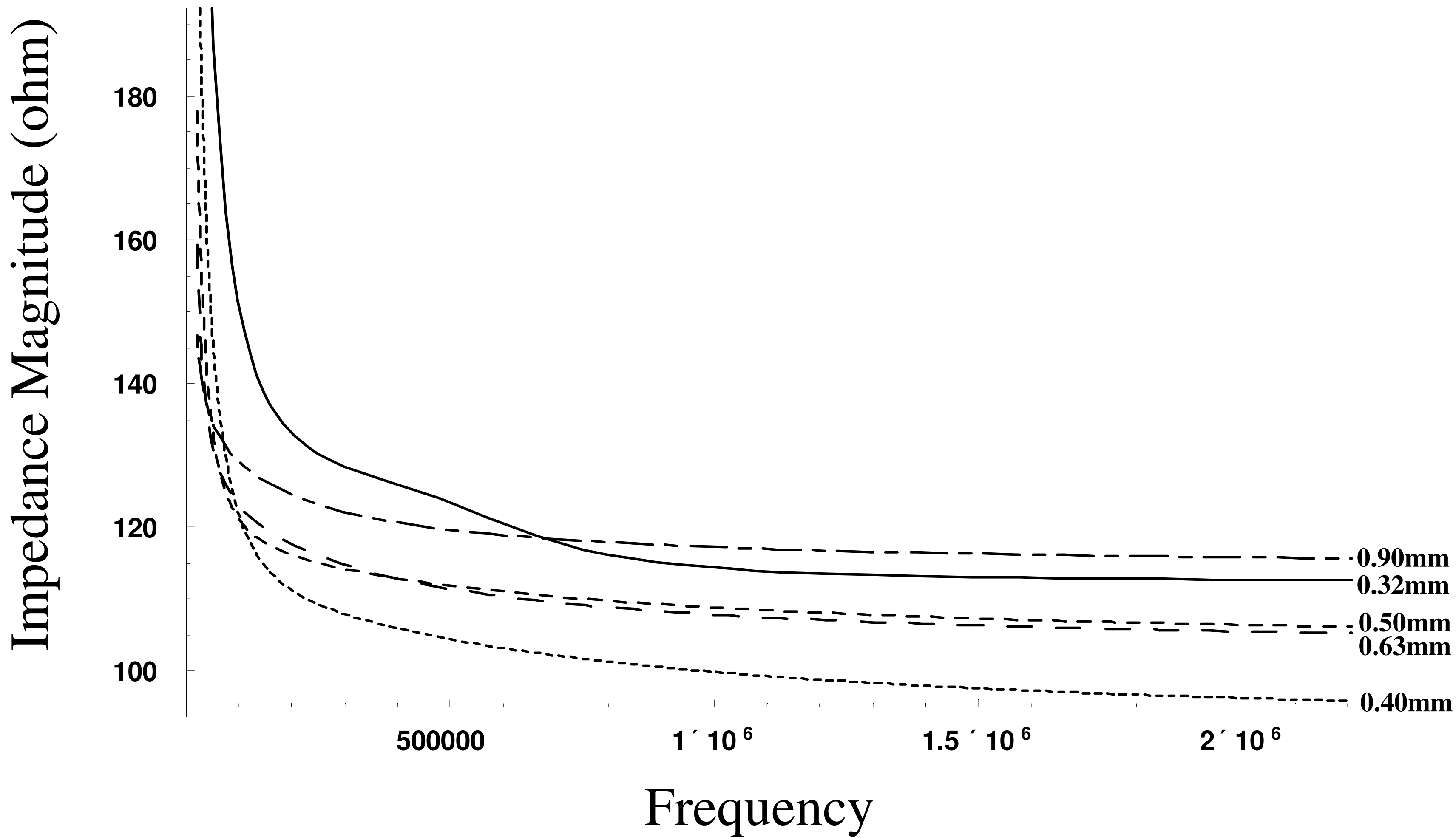



Downstream PSD on 26awg Loops
PSD (dBm/Hz)
- 40
- 60
- 80
- 100
- 120
- 140
- 160
1kft
5kft
10kft
15kft
200000
400000
600000
800000
1 × 10^6
1.2 × 10^6
Frequency

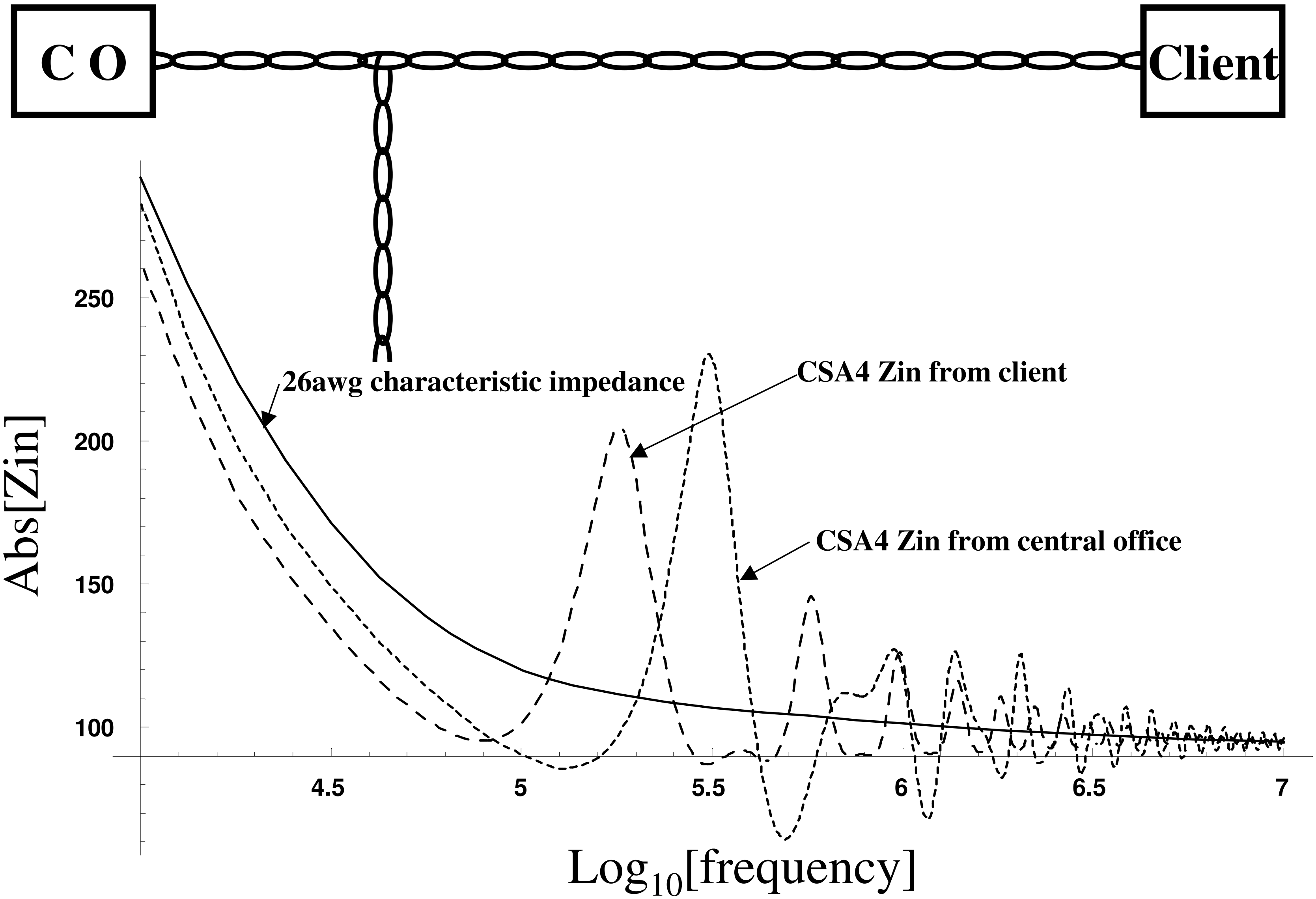
Loop Variability



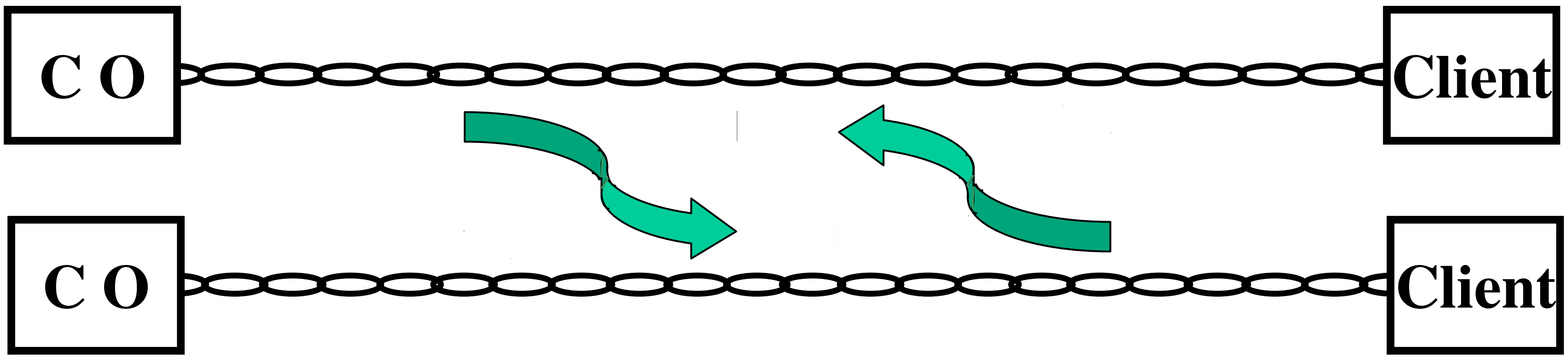
Loop Impedance



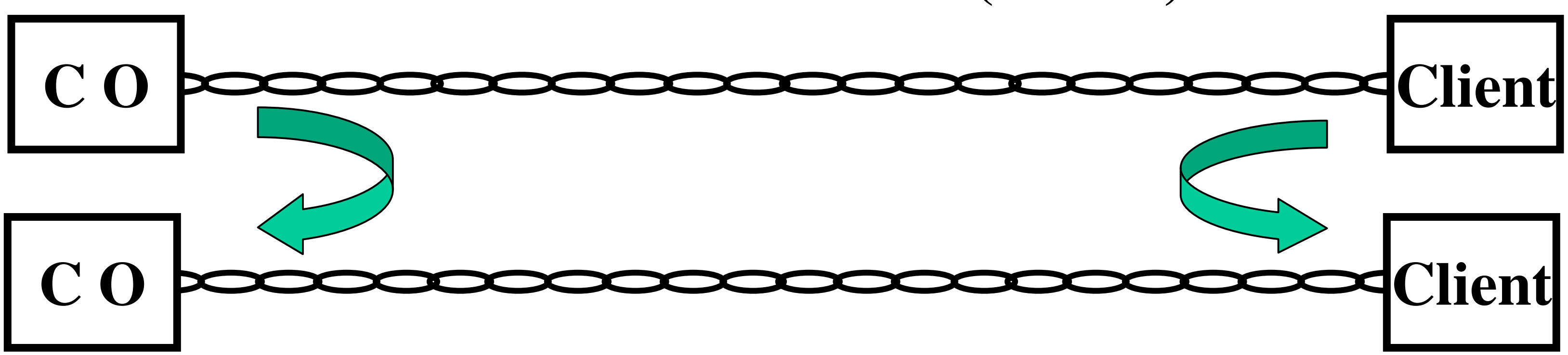
Bridged Taps



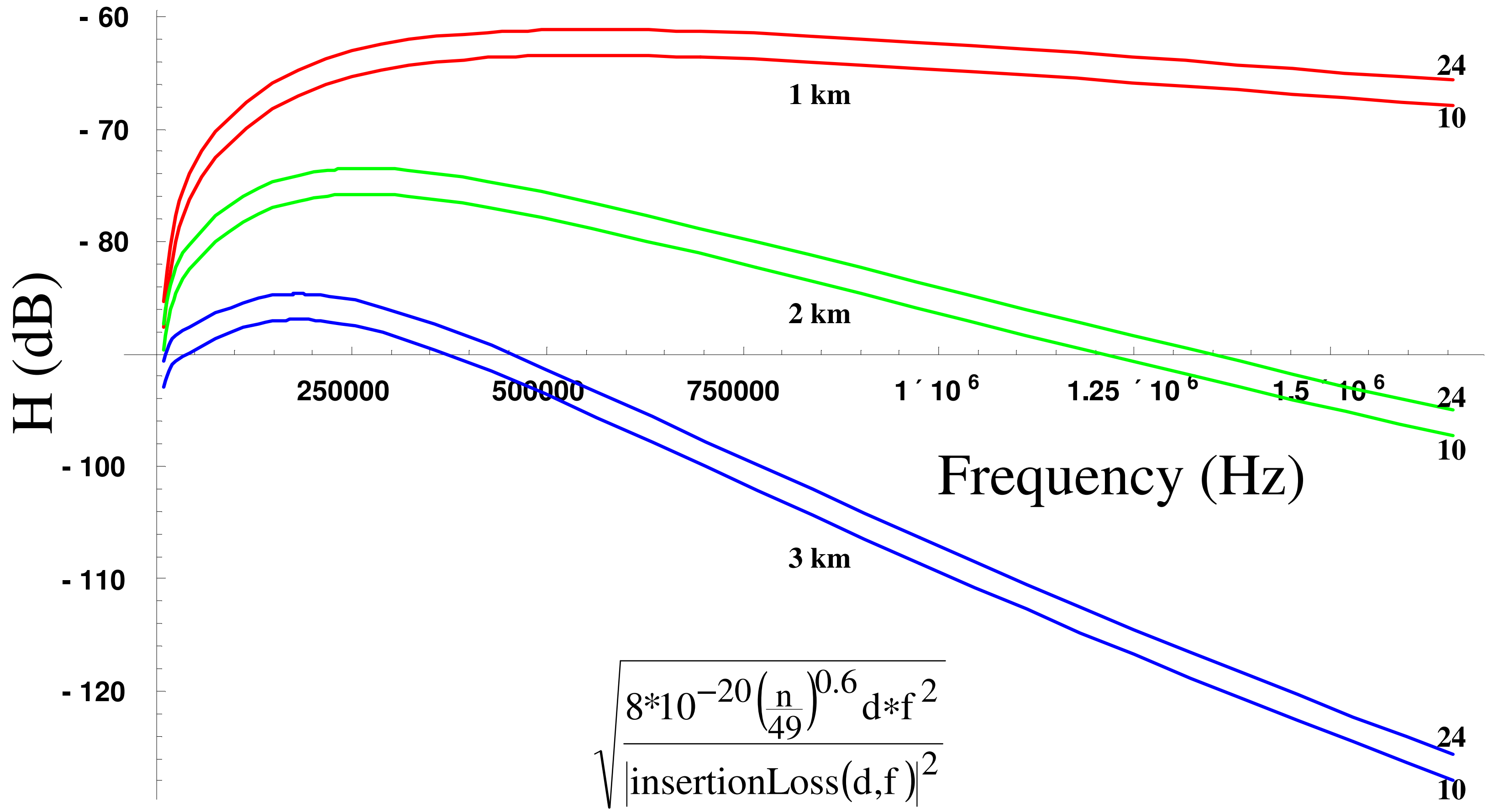
Far End Cross Talk (FEXT)



Near End Cross Talk (NEXT)

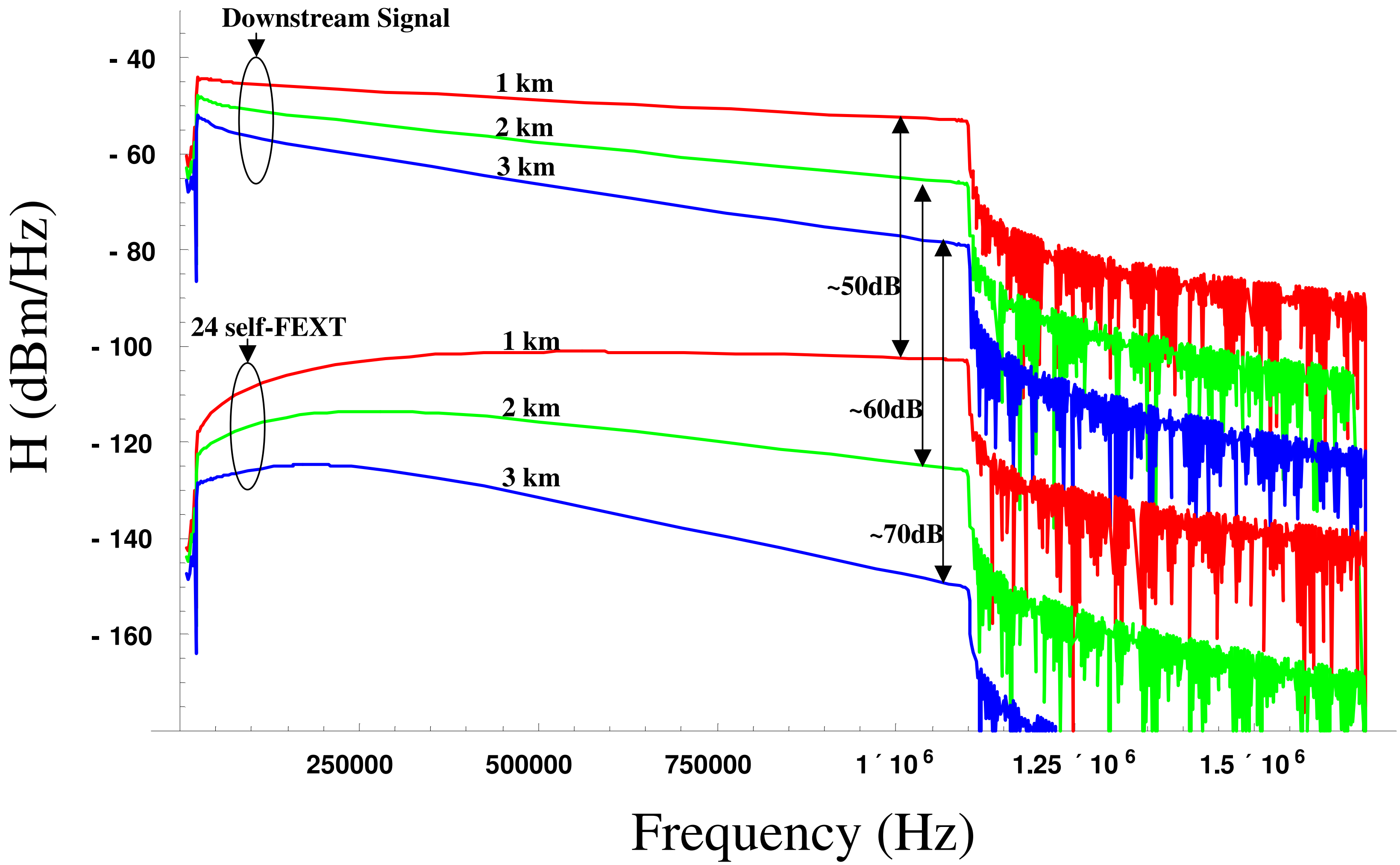


Far End Crosstalk Transfer Function (FEXT)

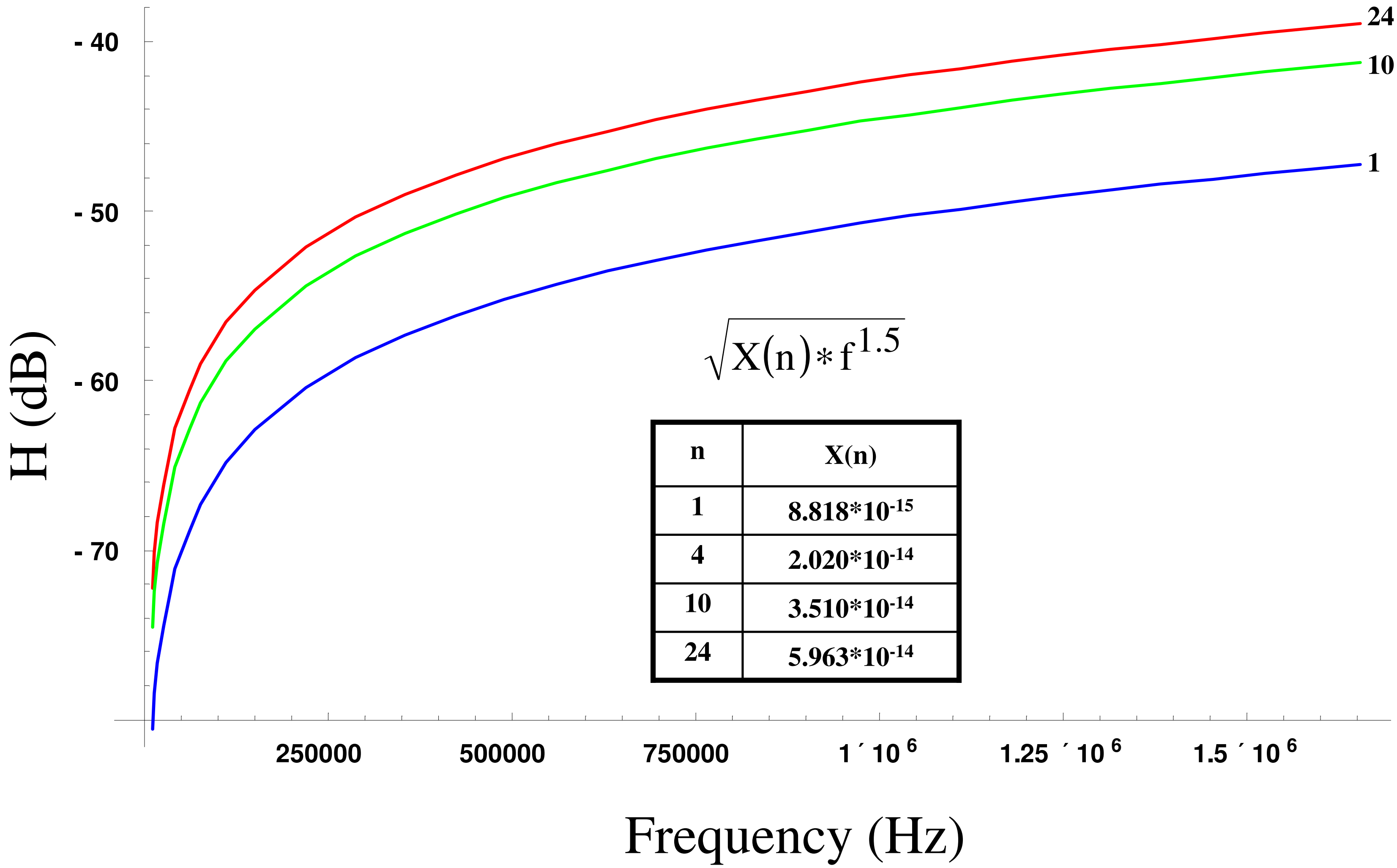


$$\sqrt{\frac{8*10^{-20}\left(\frac{n}{49}\right)^{0.6} d*f^{2}}{\left|\text{insertionLoss}(d,f)\right|^{2}}}$$

24-Self FEXT Example

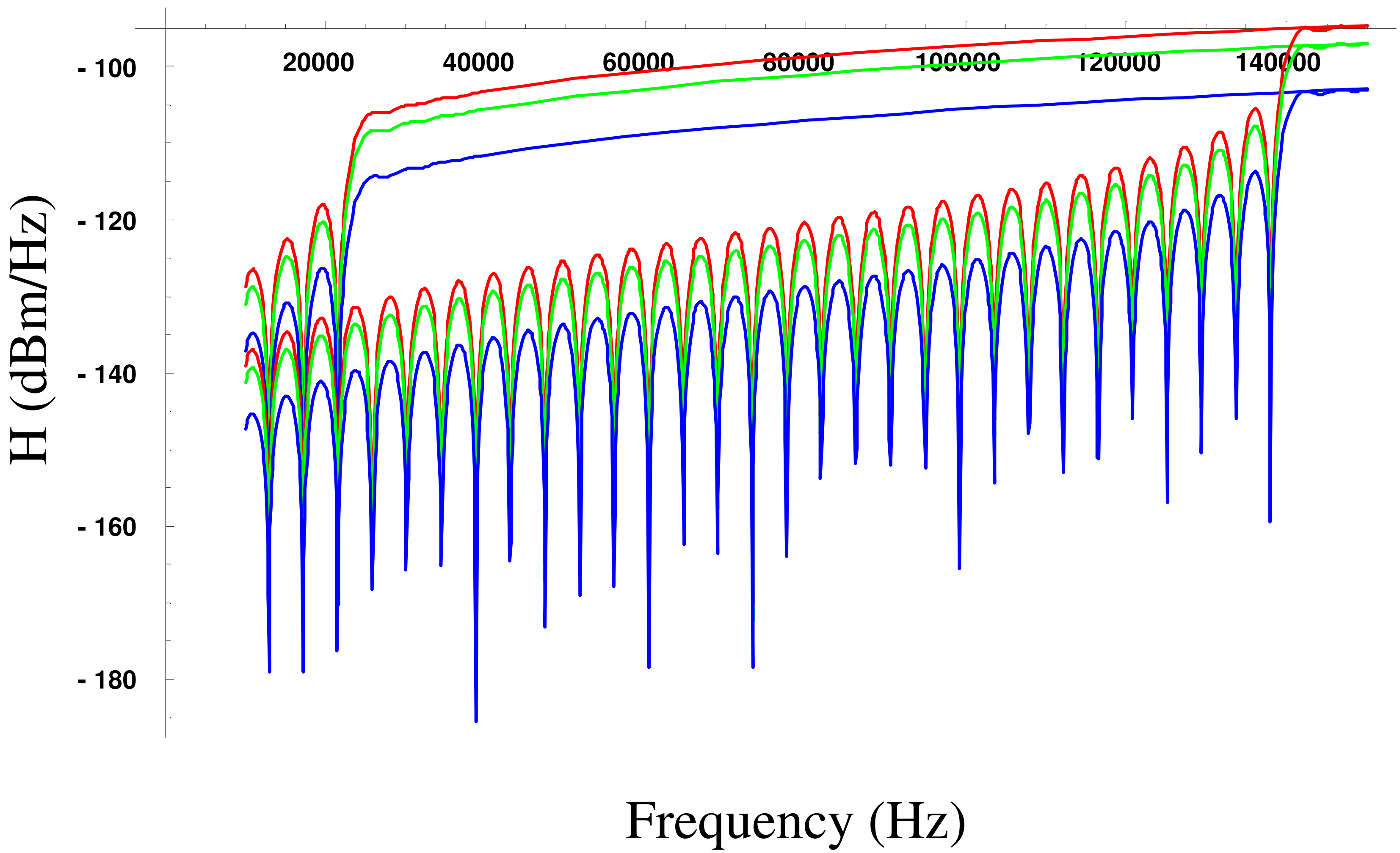


Near End Crosstalk Transfer Function (NEXT)



n	X(n)
1	$8.818*10^{-15}$
4	$2.020*10^{-14}$
10	$3.510*10^{-14}$
24	$5.963*10^{-14}$

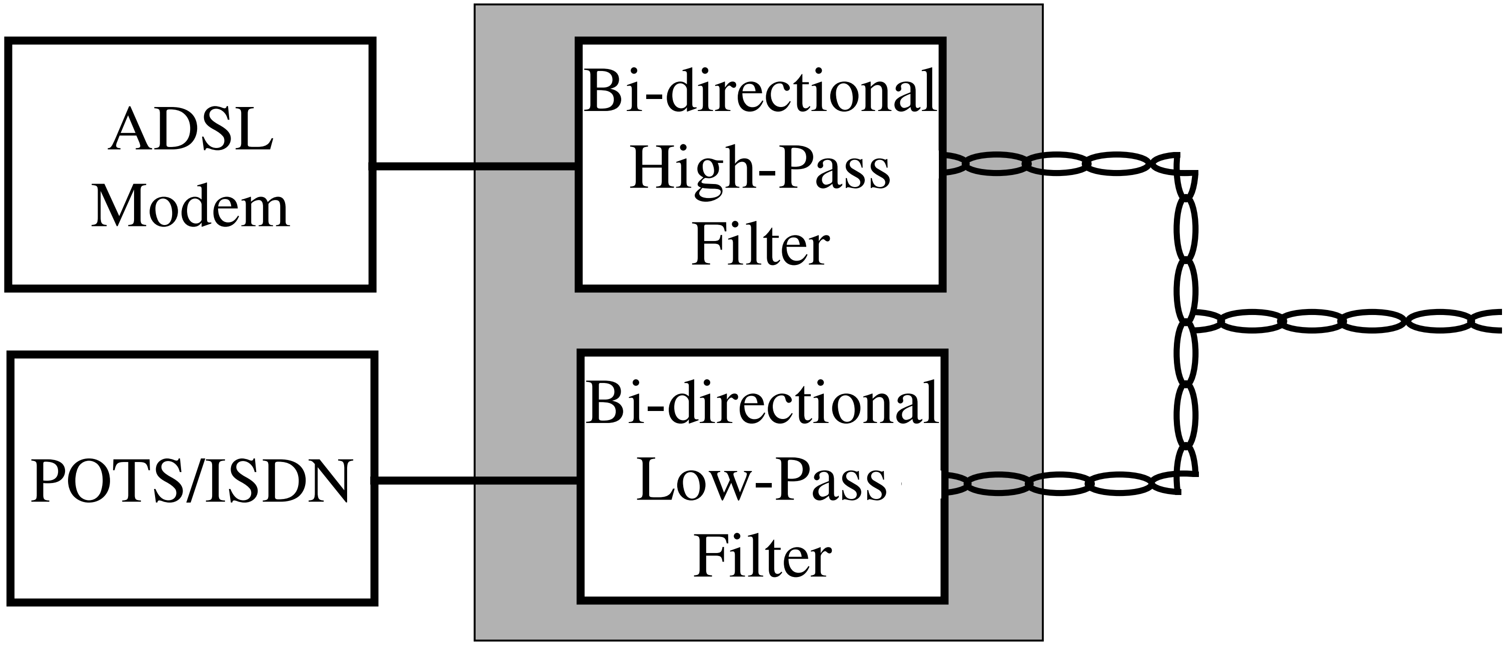
1-, 10- and 24-Self NEXT Example



Line Coupling Circuit

- Splitter
- Active termination
- Hybrid

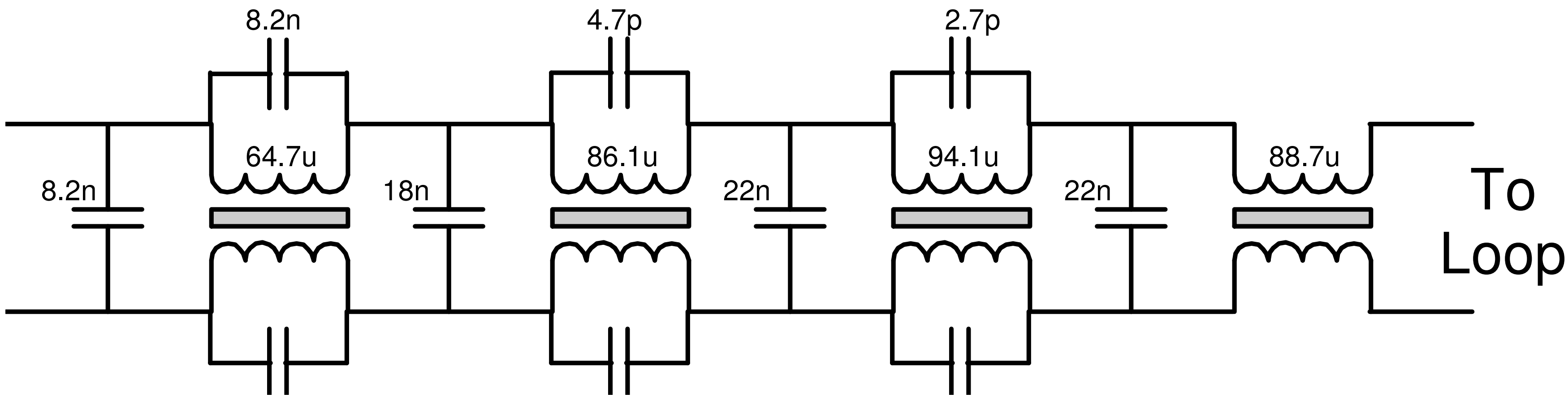
Splitter



- **In the POT/ISDN frequency band, the high-pass, generally built into modem transformer circuit, presents high impedance to loop and reduces ADSL modem-generated noise.**

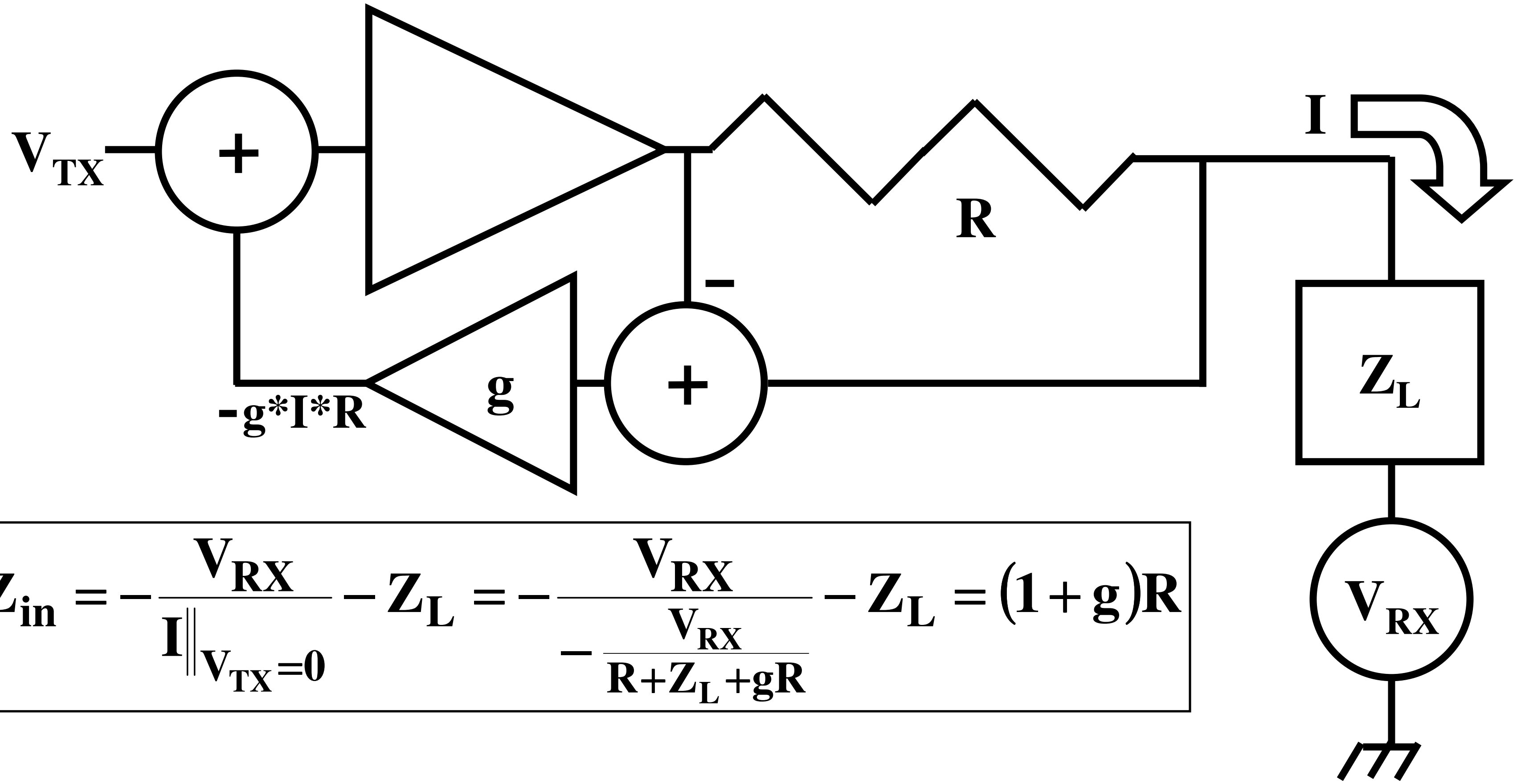
- **In the ADSL frequency band, the low-pass presents high impedance to loop and reduces POTS/ISDN-generated noise.**

Annex B Splitter Low-Pass Example



- **Very high quality (low distortion) components are required**
- **DC current feed (POTS) may not saturate transformers**
- **Cost is high, both the bill of materials and the PCB area**

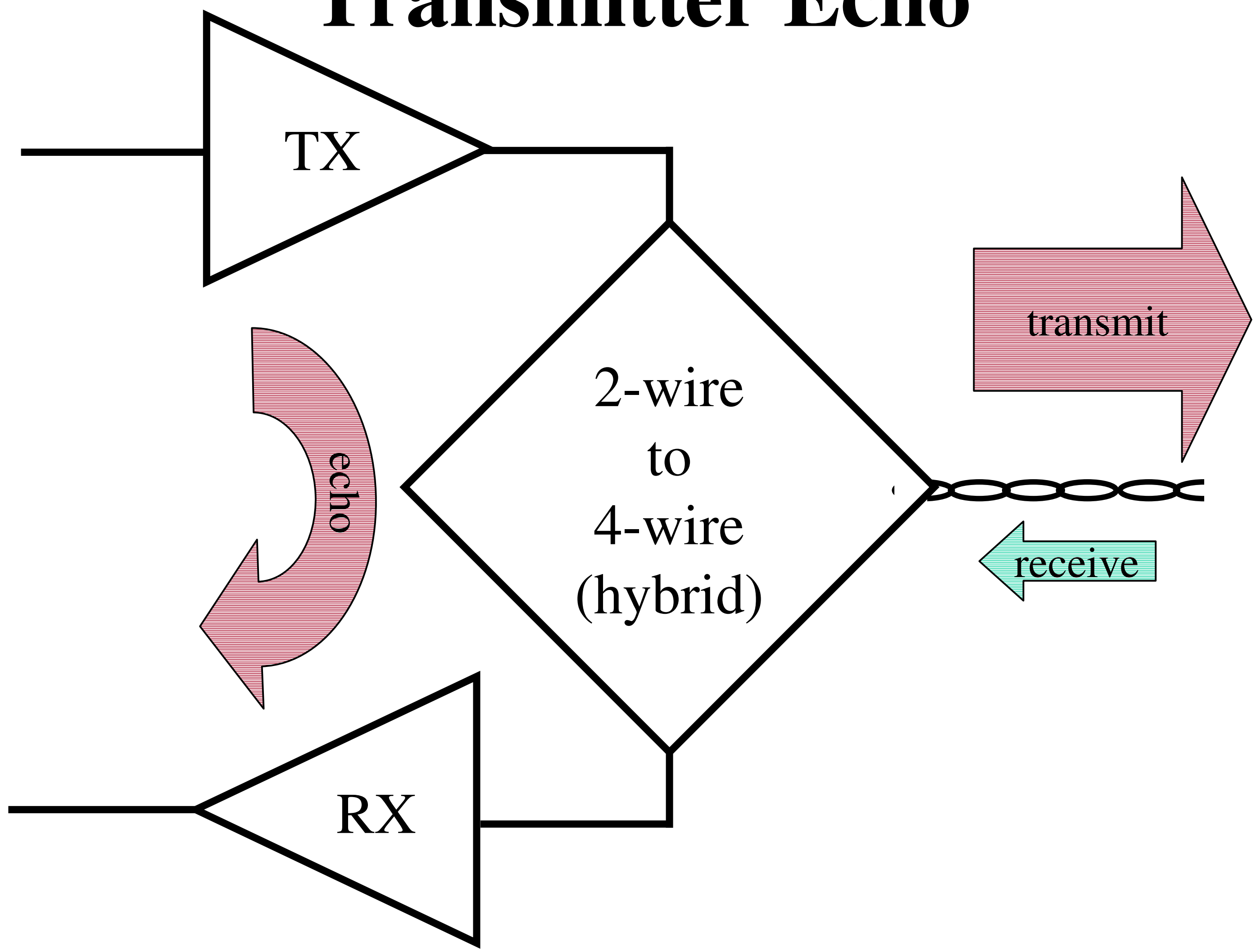
Active Termination



$$Z_{in} = -\frac{V_{RX}}{I\|_{V_{TX}=0}} - Z_L = -\frac{V_{RX}}{-\frac{V_{RX}}{R+Z_L+gR}} - Z_L = (1+g)R$$

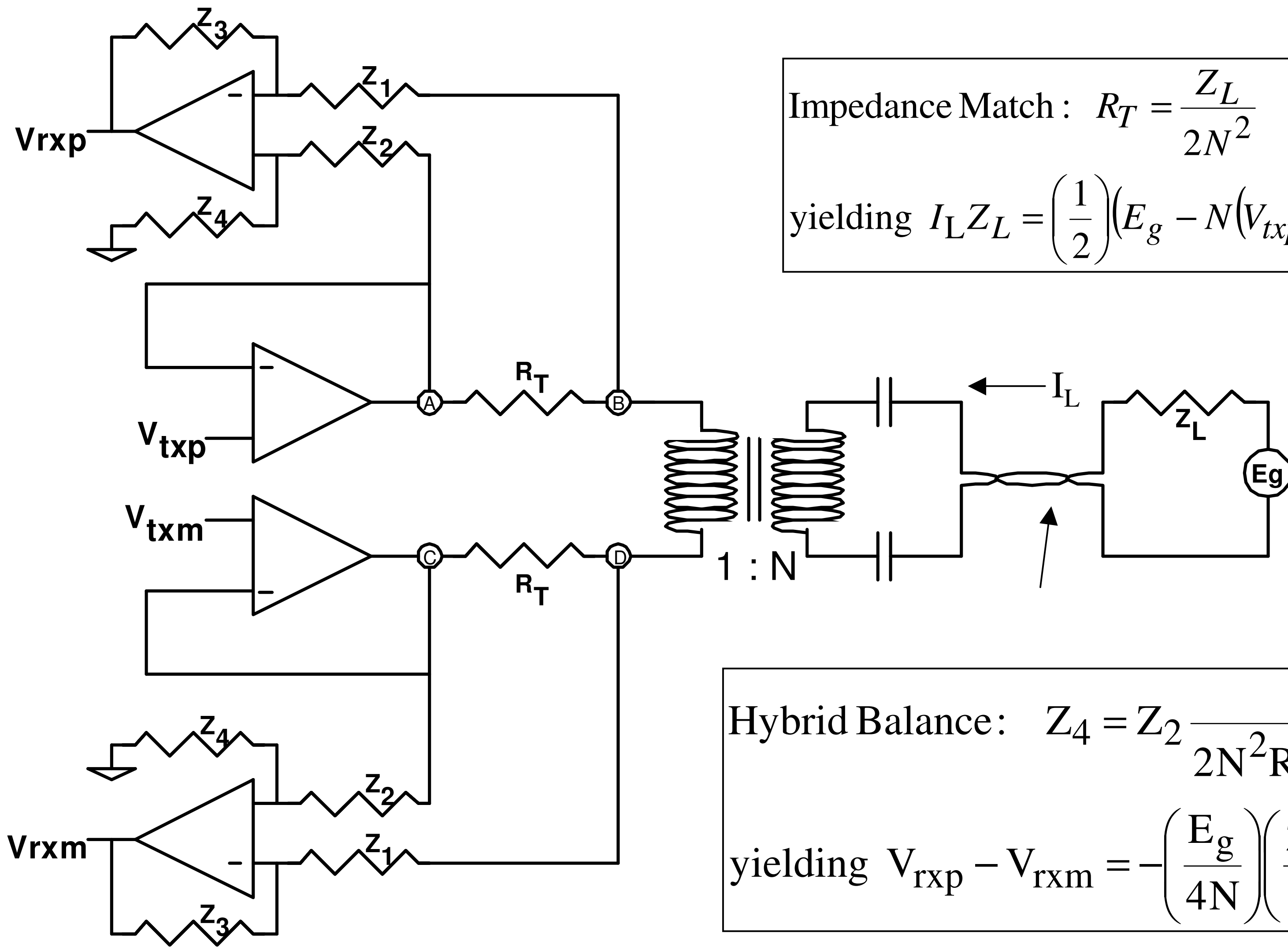
- Reduces driver power supply voltage requirement
- Downside: Reduces receiver gain by 20Log10[(1+g)]

Transmitter Echo



On long loops, the echo power is greater than the receive power

2nd Order High-Pass with Passive Termination and Hybrid



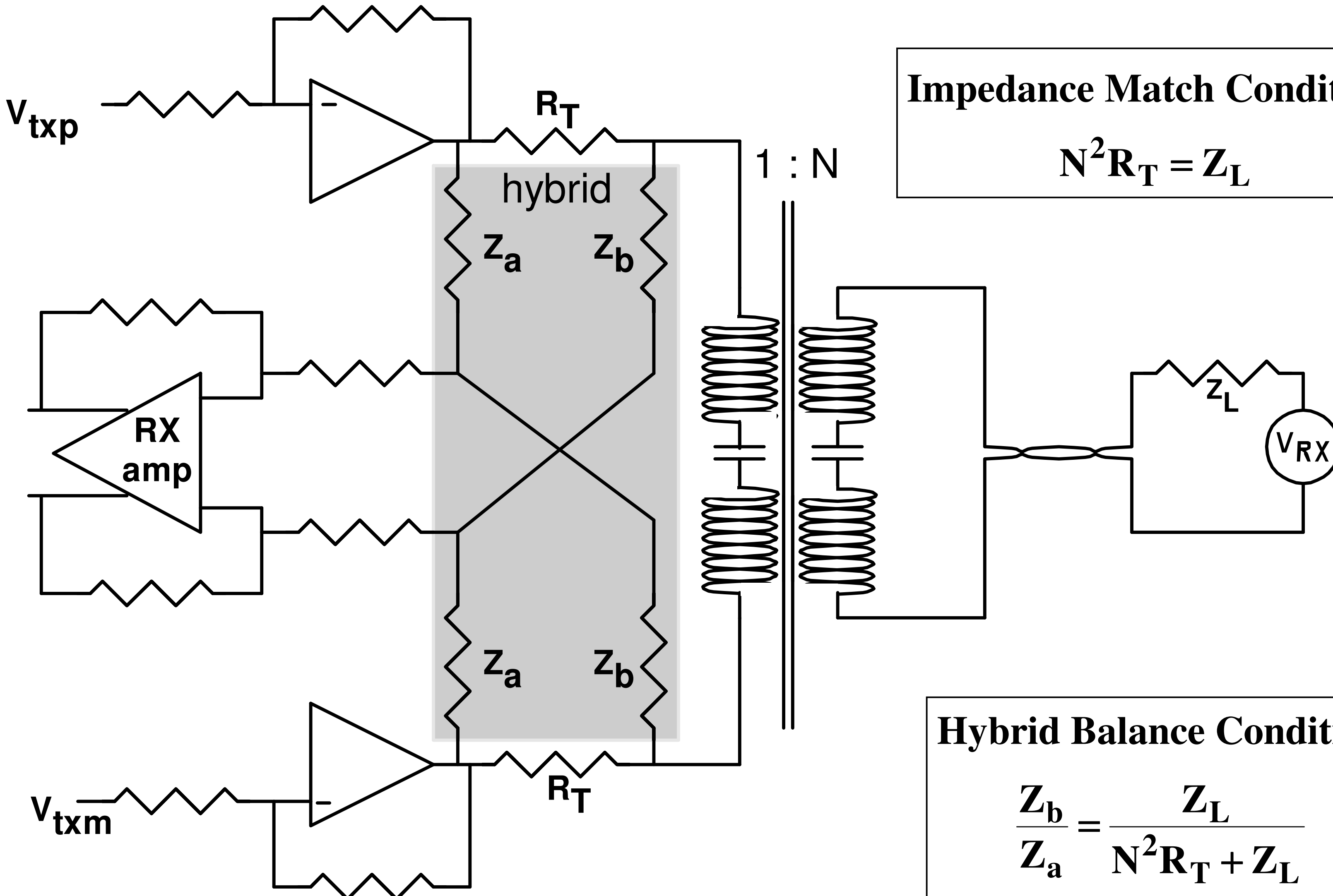
Impedance Match: $R_T = \dfrac{Z_L}{2N^2}$

yielding $I_L Z_L = \left(\dfrac{1}{2}\right)\left(E_g - N\left(V_{txp} - V_{txm}\right)\right)$

Hybrid Balance: $Z_4 = Z_2 \dfrac{Z_3 Z_L}{2N^2 R_T (Z_1 + Z_3) + Z_L}$

yielding $V_{rxp} - V_{rxm} = -\left(\dfrac{E_g}{4N}\right)\left(\dfrac{Z_3}{Z_1}\right)$

3rd Order High-Pass With Passive Termination and Hybrid



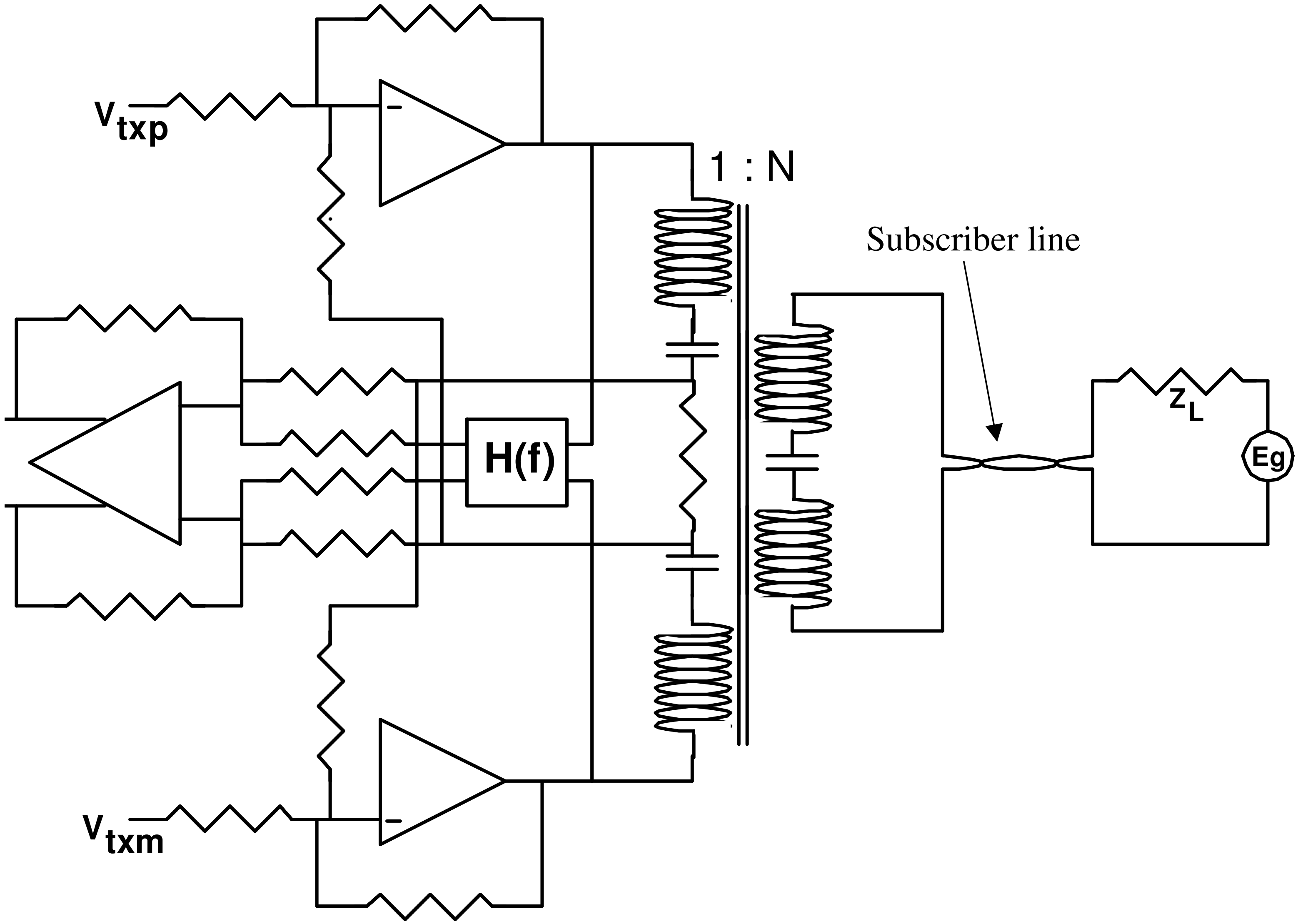
Impedance Match Condition

$$N^2 R_T = Z_L$$

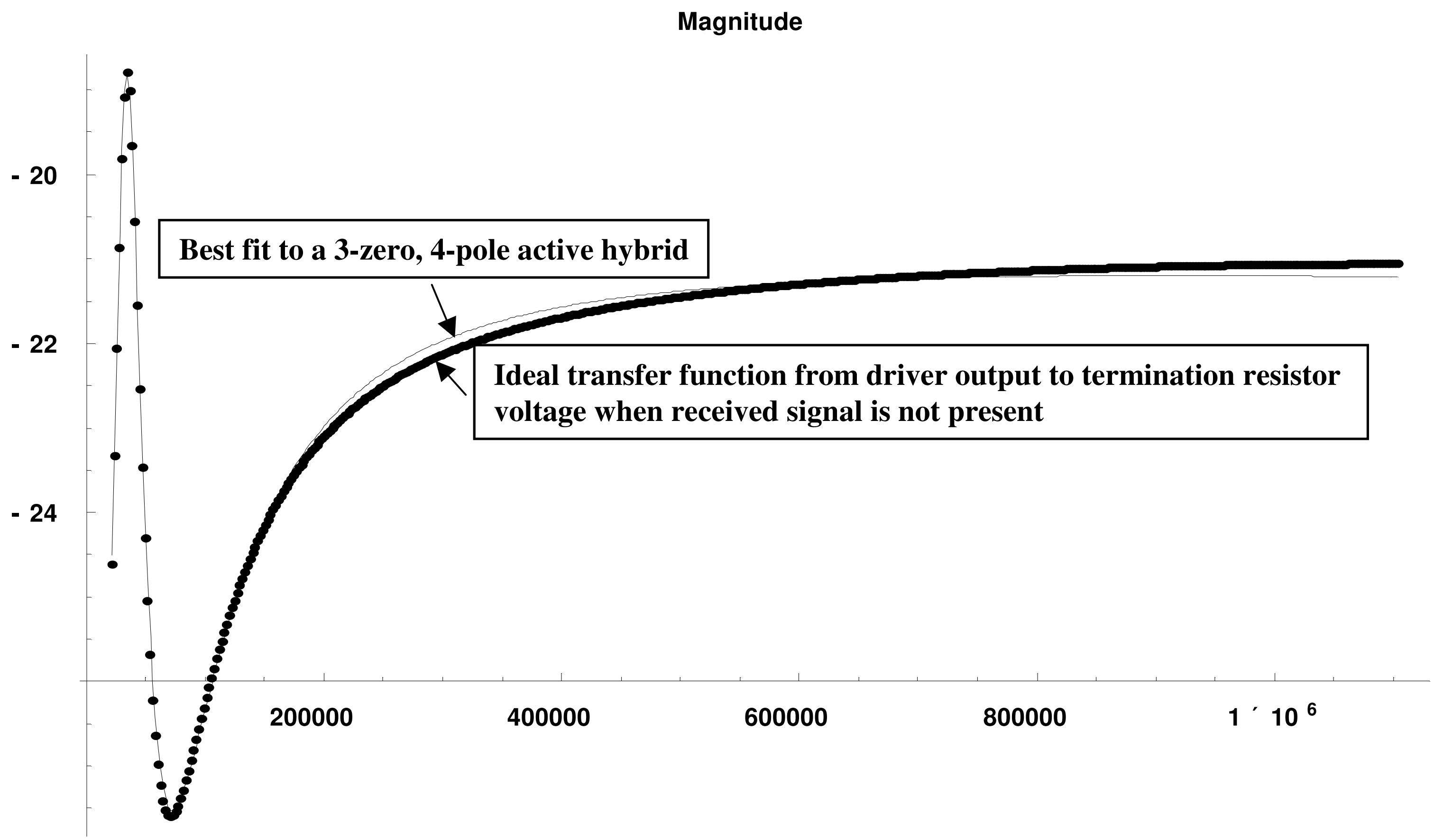
Hybrid Balance Condition

$$\frac{Z_b}{Z_a} = \frac{Z_L}{N^2 R_T + Z_L}$$

3rd Order High-Pass With Active Termination and Hybrid



Active Hybrid Transfer Function



Hybrid Rejection Definitions

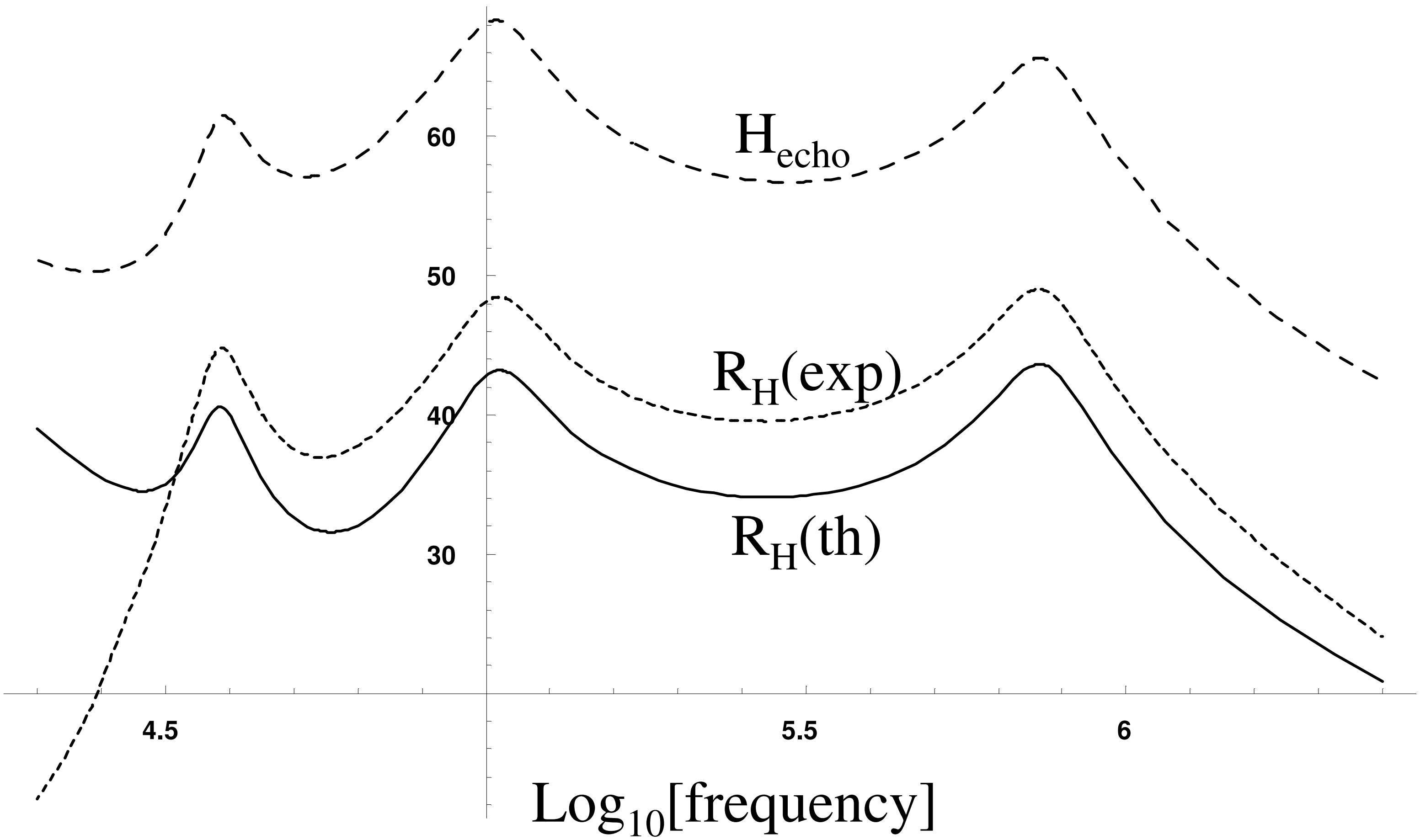
$$R_H(\text{exp}) = 20\text{Log}_{10}\left[\frac{\dfrac{\text{transmitter signal at tip/ring}}{\text{transmitter signal at receiver amplifer output}}}{\text{received signal gain from tip/ring to receiver amplifier output}}\right]$$

$$R_H(\text{th}) = 20\text{Log}_{10}\left[\frac{\text{transmitter signal at tip/ring when hybrid is removed}}{\text{transmitter signal at tip/ring when hybrid is present}}\right]$$

Echo Response

$$H_{Echo} = 20\text{Log}_{10}\left[\frac{\text{transmitter signal at driver output}}{\text{transmitter signal at receiver amplifier}}\right]$$

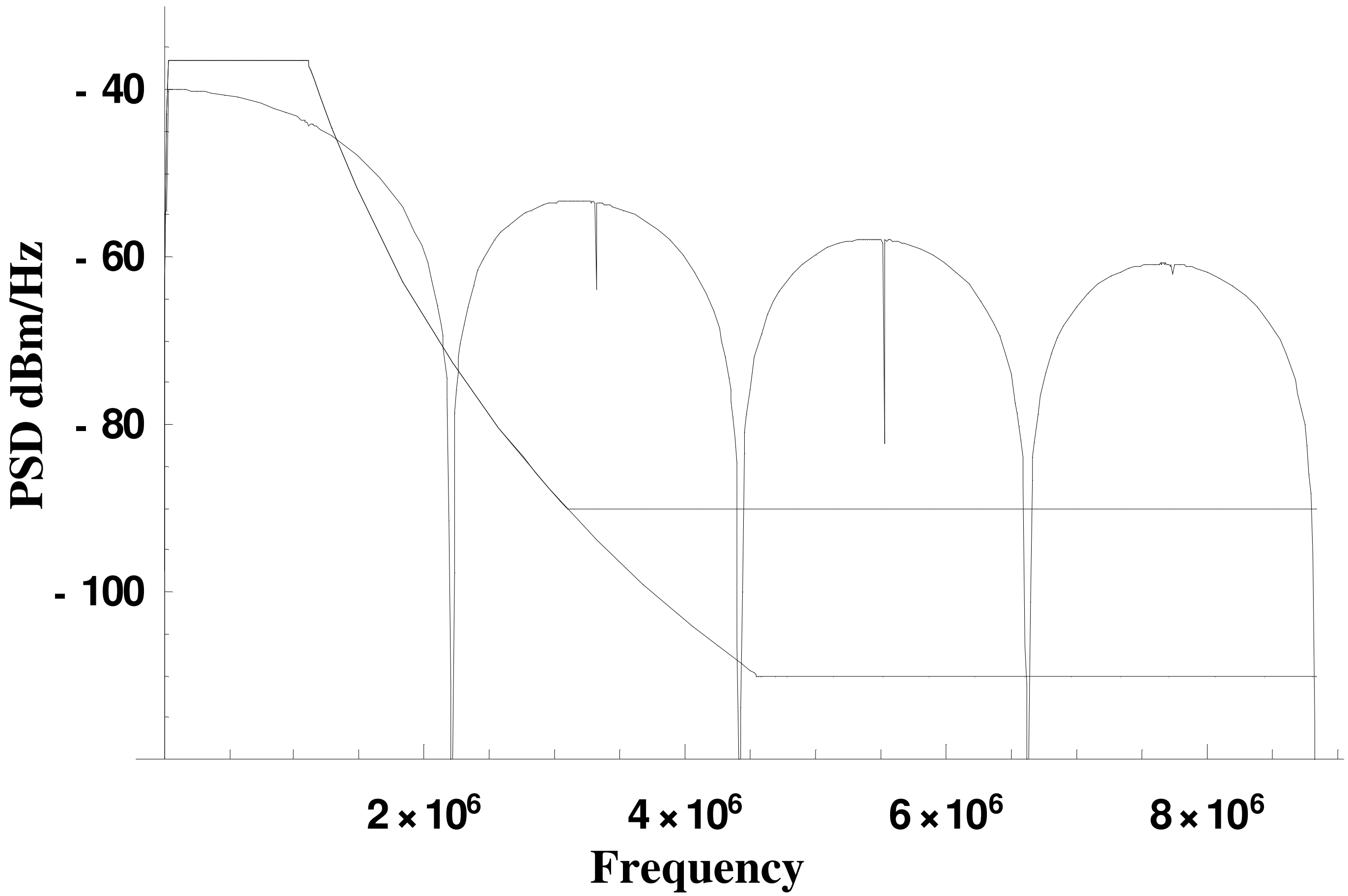
Hybrid Rejection Example



Transmitter Signal Path

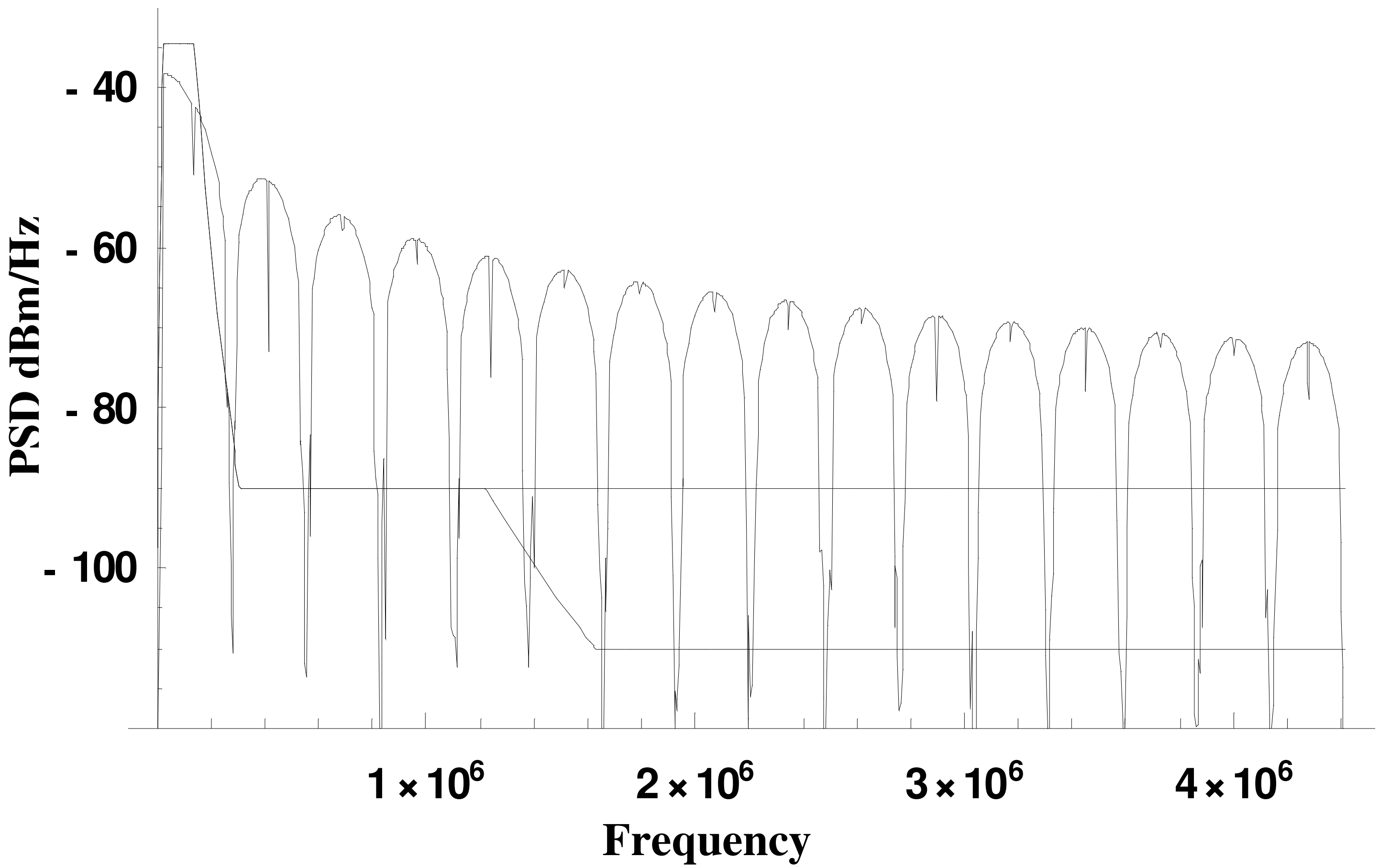
- Over-sampling
- Managing PAR
- MTPR requirement
- Line Drivers

Downstream PSD With Minimum Sample Rate



• Conversion of downstream signal to continuous-time at 2208kS/sec produces in-band droop and significant standard's non-compliance.

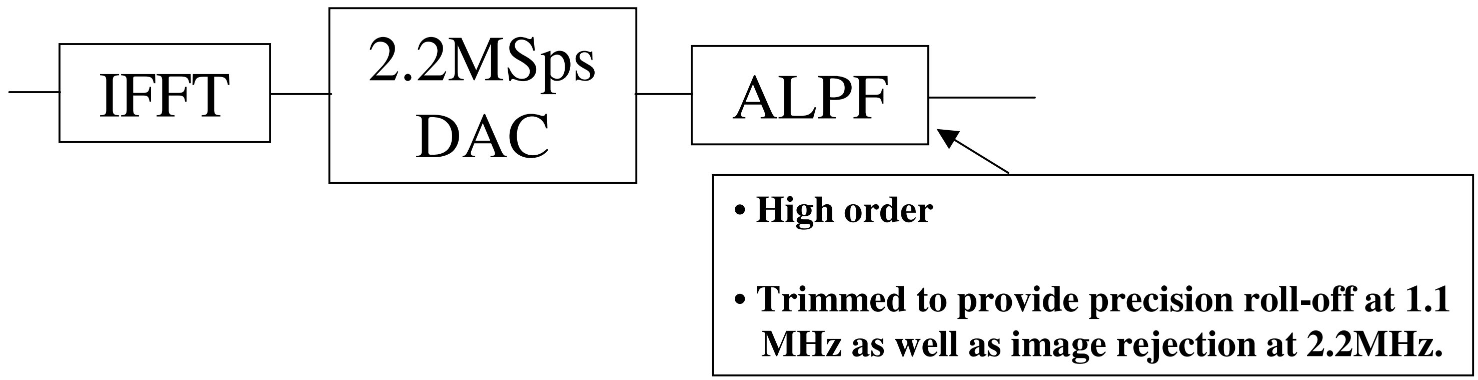
Upstream PSD With Minimum Sample Rate (276kS/sec)



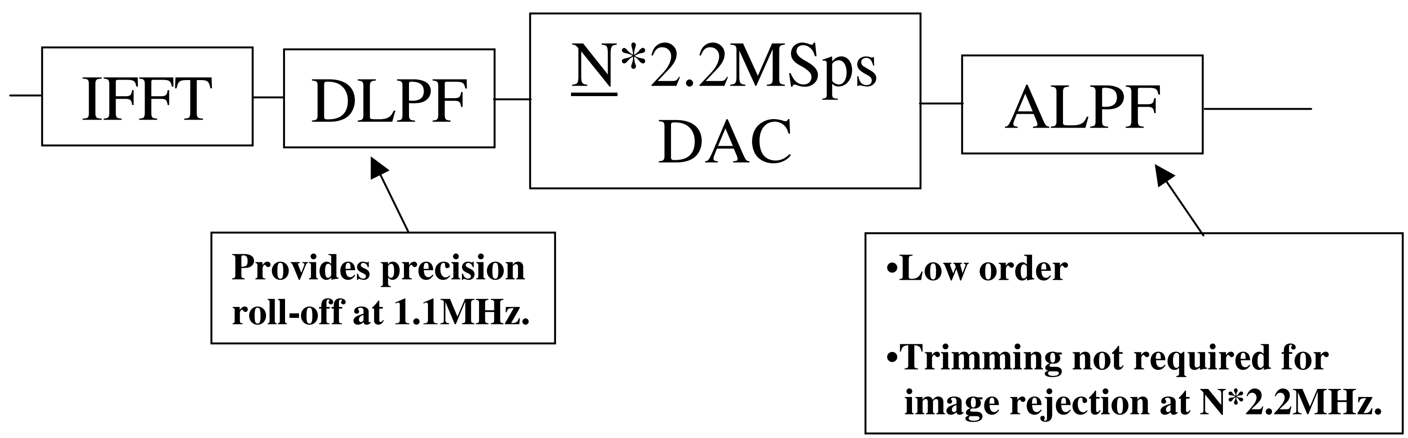
- Conversion of upstream signal to continuous-time at 276kS/sec produces in-band droop and significant standard’s non-compliance.

Low-Pass Reconstruction Filter Architectures

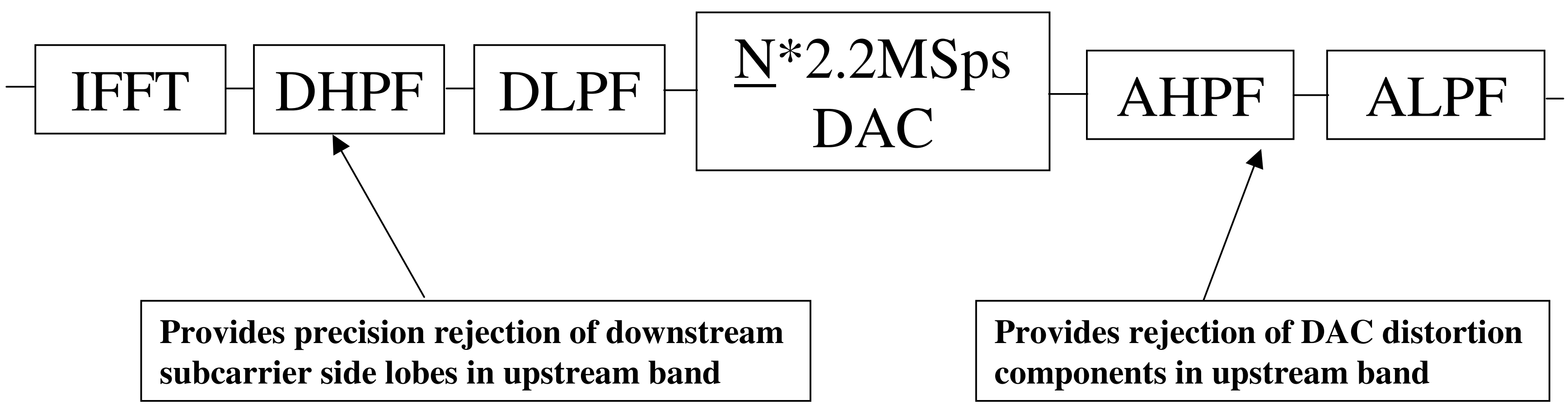
(A) Nyquist rate DAC (Analog filter)



(B) Over-sampled DAC (Digital/Analog filter combination)

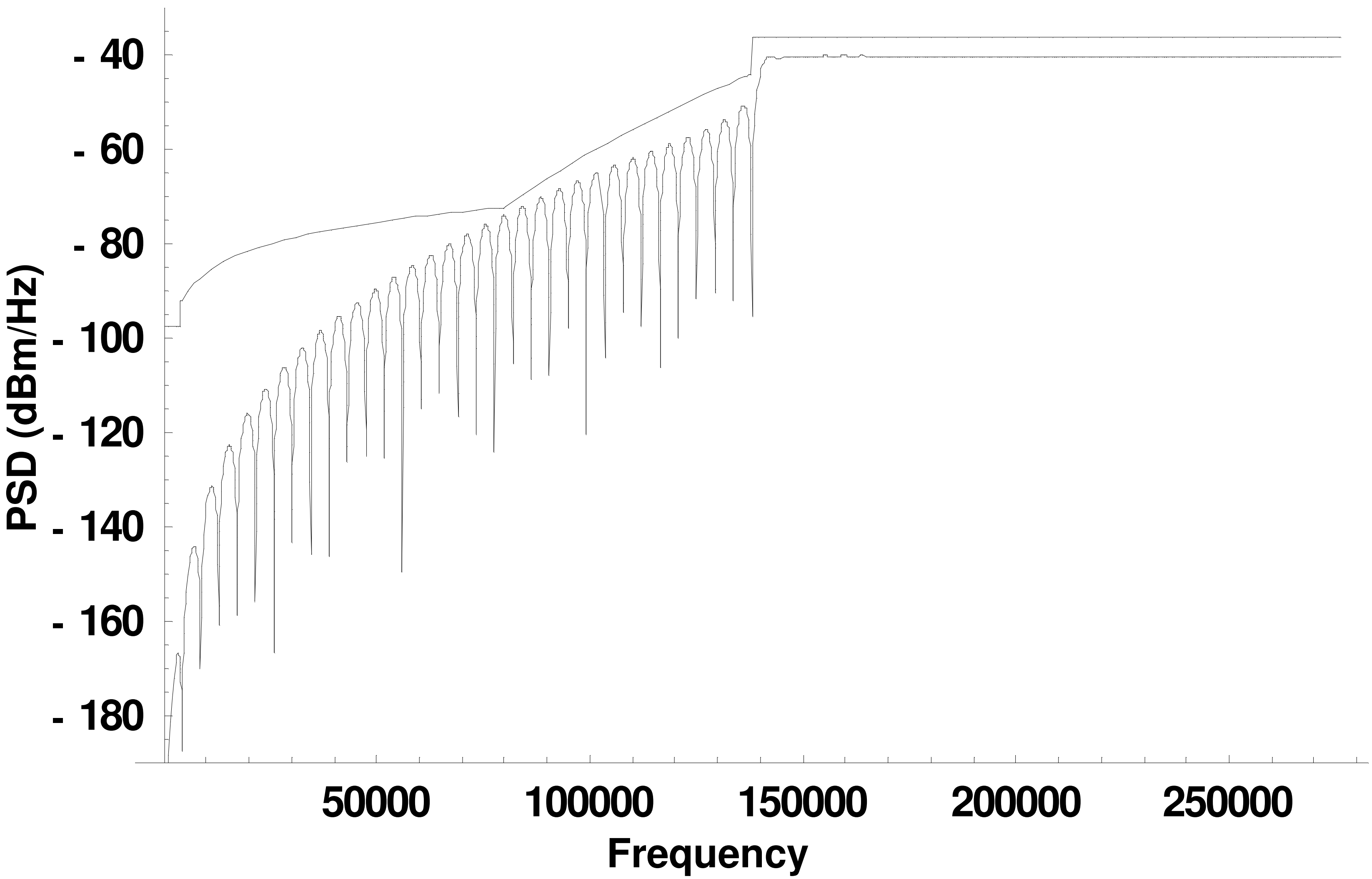


Helping Out the Central Office Hybrid

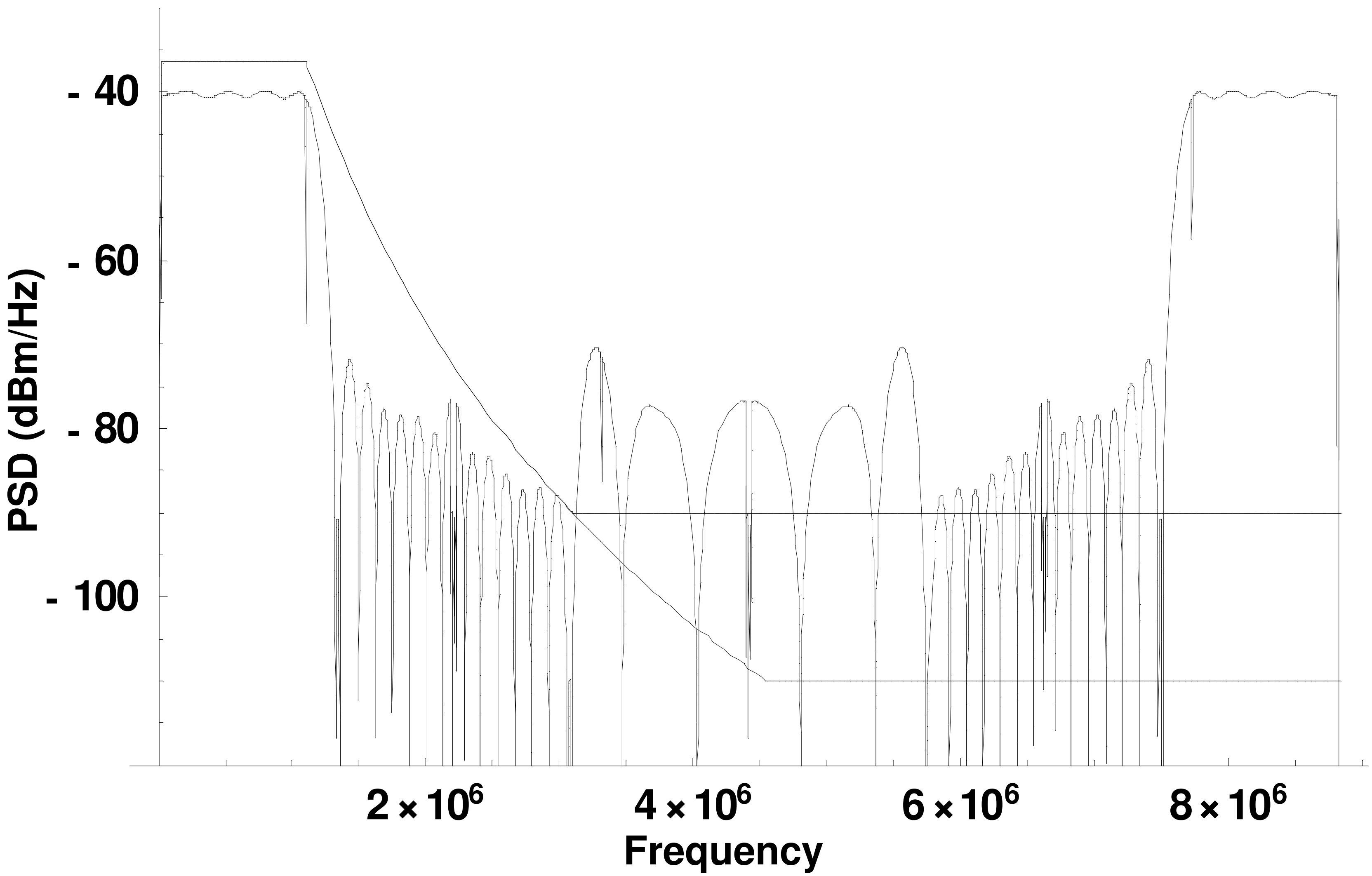


Digital High-Pass Output Spectrum

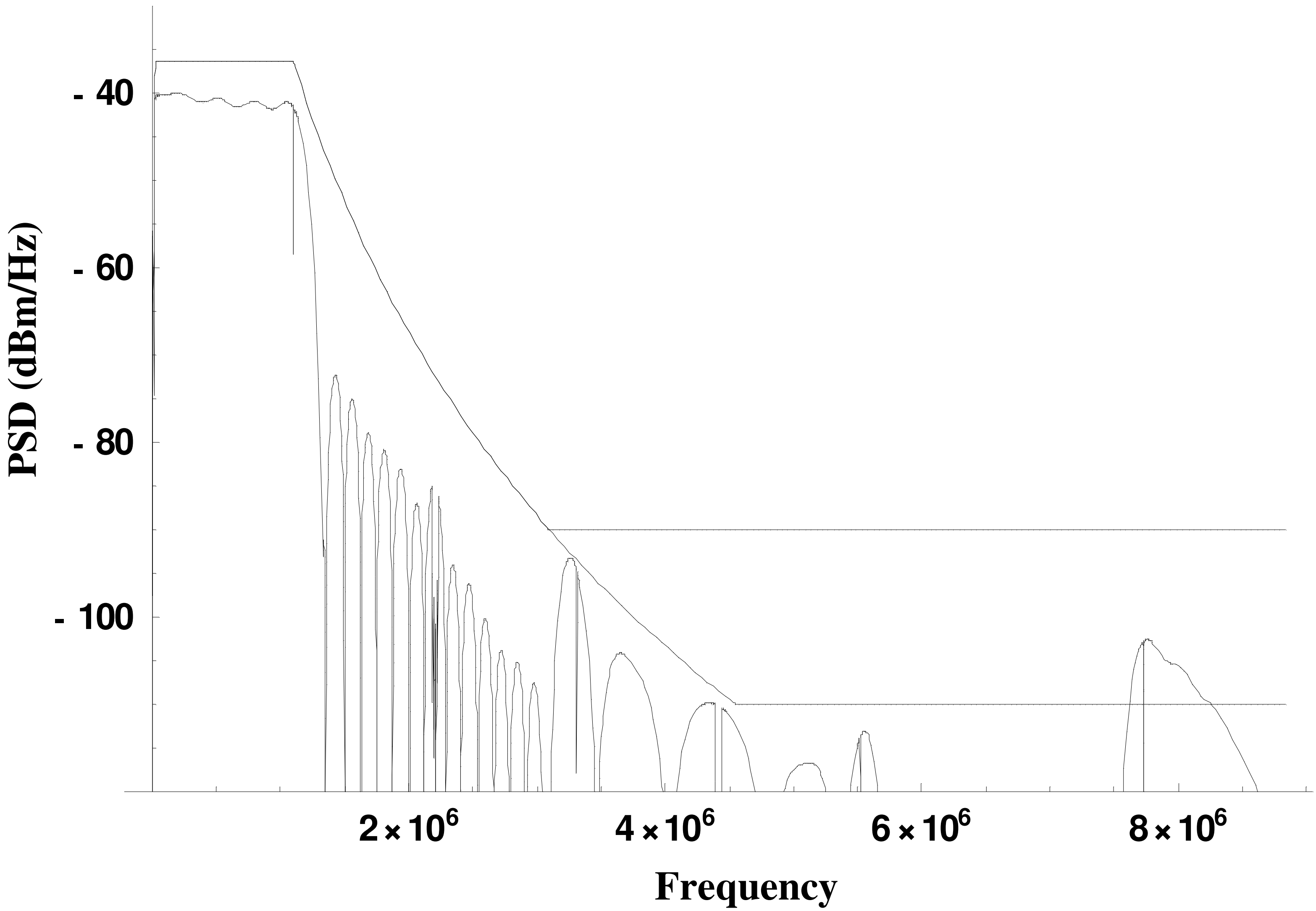
(downstream bin 32-255 employed)



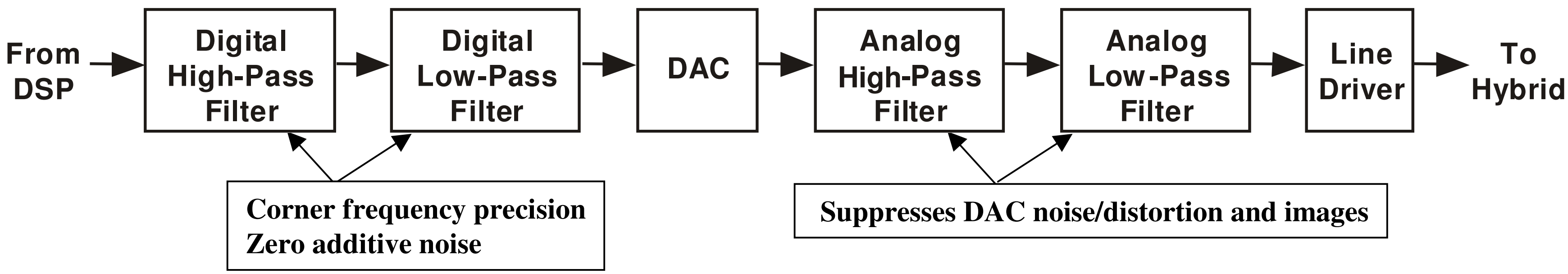
Digital Low-Pass Filter Output Spectrum



Analog Low-Pass Filter Output Spectrum



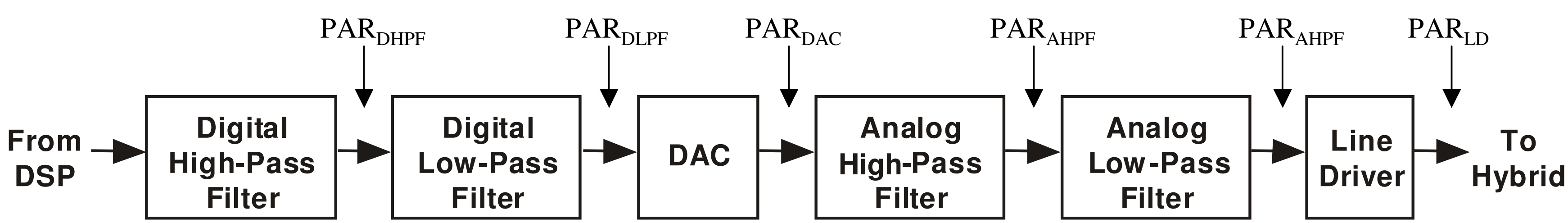
Transmitter Template



- **DHPF**
  - **High order DHPF is critical to downstream transmitter signal suppression in FDD modems**
  - **Reduced-NEXT compliance in echo-canceling modems employing non-overlapping spectra**
- **DLPF**
  - **High order is critical to upstream transmitter signal suppression in FDD modems**
  - **Interpolating stages increase sample rate, reducing signal droop and relaxing analog low-pass**
- **DAC**
  - **Precision (<12 effective bits) depends upon analog filtering, hybrid rejection and receiver sensitivity**
- **AHPF**
  - **Suppresses DAC noise/distortion in upstream band in FDD central office modems.**
- **ALPF**
  - **Eliminates signal images centered at multiples of DAC sample rate.**
  - **Suppresses DAC noise/distortion in downstream band in FDD client modems.**
- **Line Driver**
  - **High voltage technology.**
  - **Very low distortion required.**

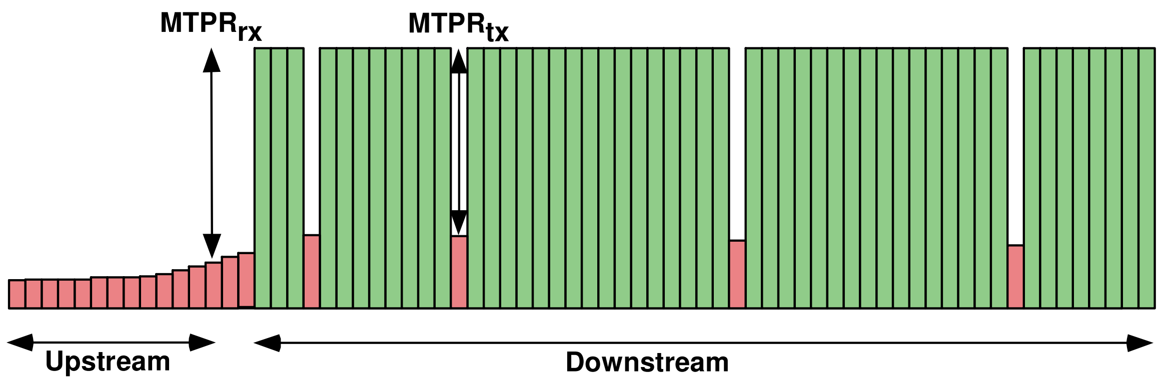
Managing Peak Signal to Average Signal Ratio

- **Bit Error Rate is proportional to the frequency of signal clipping**
- **Clipping rate of gaussian signal is determined by PAR**
- **PAR is determined by circuit NOT a property of signal**
- **Managing PAR in digital or analog domains – node by node**
  - **Usually desirable to limit the number of clipping nodes to one (driver)**
  - **For given signal swing (volts or bits), PAR is increased (decreased) by decreasing (increasing) signal power**
  - **For given signal power, PAR is increased (decreased) by increasing (decreasing) swing (volts or bits)**



Missing Tone Power Ratio Test

- **Equivalent of spurious free dynamic range in narrow band systems**



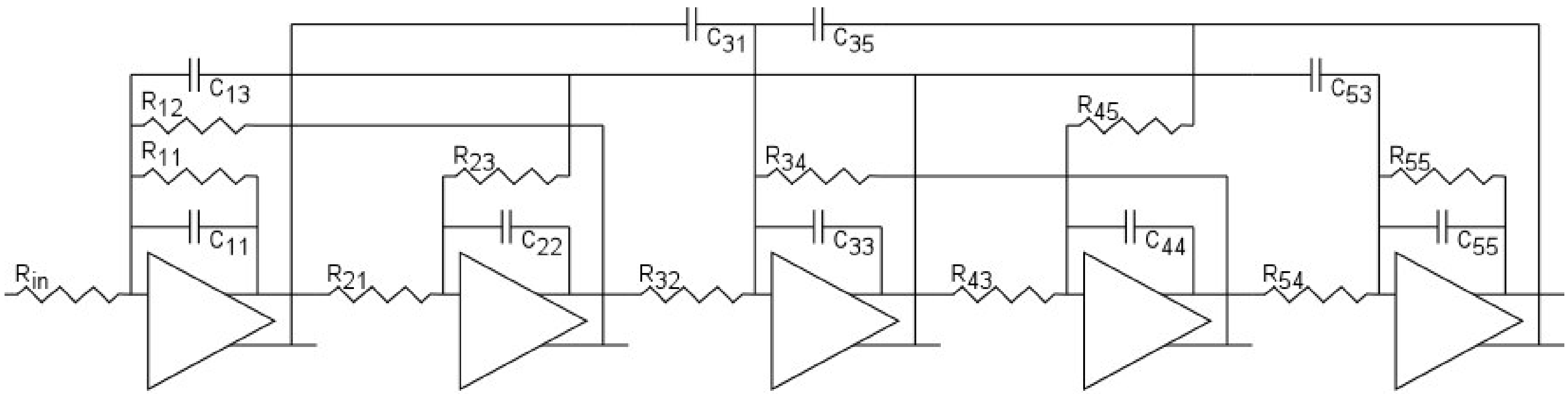
FDD (EC) Central Office Example (frequency-independent echo response)

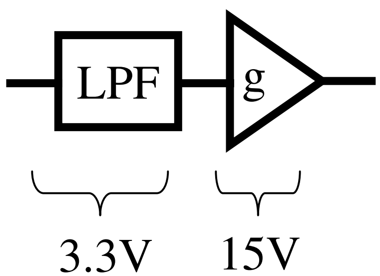
MTPRtx=65 (75)

MTPRrx=75 (75)

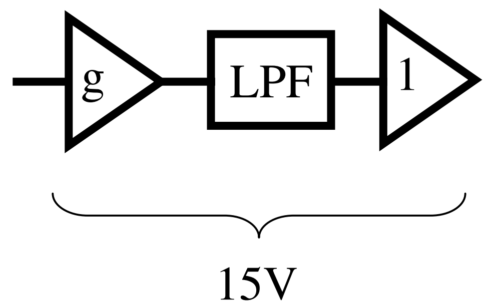
Virtue of High Voltage IC Processes

Client Reconstruction Low-Pass Filter Example
(138kHz corner frequency, -140dBm/Hz noise in downstream band)

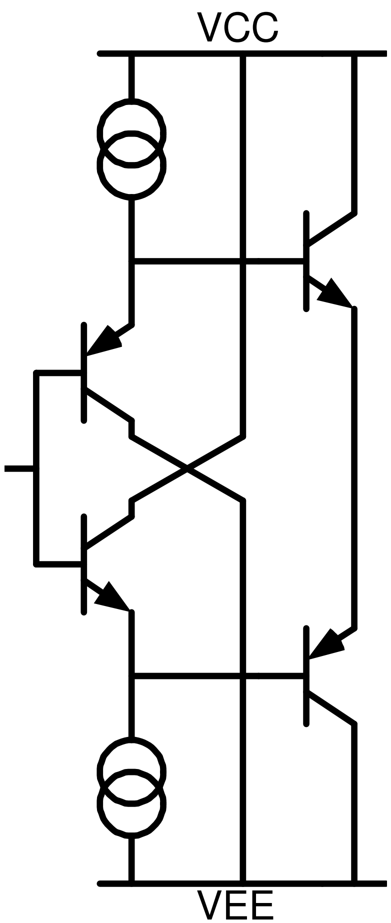


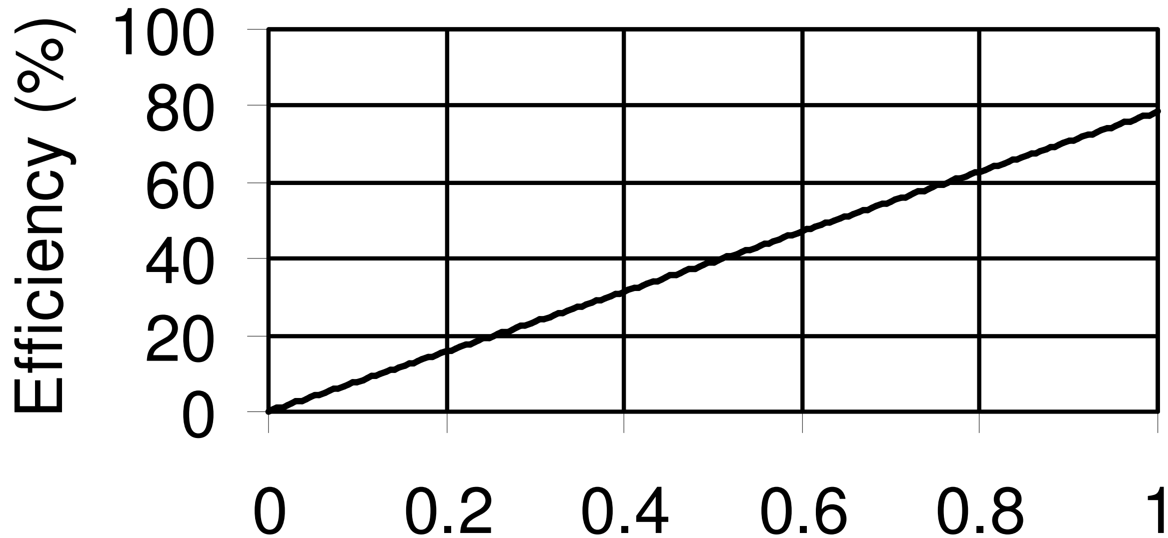


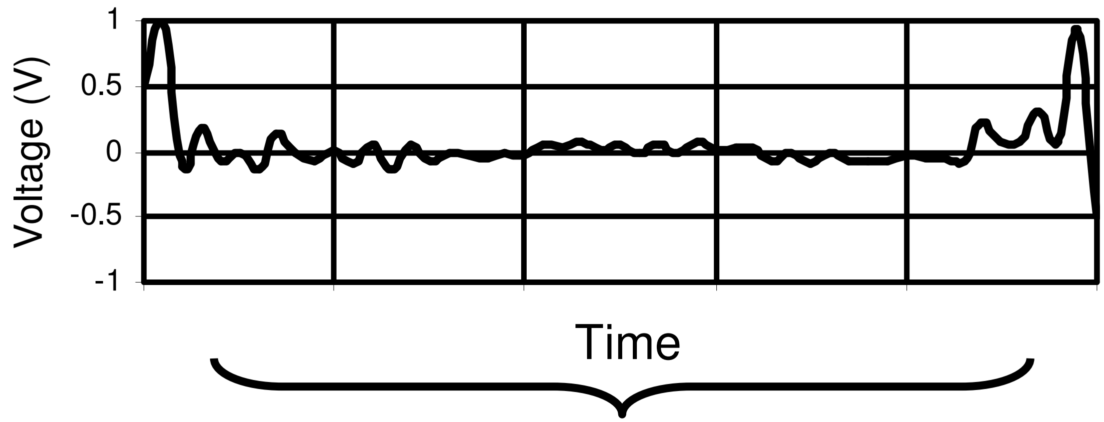
3.3V Process	15V Process
C_{11}= 89.6pF	C_{11}= 2.36pF
C_{13}= 428.pF	C_{13}= 11.3pF
C_{22}= 1157pF	C_{22}= 30.4pF
C_{33}= 3292pF	C_{33}= 86.6pF
C_{31}= 358.pF	C_{31}= 9.43pF
C_{35}= 1142pF	C_{35}= 30.0pF
C_{44}= 7122pF	C_{44}= 187.pF
C_{55}= 10351pF	C_{55}= 272.pF
C_{53}= 5710pF	C_{53}= 150.pF
total = 29.6nF	total = 779pF



Class AB Output Stage

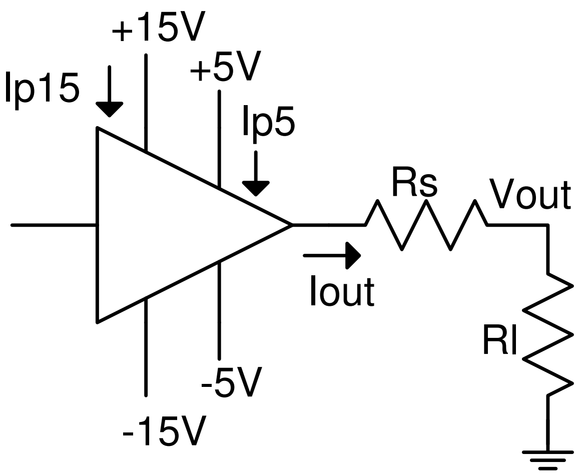






<20% efficiency

Class G Topology



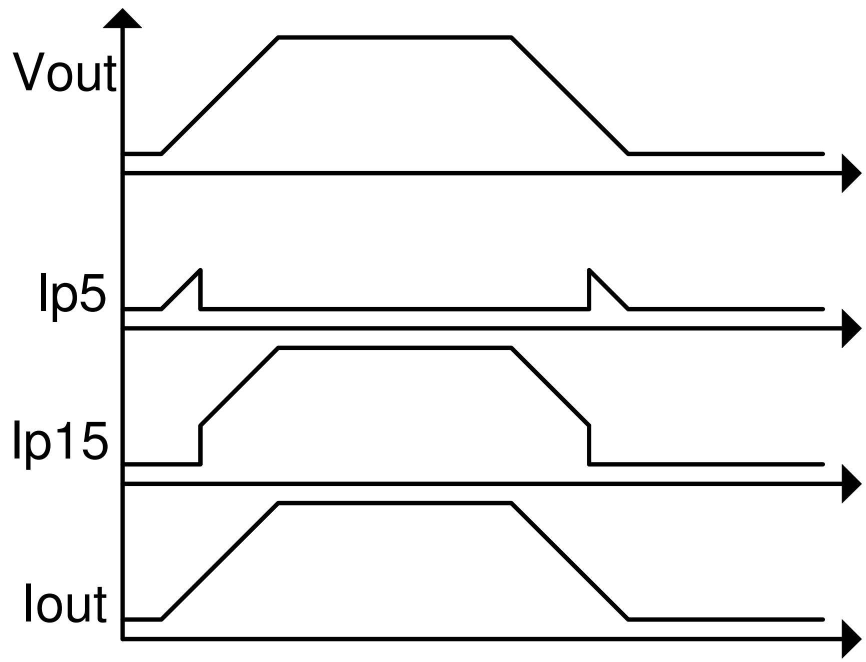
- **Multiple supply output stage**

- **For V_{OUT} low, current comes from +5 V**

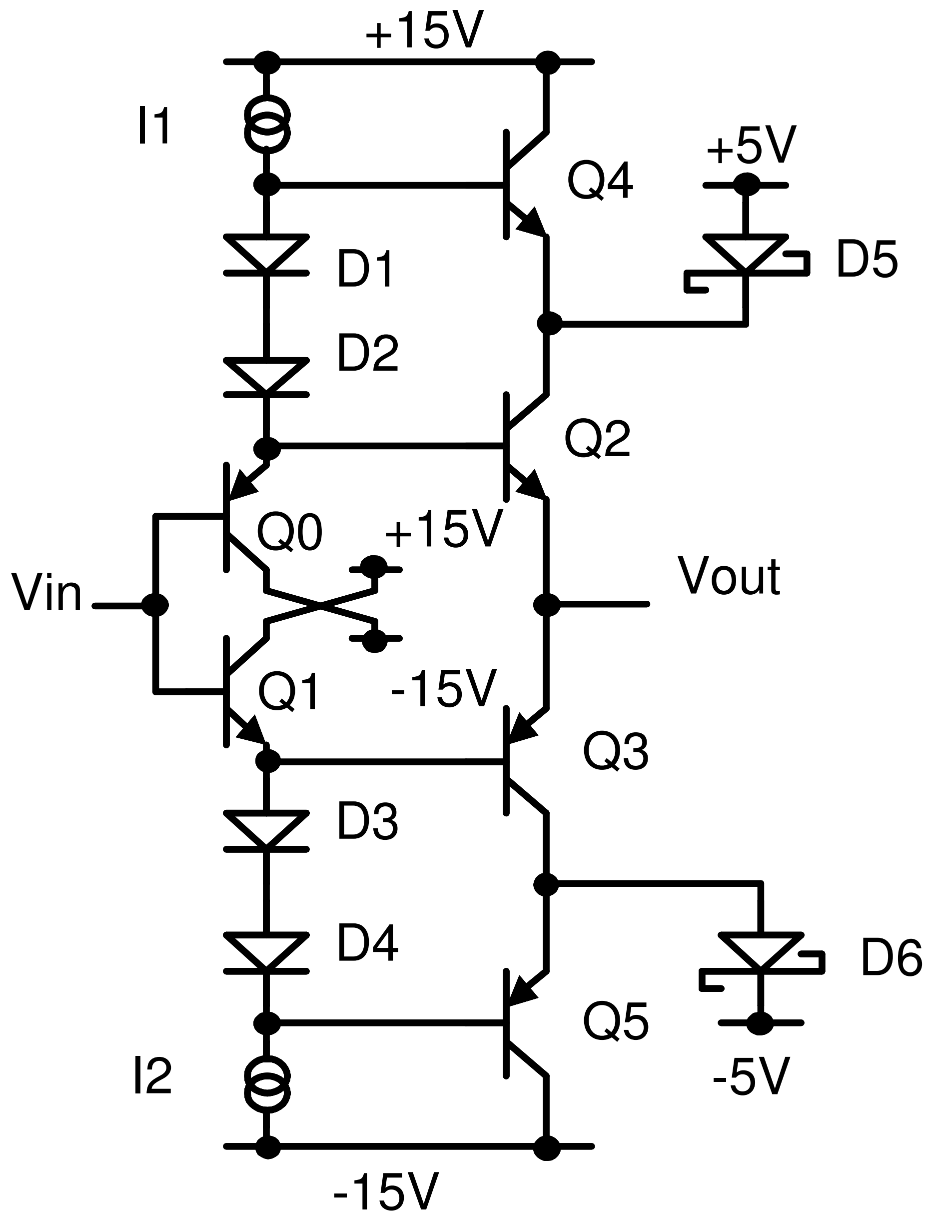
- **For V_{OUT} high, current comes from +15 V**

- **Current is mostly drawn from low supply**

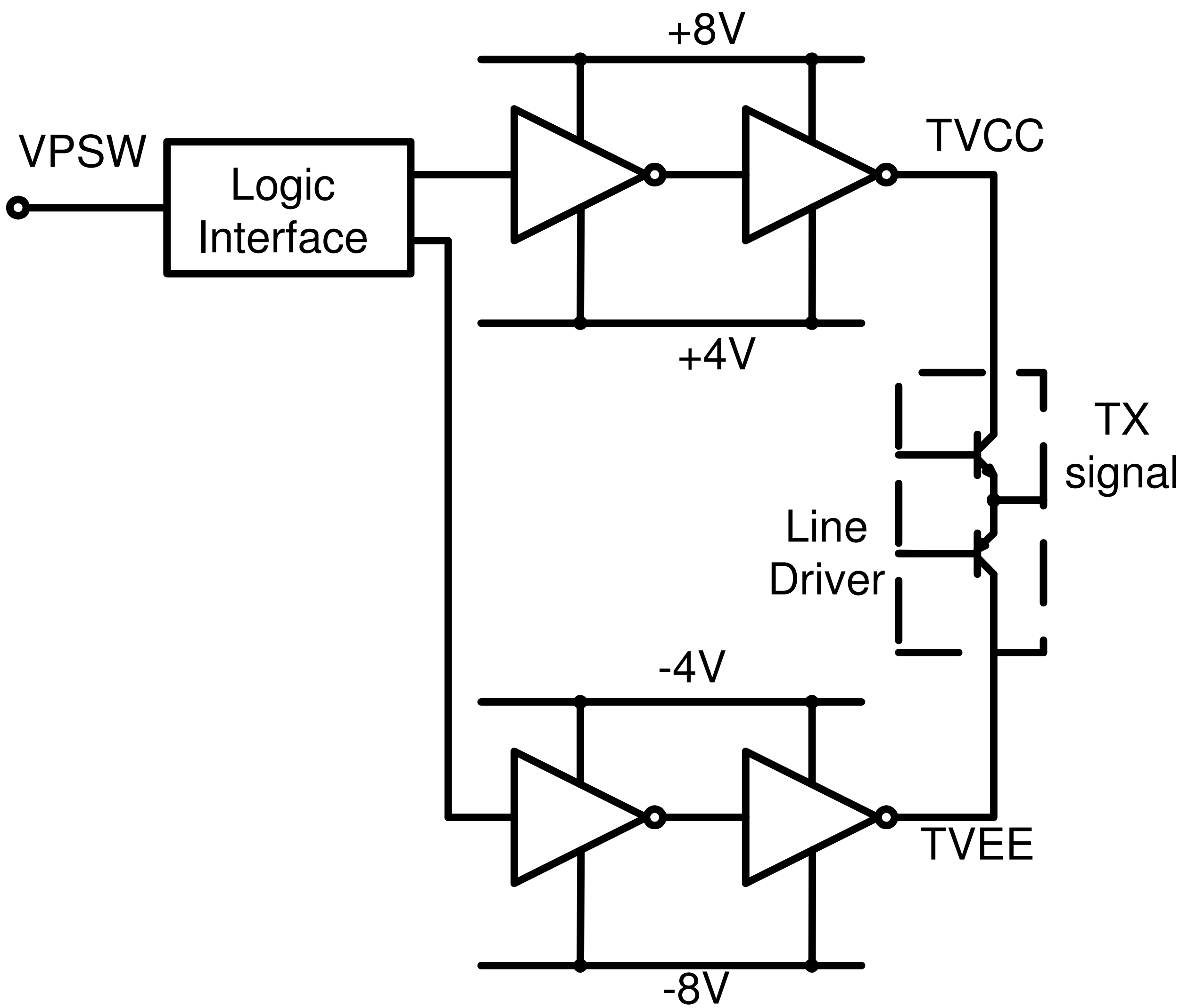
- **Challenge in DSL is low distortion at 1 MHz**



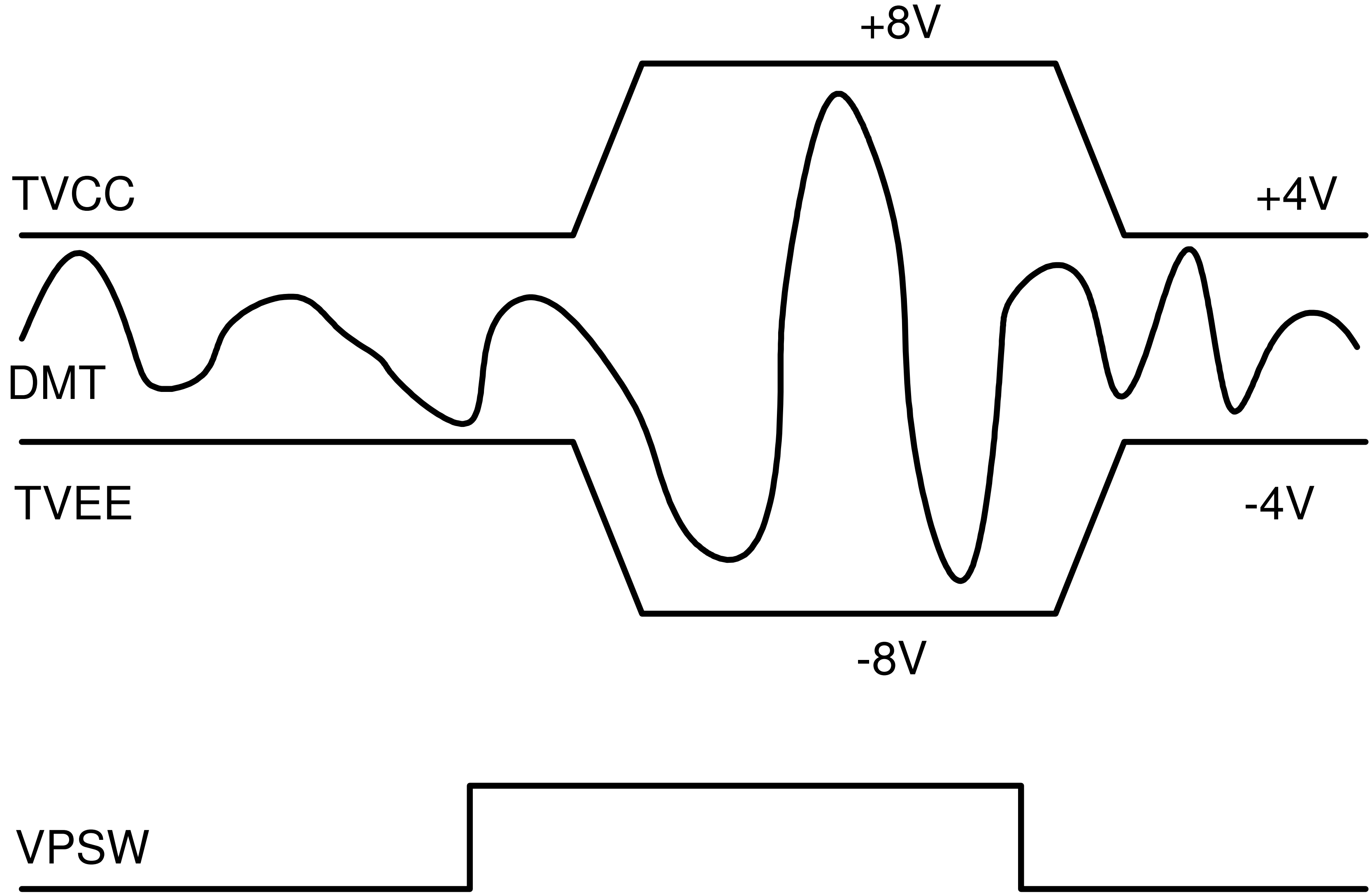
Continuous Class G Circuit



"Zero Overhead" Class G Concept – Block Diagram



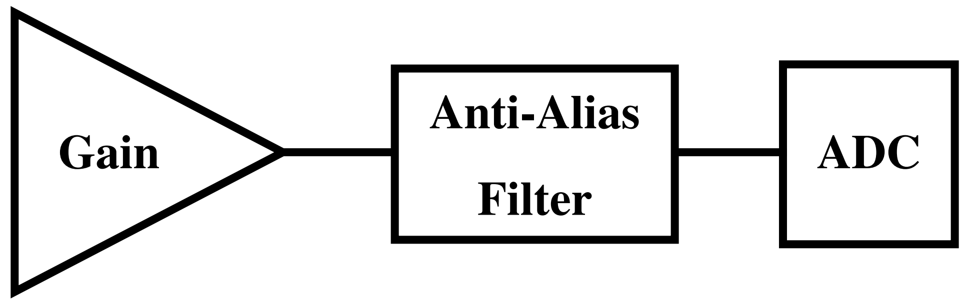
"Zero Overhead" Class G Concept - Waveforms



ZOCG Design Challenges

- Peak prediction
  - Analog signal blocks change peak positions and magnitudes
- Low voltage drop switches
  - Mus swing as close as possible to the rail
- Shoot through currents
  - Must minimize the time that switches to both supplies are on
- Switching edge coupling
  - Changing supply AC can couple into signal output

Receiver Signal Path



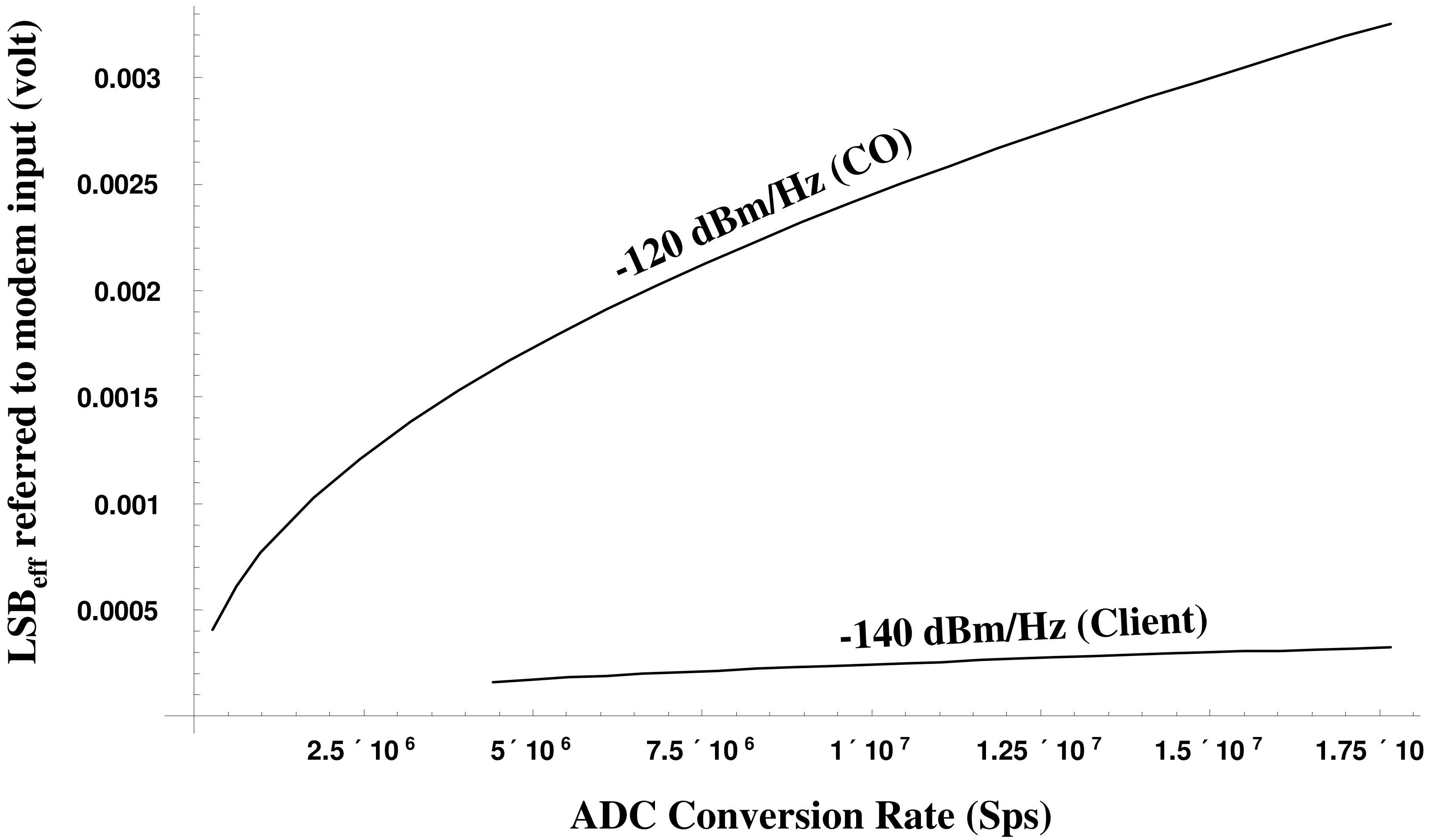
- Signals
- Minimizing ADC requirements
- ADC precision
- PAR management

Receiver Noise/Distortion Floor

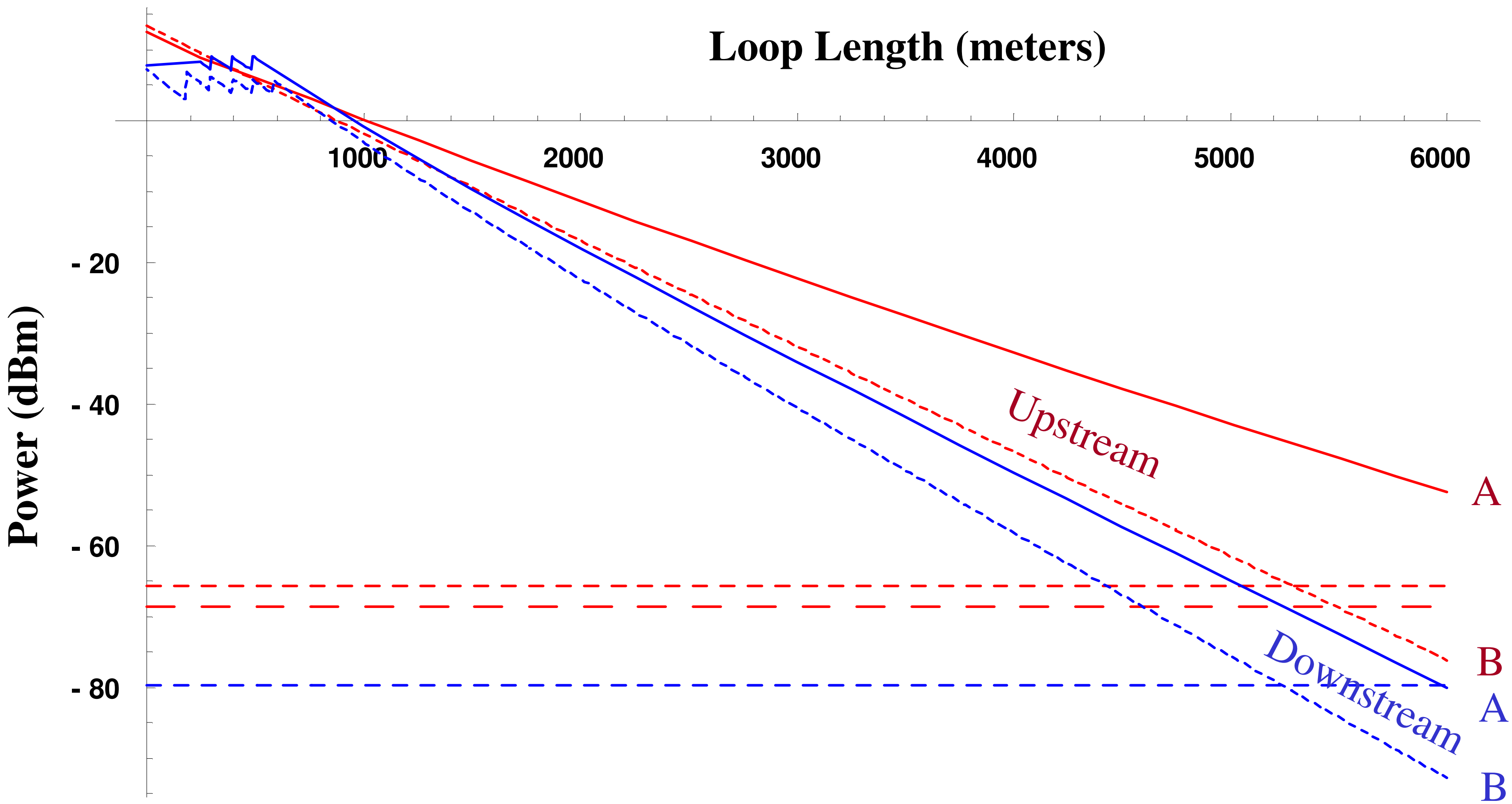
- **Inherent loop noise**
  - **Loop impedance is ~100 ohms, corresponding to <-173 dBm/Hz**
  - **Measured loop noise is usually in the neighborhood of –140 dBm/Hz**
  - **Central off ice noise is much higher**
    - **ISDN, T1, SHDSL, ….**

- **Typical noise floor targets for ADSL front ends**
  - **Central office: <-120 dBm/Hz at loop**
  - **Client: <-145 dBm/Hz at loop**

ADC Resolution Versus Conversion Rate

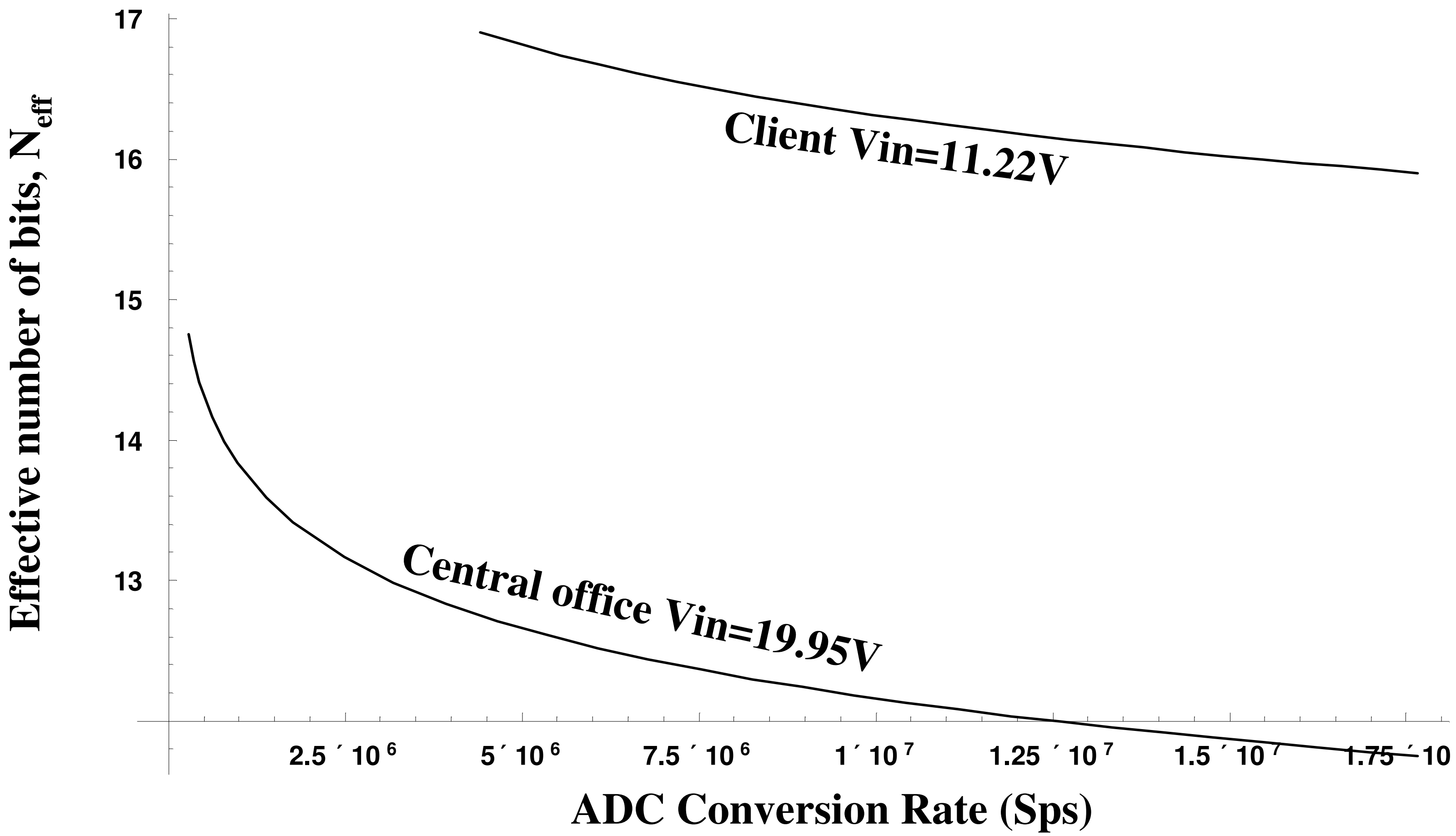


Signal Power Reaching Receiver



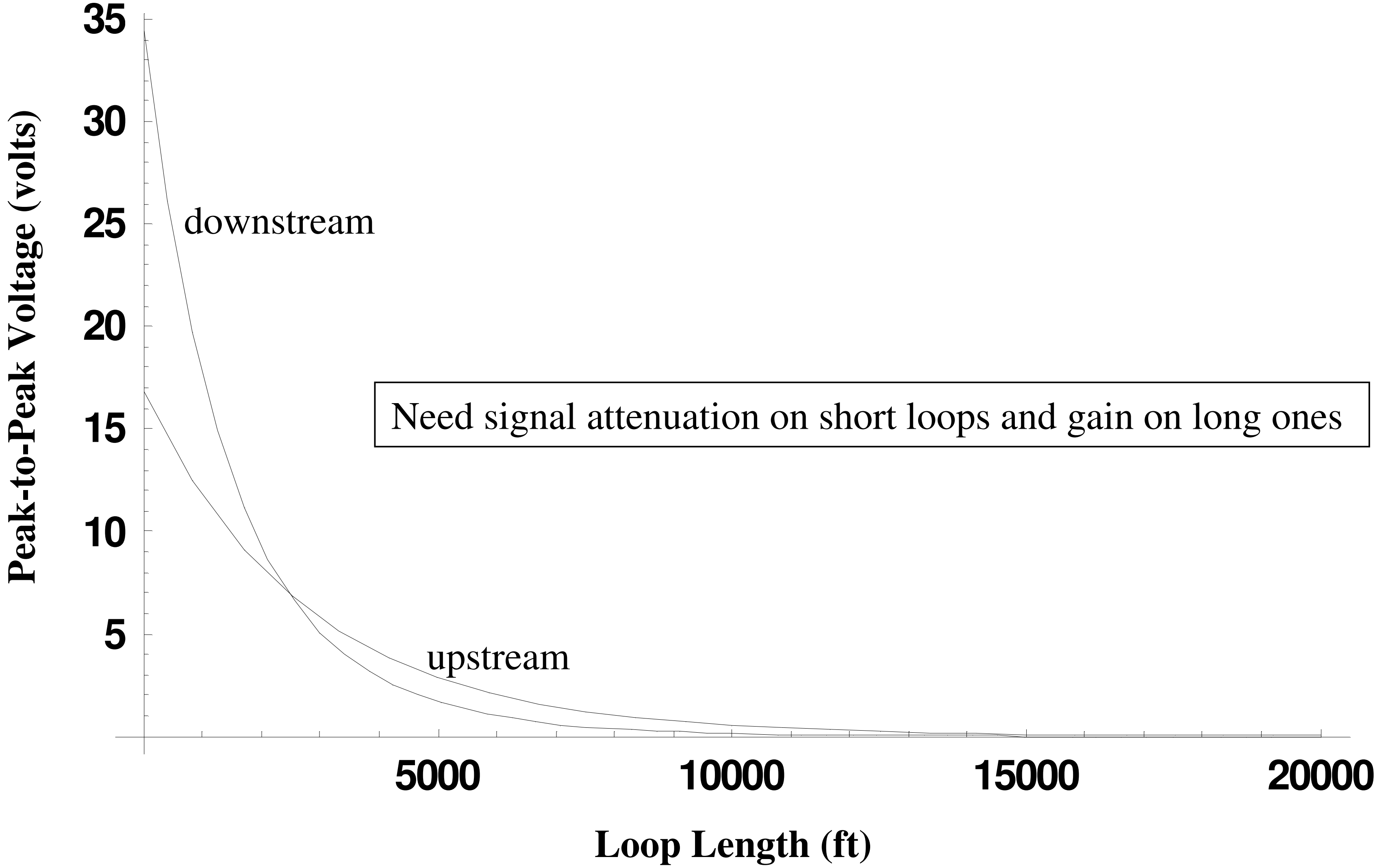
Largest voltage on null loop: 11.2Vpp at client and 19.95Vpp at central office

Minimum ADC Neff versus Conversion Rate

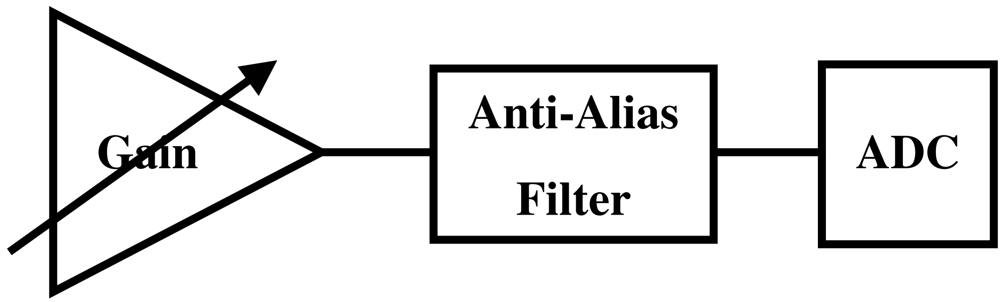


- Input voltages are too high to integrate – must reduce gain from loop to ADC
- Reducing channel gain drives ADC lsb too small

Received Input Peak-to-Peak Voltage versus Loop Length



Programmable Gain to the Rescue



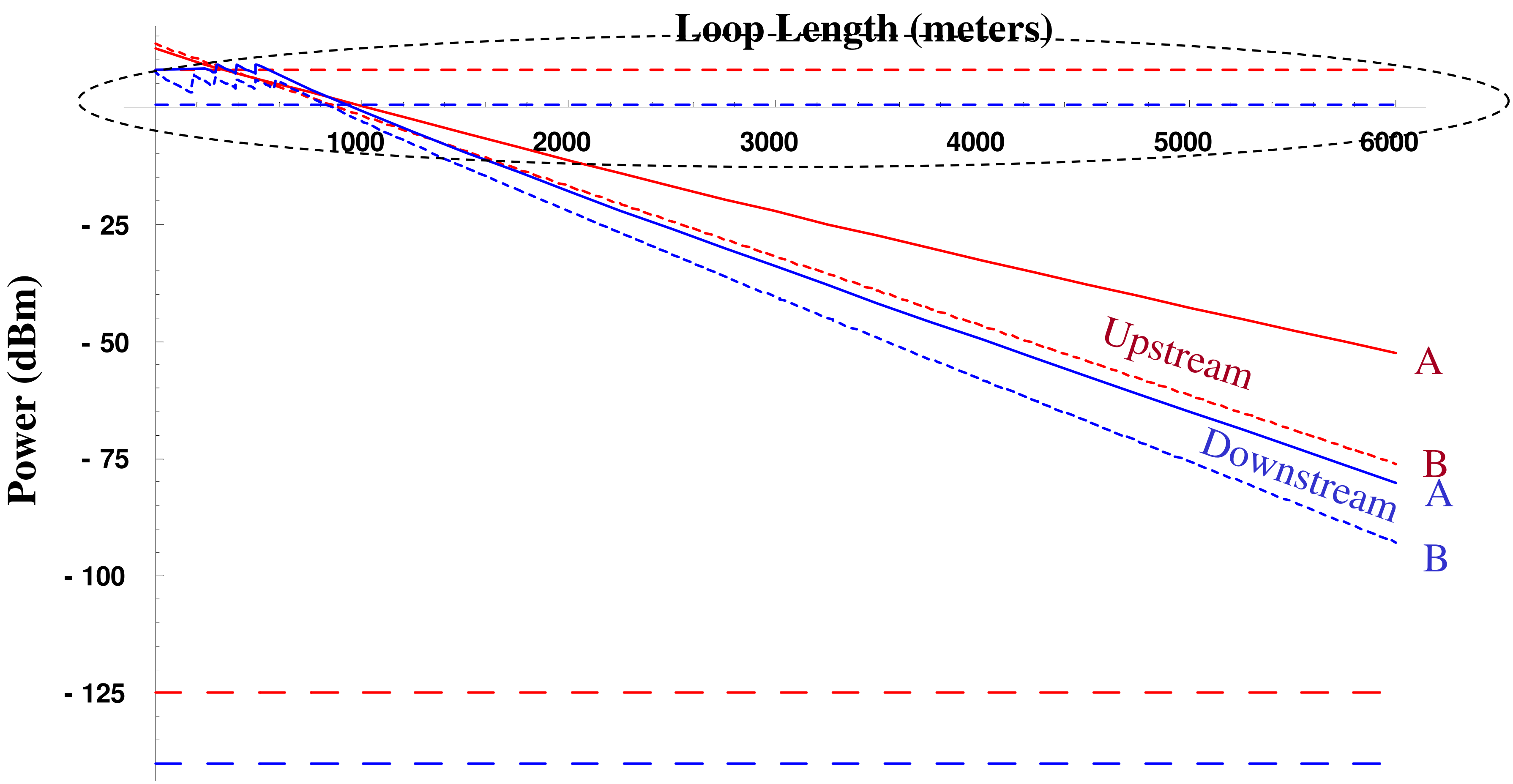
- The noise floor targets were set using loop noise measurements, and represent reasonable goals for long loops where signals are small

- On short loops we only need noise floors sufficient to handle 15 bits per subcarrier, 12.5Neff

- Use programmable gain to increase the channel gain for small signals from long loop
  - gives low channel gain when signals are large
  - gives high channel gain when signals are small

- Remaining problem: the echo

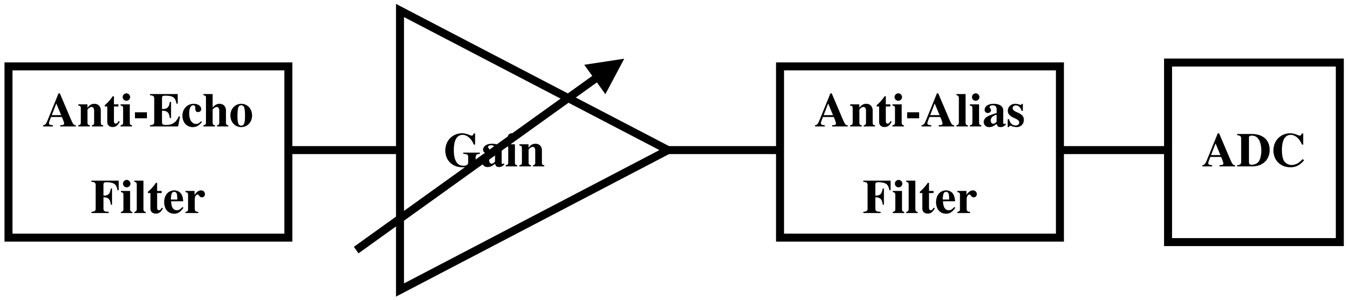
Total Signal Power at Receiver



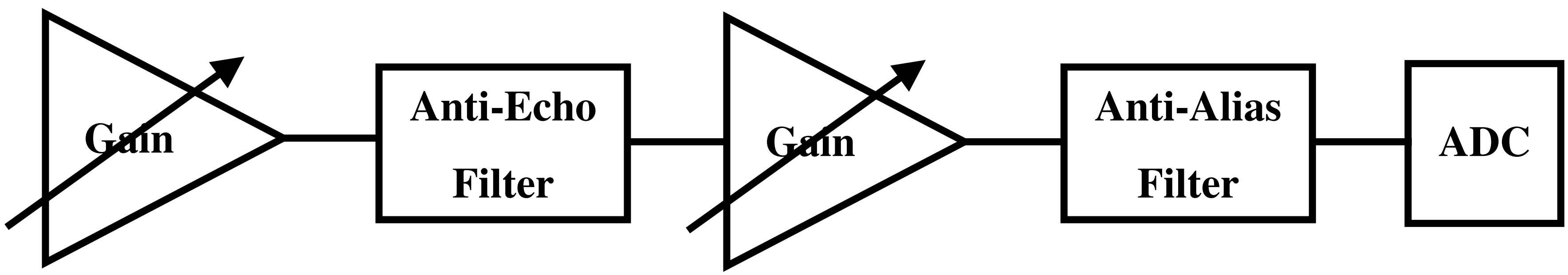
Largest voltage on null loop: 11.2Vpp at client and 19.95Vpp at central office

Killing the Echo

- **Better**

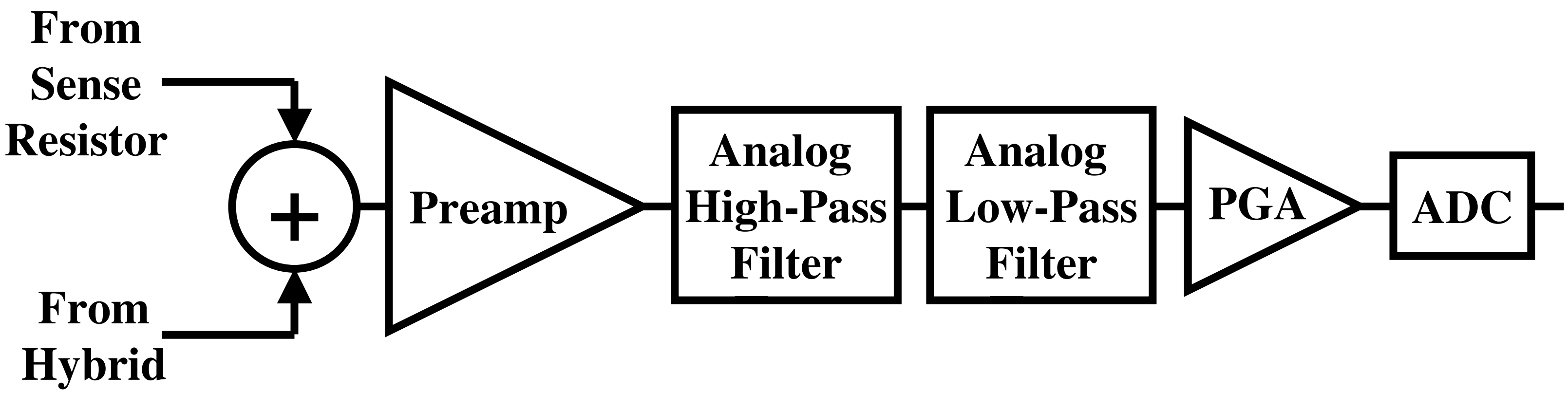


- **Best**

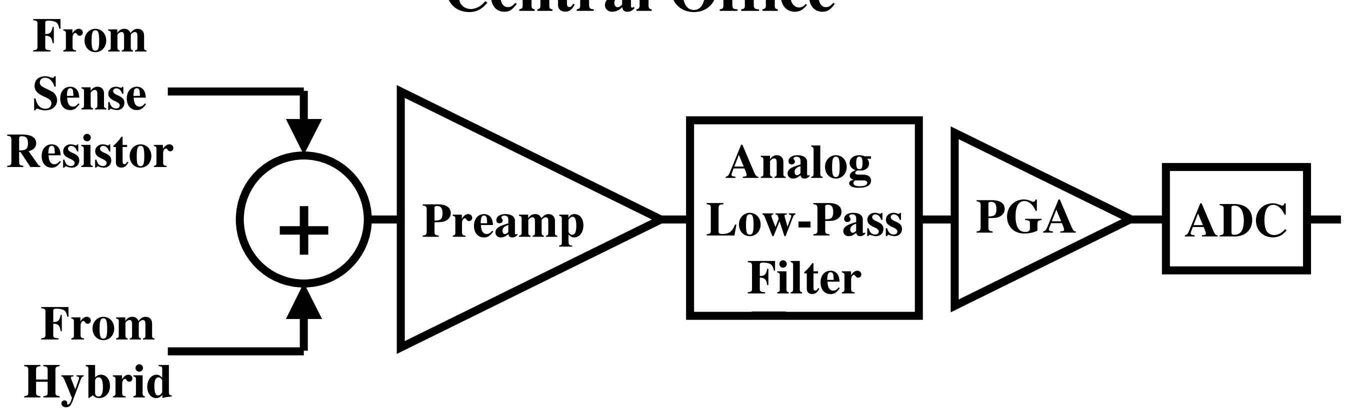


Receiver Architectures

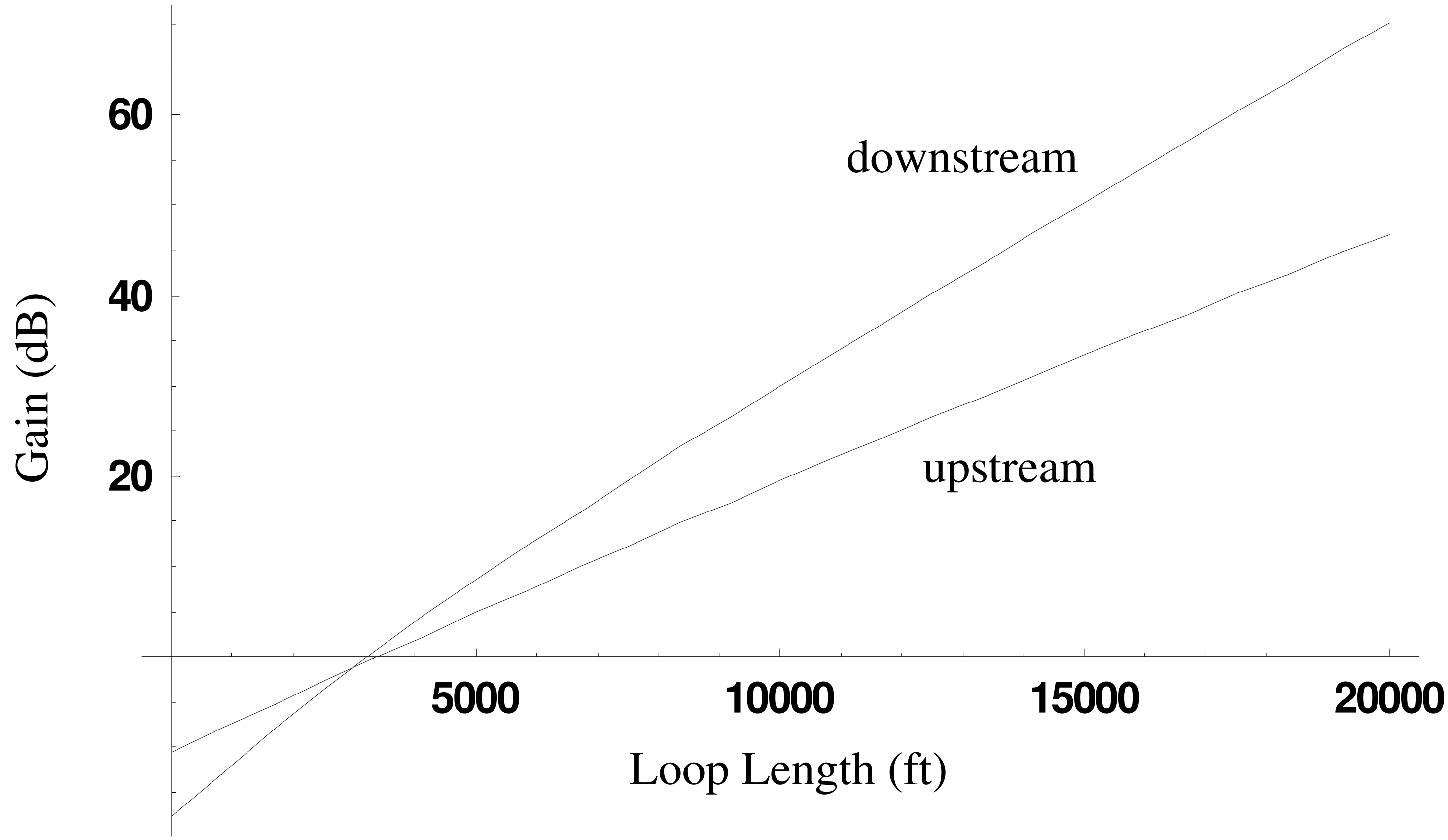
Client



Central Office

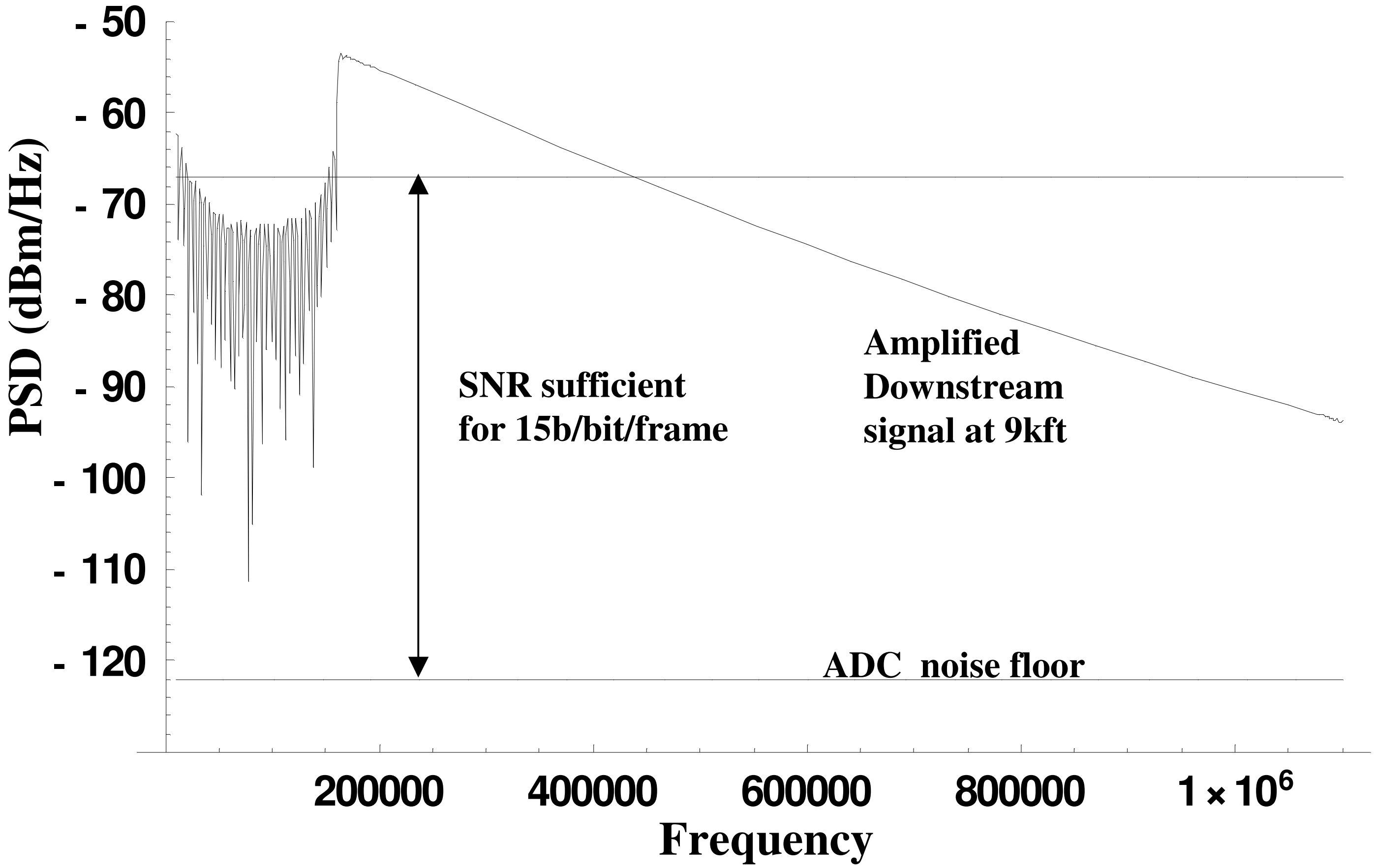


Receiver Programmable Gain



- Receiver gain improves SNR only when the ADC quantization noise is dominant.
- Typically 20 dB gain will amplify the receiver analog noise above the ADC noise. Additional gain will not improve the SNR, so the typical programmable gain range is ~ -20dB to +20dB at the remote terminal and ~ -12dB to +20dB at the central office.

Equalization

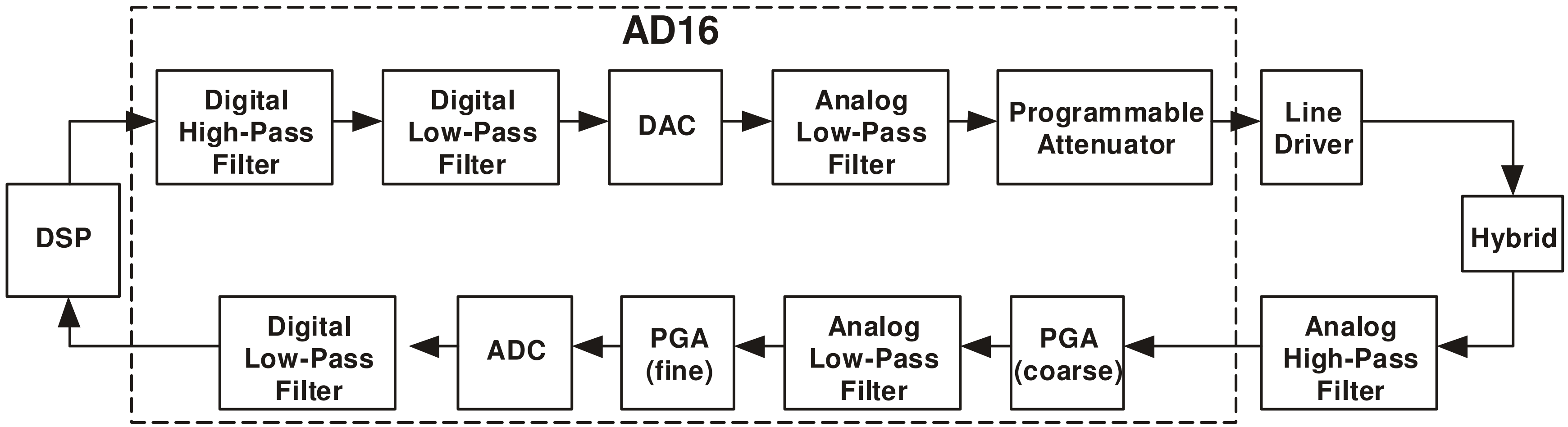


- Equalization is frequency dependent gain
- Improves data rate when
  - SNR is limited by noise source subsequent to equalizer
  - Low-Frequency subcarrier SNR exceeds that required to support 15b/frame
- Programmable gain should follow equalizer

Generic Template

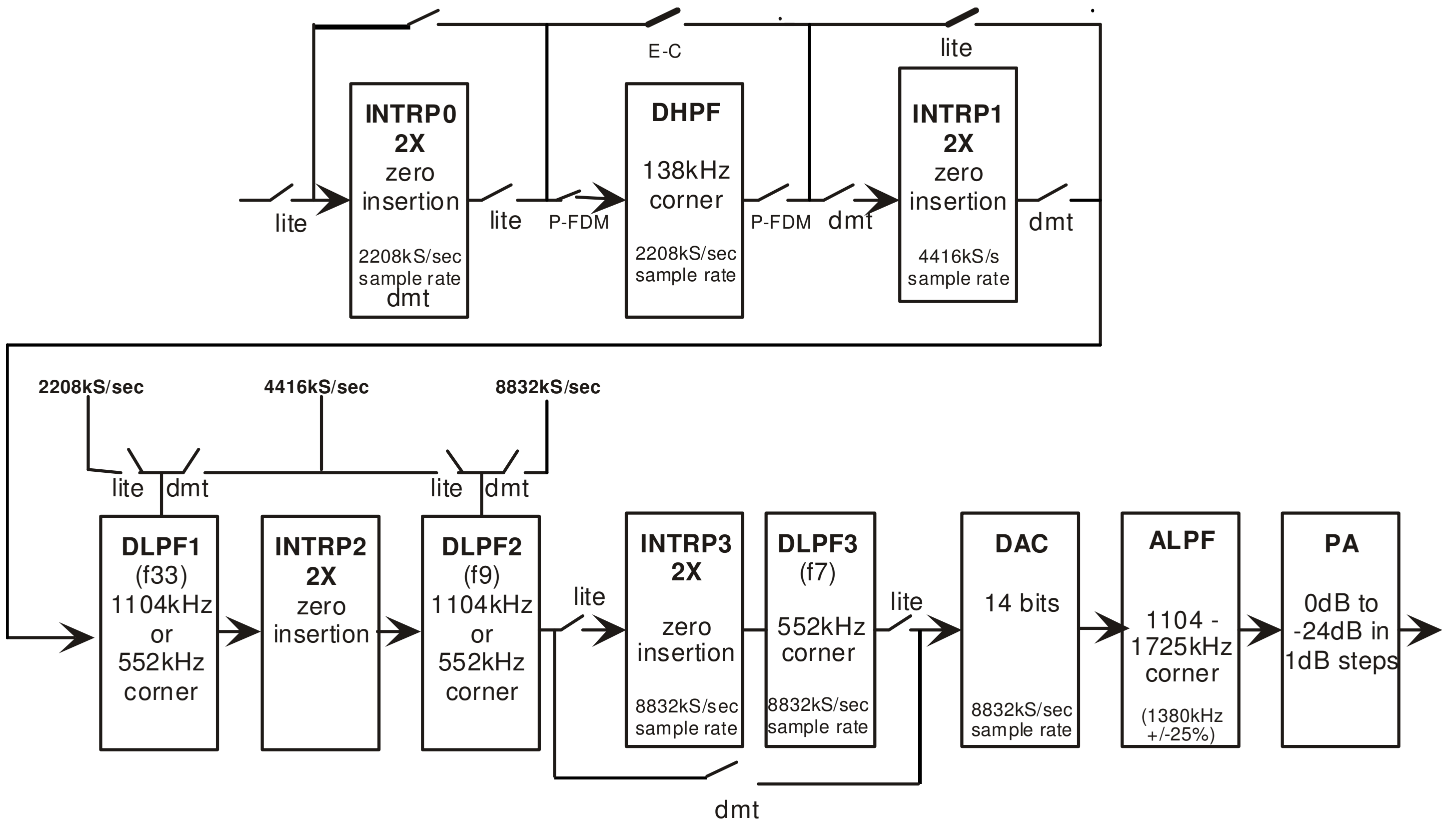
- **AHPF**
  - **In client FDD modems, it may reject virtually all of the upstream echo power and enable higher PGA gain.**
  - **Frequently employed in Annex B central office modem to reject ISDN power in front of PGA.**
- **Equalizer**
  - **Provides frequency dependent gain to amplify weak high-frequency subcarriers above ADC noise.**
  - **Not useful in central office receiver**
- **ALPF**
  - **Provides anti-alias filtering for ADC.**
  - **In central office FDD modems, it also rejects upstream echo and enables higher PGA gain.**
- **PGAs**
  - **Placed both before and after filters when echo is rejected by integrated filter.**
- **ADC**
  - **Resolution depends upon duplexing, EC being more demanding than FDD because echo power is dominant on long loops.**
- **DLPF**
  - **Decimates sample rate to that of FFT.**

Design Example:
Echo-Canceling Central Office Modem

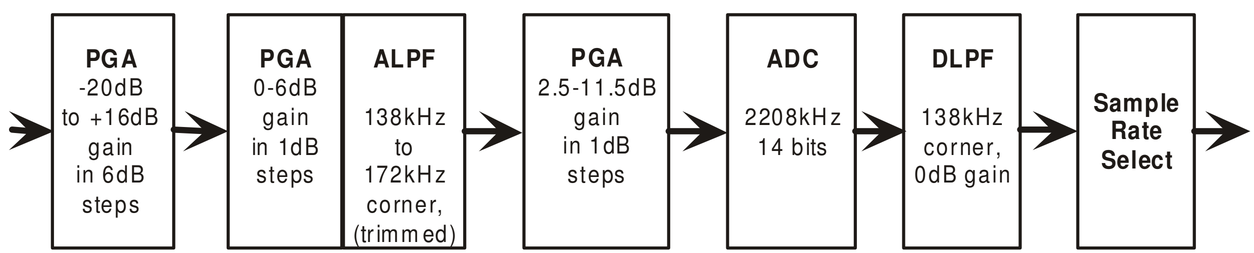


- **Deviations from generic topologies**
  - **Analog transmitter high-pass deleted to support echo cancellation**
  - **Programmable attenuator added to support power cutback on short loops**
  - **Programmable gain amplifiers precede and follow receiver analog low-pass to adjust signal to 3Vpp before non-overlapping portion of echo is removed**
  - **Equalizer is not necessary on central office receivers**
- **DSP sample rates**
  - **2208kS/sec transmitter in full rate mode and 1104kS/sec in "lite" mode**
  - **276kS/sec receiver**

AD16

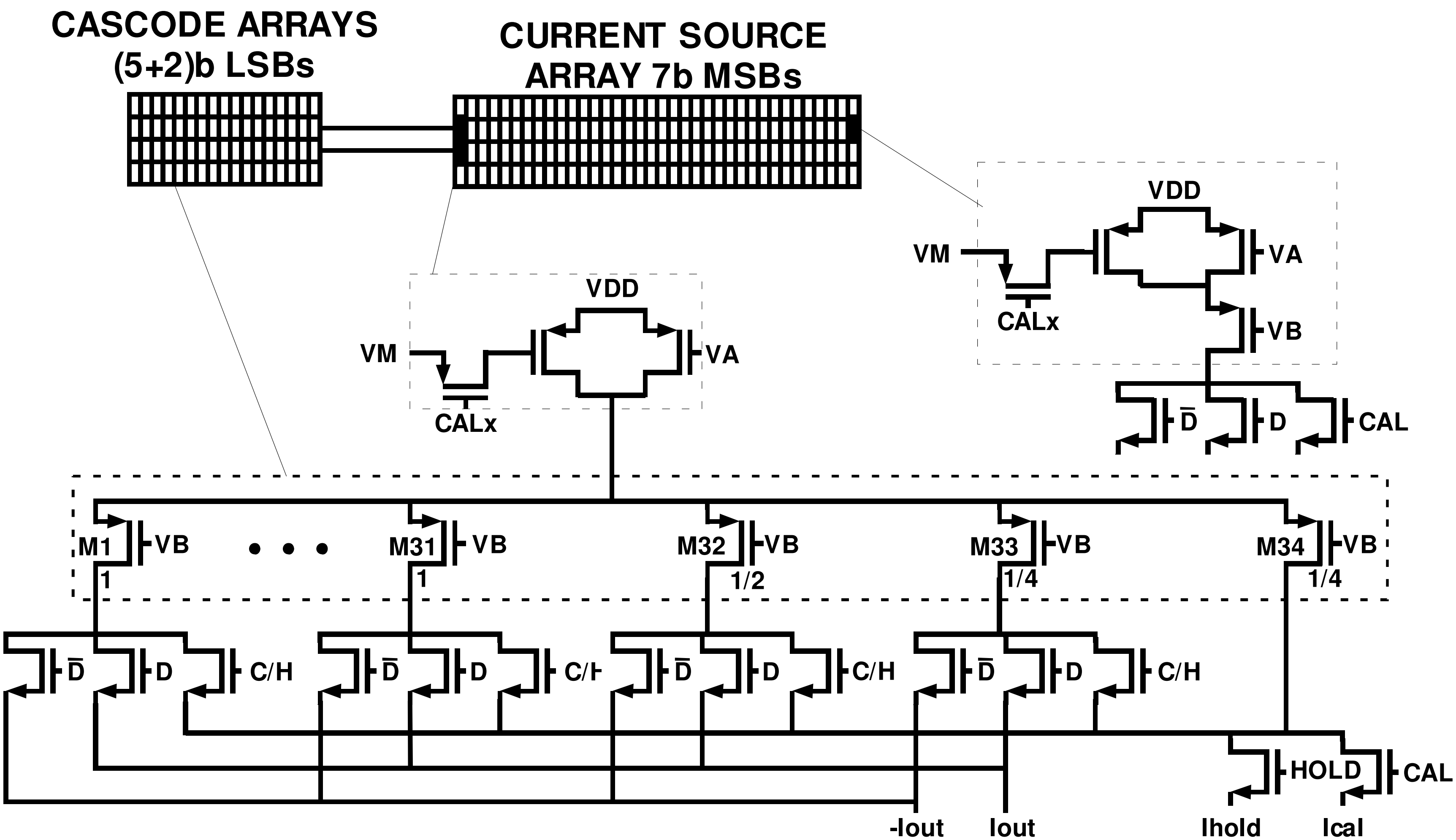


TRANSMITTER PATH

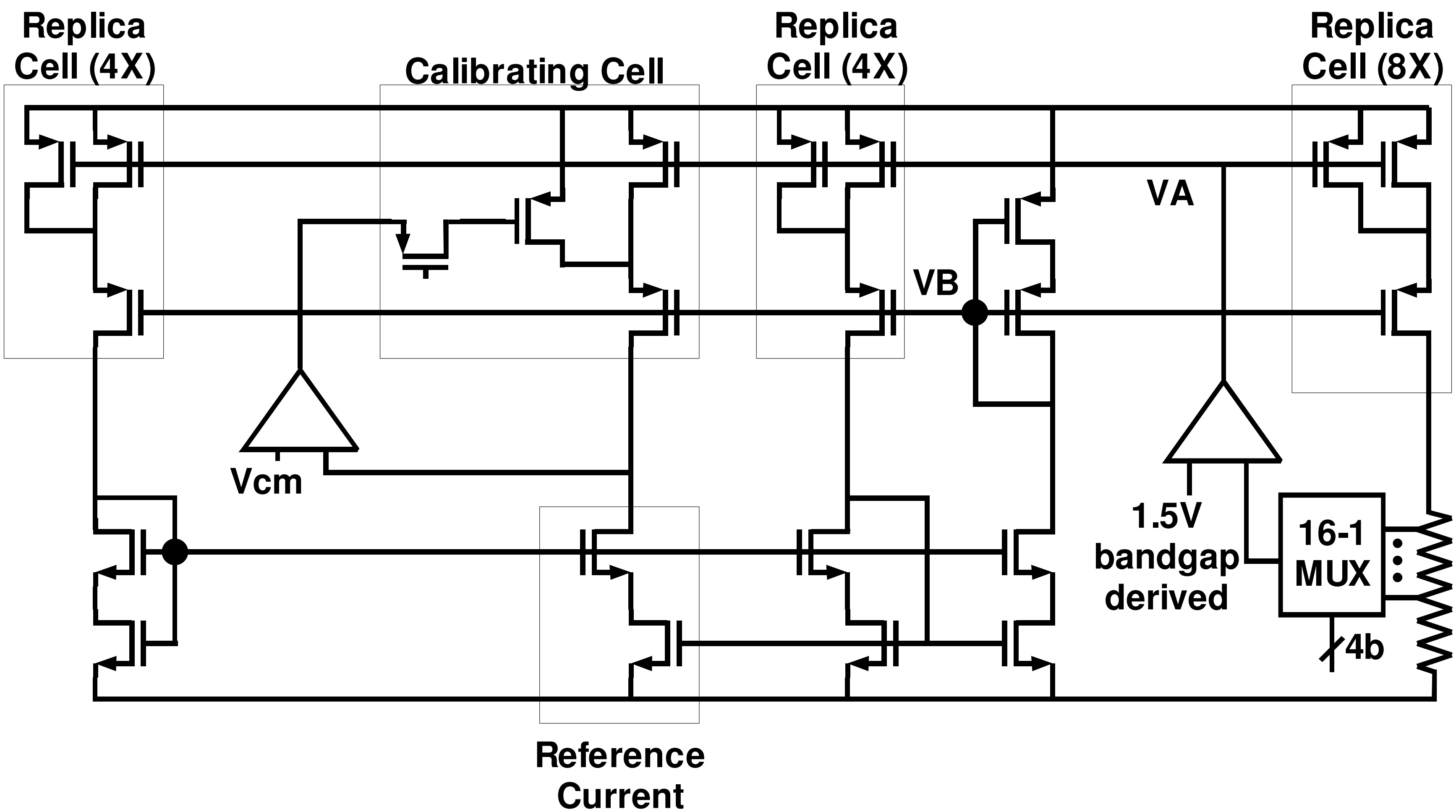


RECEIVER PATH

D/A Converter

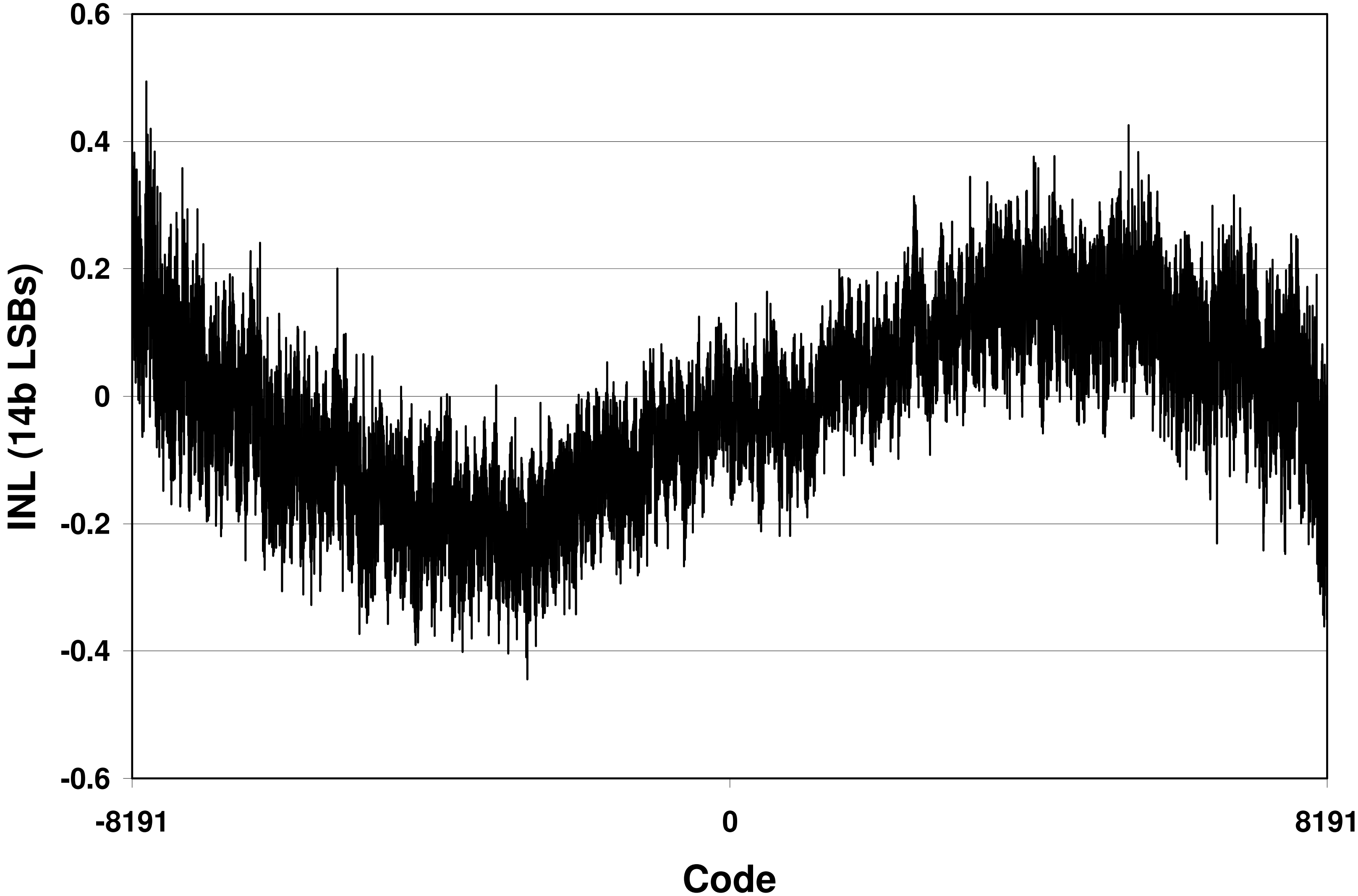


Signal DAC Current Source Bias and Calibration

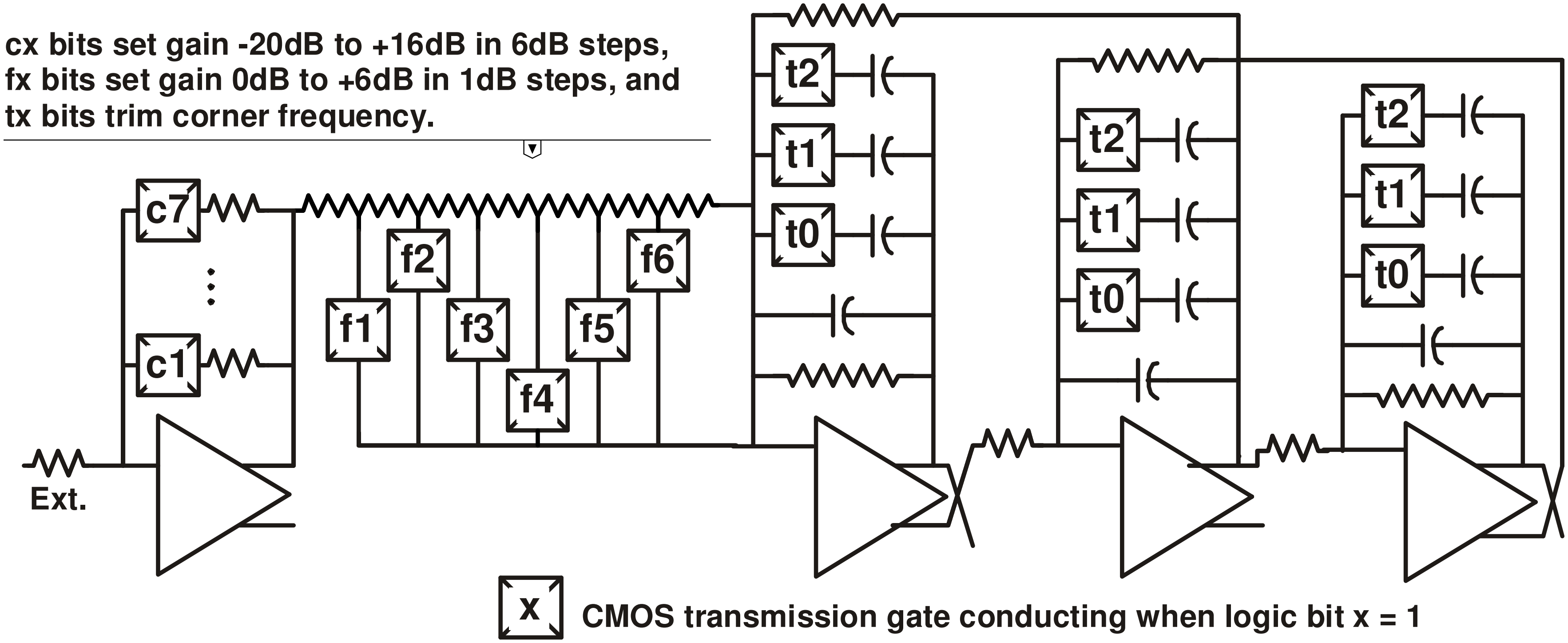


Transmitter Static Integral Non-Linearity

(digital high-pass bypassed)

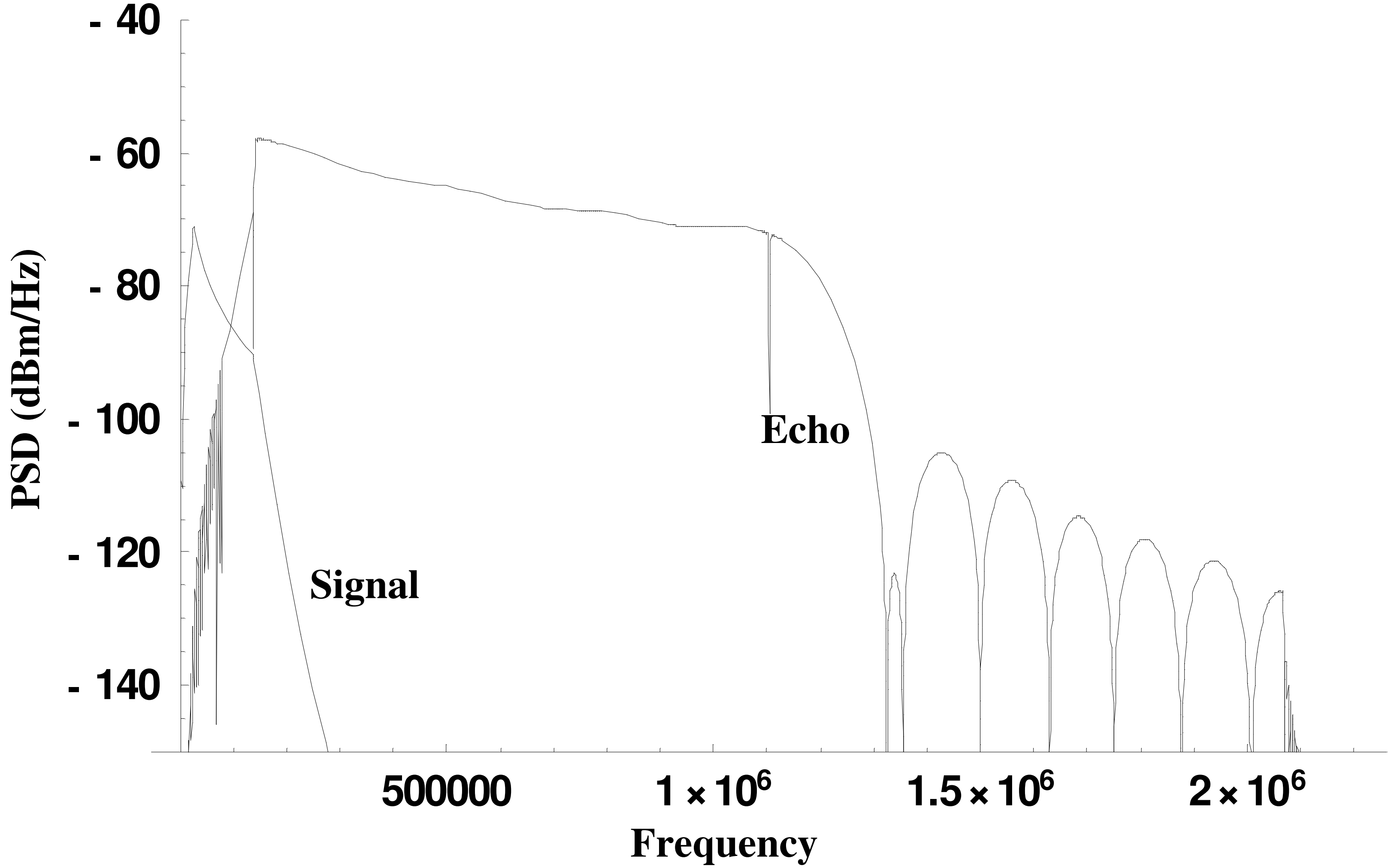


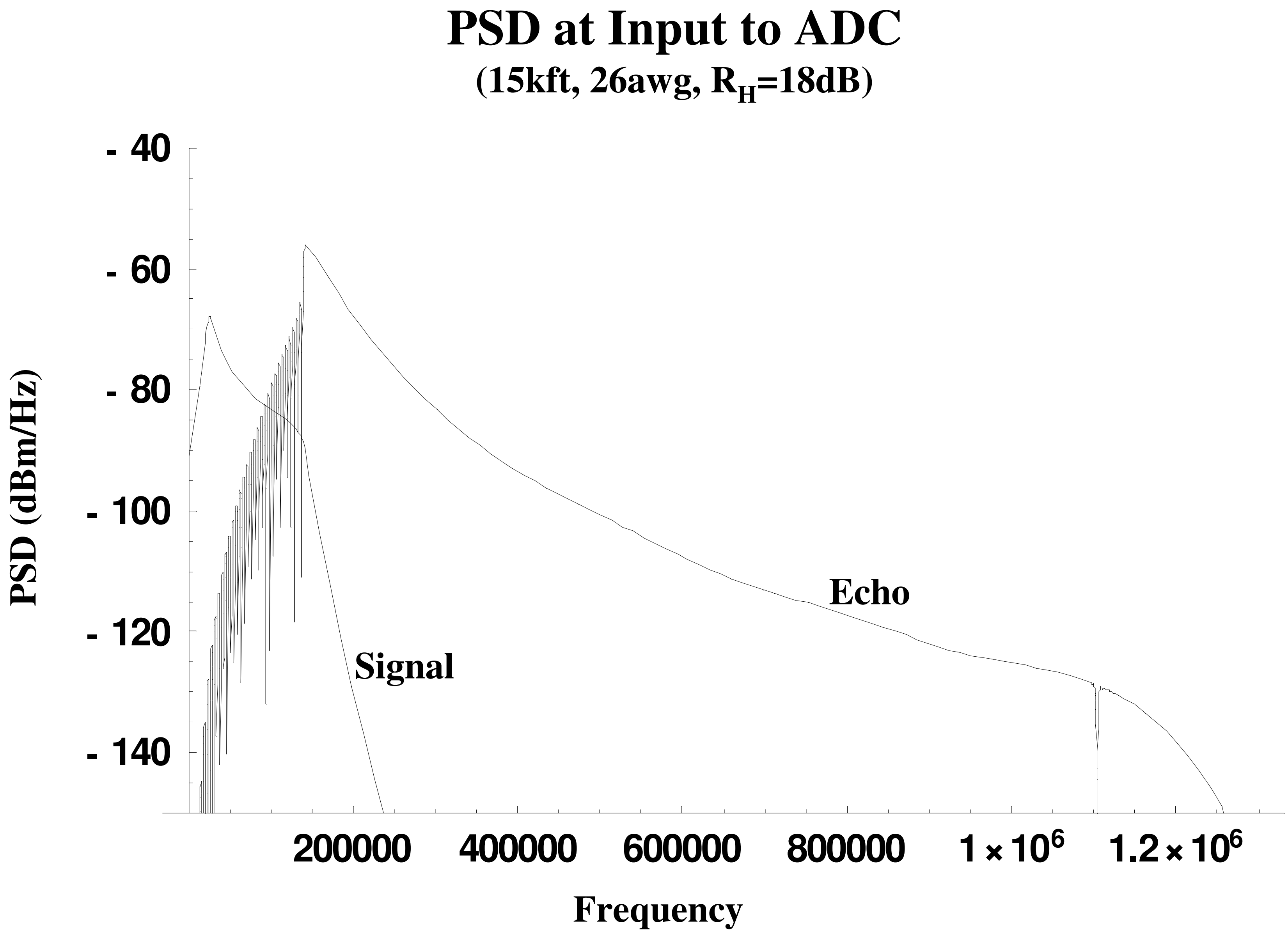
Receiver PGA/Low-Pass Combination



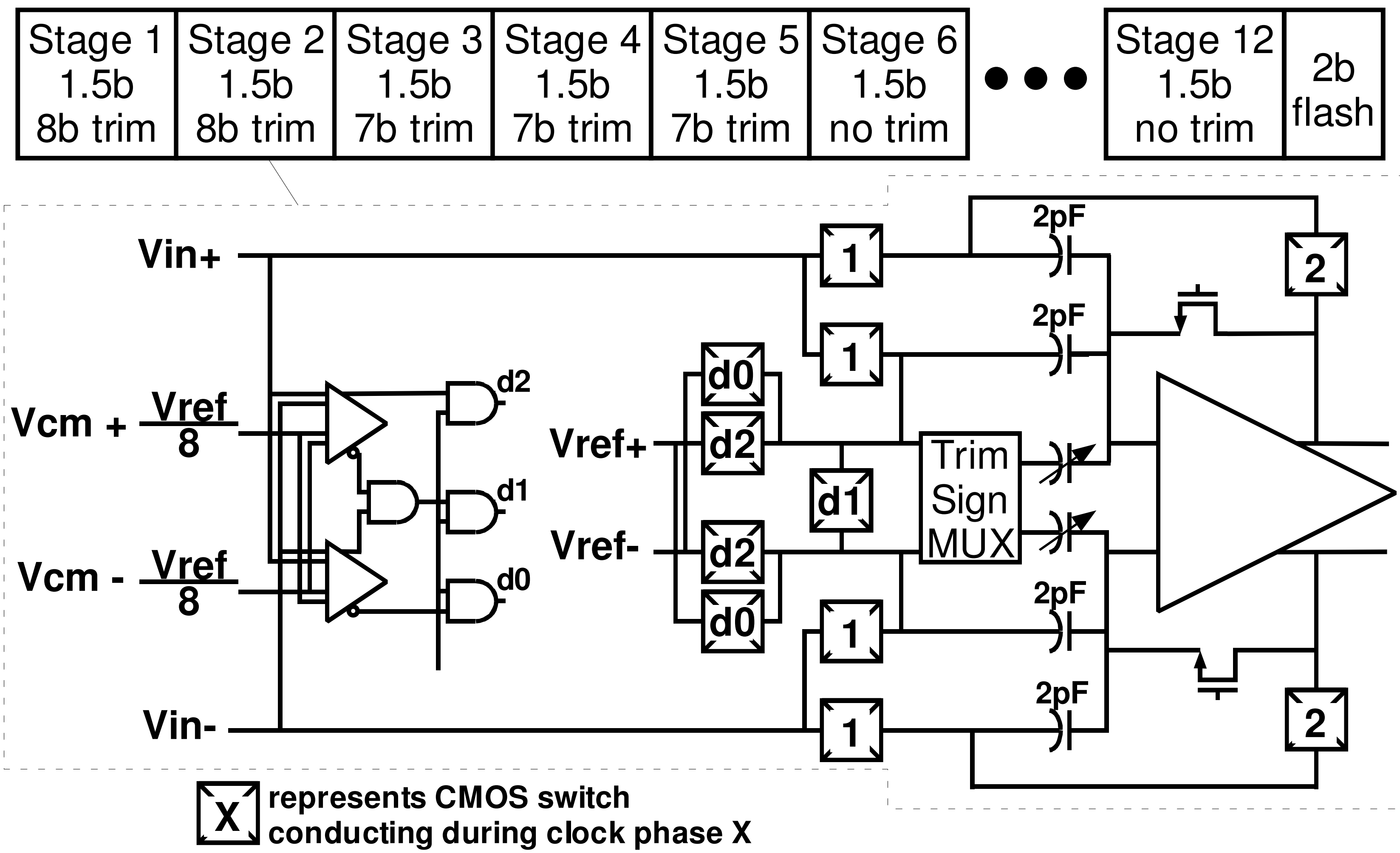
PSD at Input to Analog Low-Pass Filter

(15kft, 26awg, R_H=18dB)

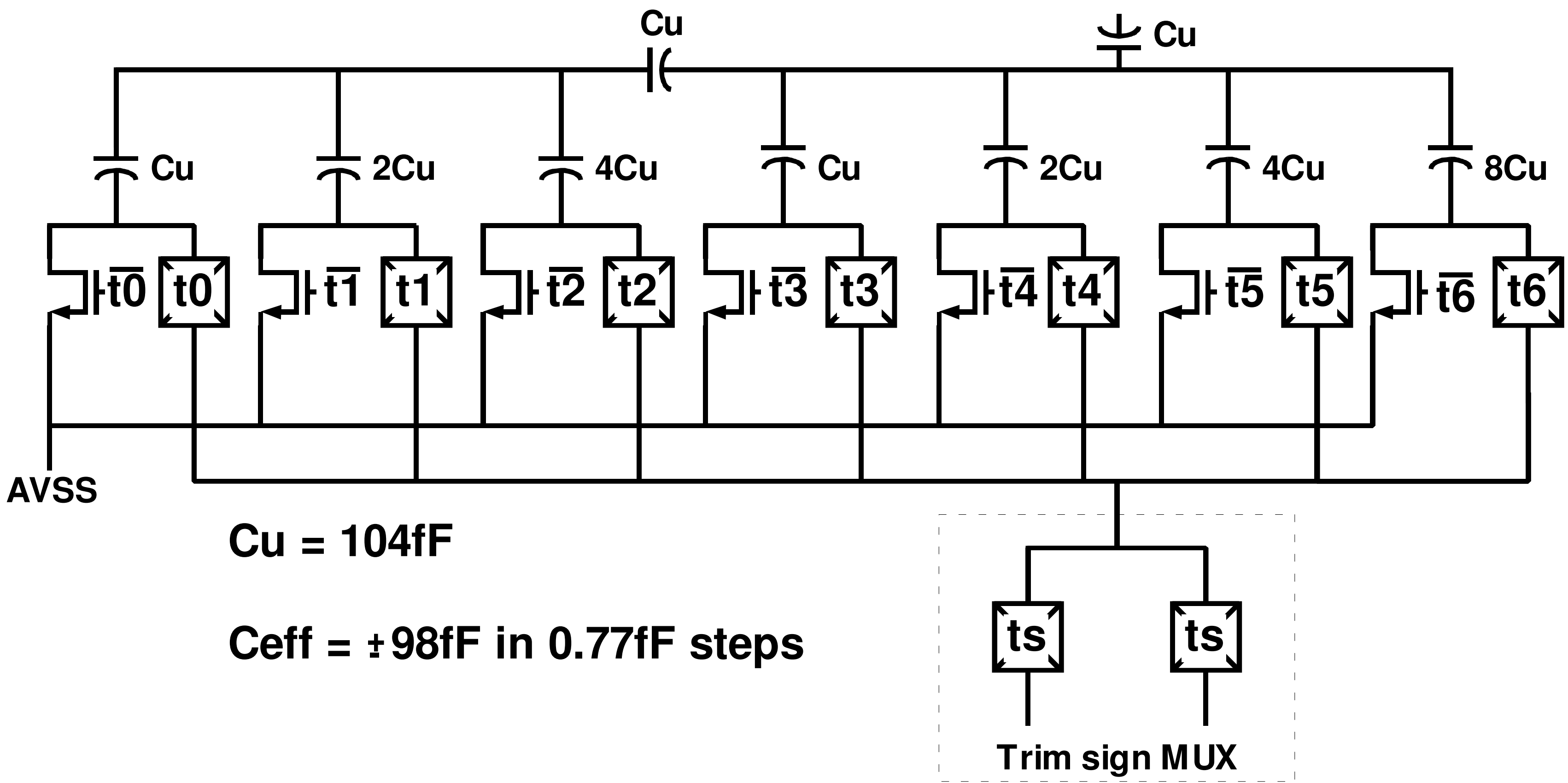



PSD at Input to ADC
(15kft, 26awg, R_H=18dB)
PSD (dBm/Hz)
- 40
- 60
- 80
- 100
- 120
- 140
Signal
Echo
200000
400000
600000
800000
1×10^6
1.2×10^6
Frequency

Pipelined Analog-to-Digital Converter



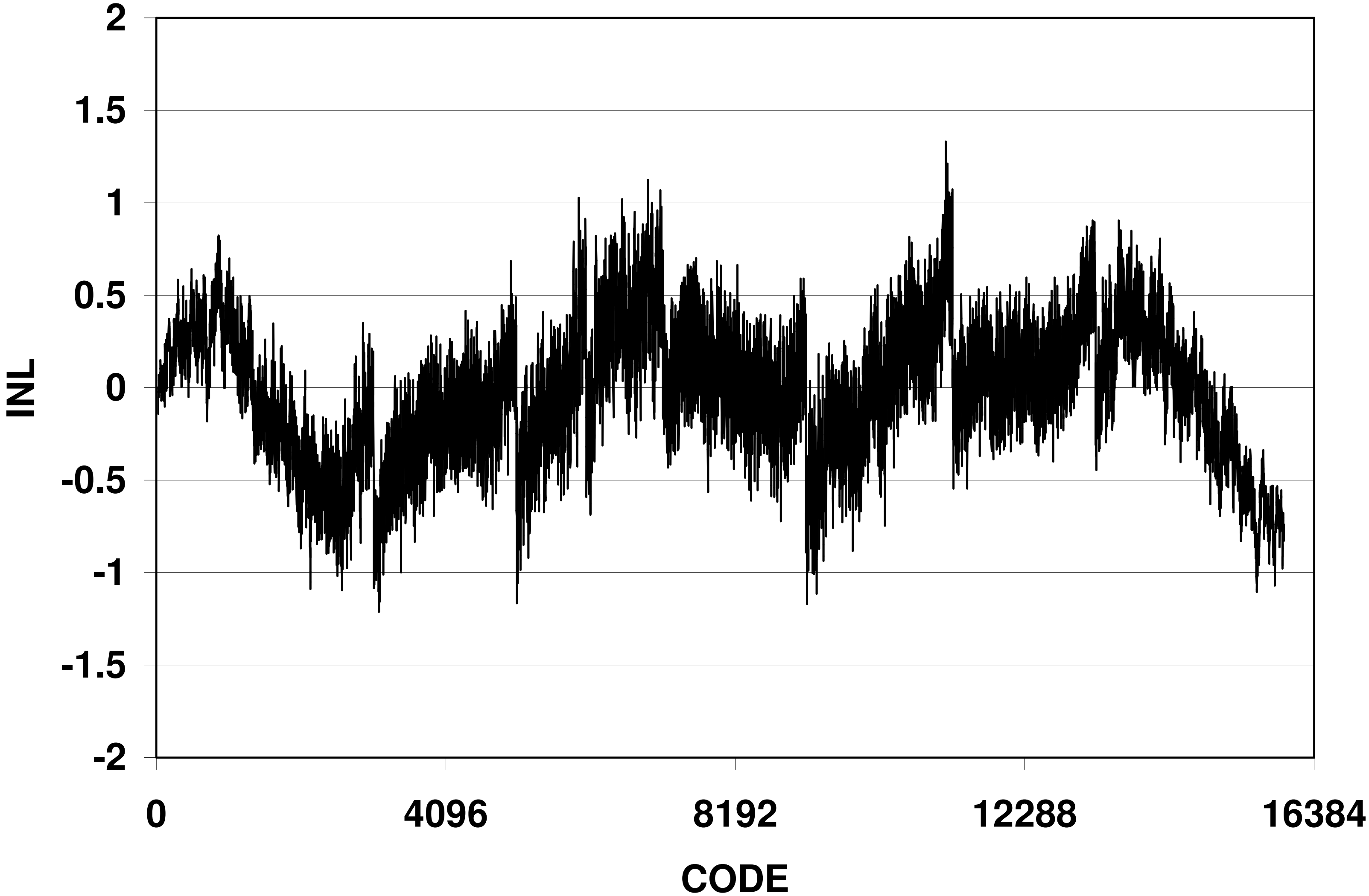
7-Bit Capacitor Trimming Array



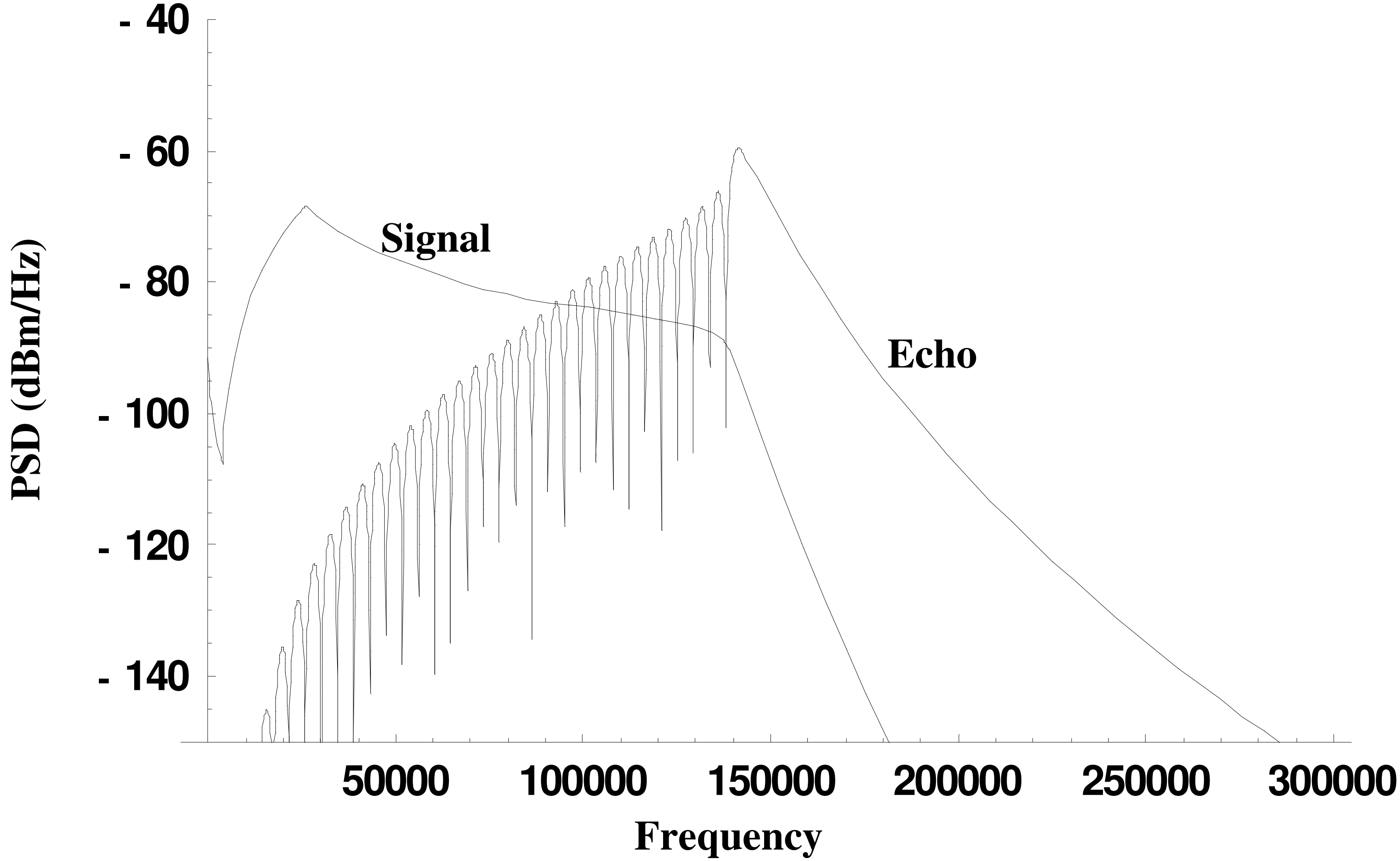
Cu = 104fF

Ceff = ±98fF in 0.77fF steps

Receiver INL



PSD at Output of Digital Low-Pass Filter
(15kft, 26awg, R_H=18dB)



Summary

- The ADSL AFE requirements depend upon multiple system parameters such as
    - Duplexing method
    - Upstream and downstream frequency allocations
    - DSP transmit and receive sample rates
    - Receiver sensitivity
    - Hybrid rejection

- An AFE design example provides the optimum integrated solution for modems employing echo cancellation.