Miscellaneous Topics in Analog Communications

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Overview

Signal Multiplexing

Signal Multiplexing

Definition (Multiplexing)

Combining separate message signals into a composite signal for transmission over a common channel is called multiplexing.

1. Frequency Division Multiplexing (FDM)
2. Quadrature Carrier Multiplexing (QCM)
3. Time Division Multiplexing (TDM)
4. Code Division Multiplexing (CDM)
5. Space Division Multiplexing (SDM)
6. Orthogonal Frequency Division Multiplexing (OFDM)

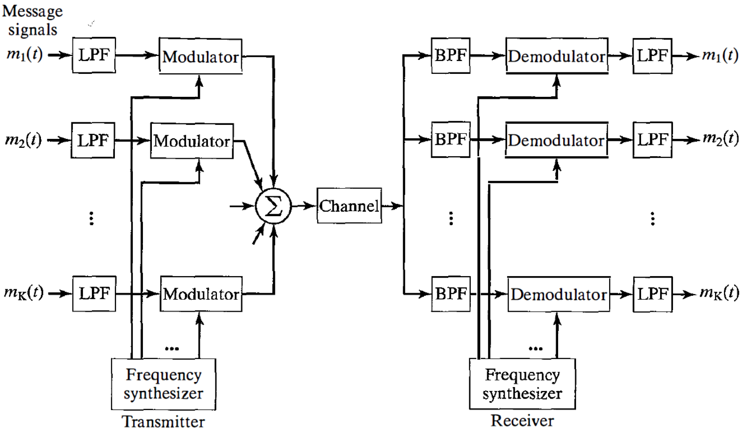


Figure: Frequency-division multiplexing of multiple signals.

✓ The distance between carriers depends on the modulation type.

Signal Multiplexing

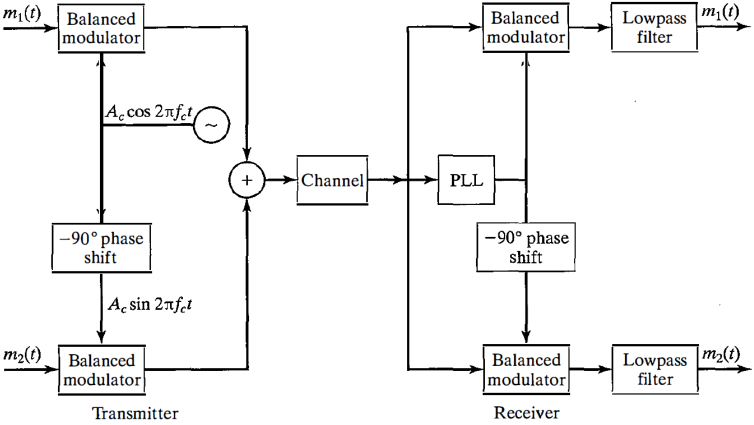


Figure: Quadrature-carrier multiplexing.

Signal Multiplexing

$$u(t) = A_c m_1(t)\cos(2\pi f_c t) + A_c m_2(t)\sin(2\pi f_c t)$$

$$u(t)\cos(2\pi f_c t) = \frac{A_c}{2}m_1(t) + \frac{A_c}{2}m_1(t)\cos(4\pi f_c t) + \frac{A_c}{2}m_2(t)\sin(4\pi f_c t)$$

$$u(t)\sin(2\pi f_c t) = \frac{A_c}{2}m_2(t) - \frac{A_c}{2}m_2(t)\cos(4\pi f_c t) + \frac{A_c}{2}m_1(t)\sin(4\pi f_c t)$$

✓ Quadrature-carrier multiplexing results in a bandwidth-efficient communication system that is comparable in bandwidth efficiency to SSB AM.

AM Radio Broadcasting

AM Radio Broadcasting

1. Commercial AM radio broadcasting utilizes the frequency band 535-1605 kHz.
2. The carrier-frequency allocations range from 540-1600 kHz with 10 kHz spacing.
3. Radio stations employ conventional AM for signal transmission.
4. The message bandwidth is limited to 5 kHz.
5. The major objective behind the design of AM radio is to reduce the receiver implementation cost.
6. The receiver most commonly used in AM radio broadcast is the so-called super-heterodyne receiver.

AM Radio Broadcasting

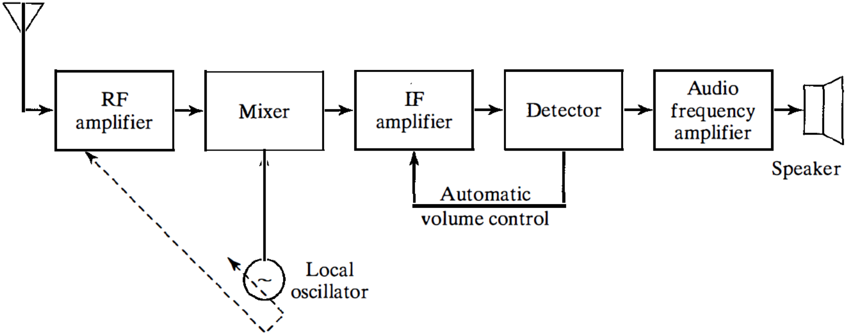


Figure: A super-heterodyne receiver.

AM Radio Broadcasting

1. In the super-heterodyne receiver, every AM radio signal is converted to a common intermediate frequency (IF) of $f_{IF} = 455$ kHz.
2. This conversion allows the use of a single-tuned IF amplifier.
3. The IF amplifier is designed to have a bandwidth of 10 kHz.
4. The frequency of the local oscillator is $f_{LO} = f_c + f_{IF}$, where f_c is the carrier frequency of the desired AM radio signal.

AM Radio Broadcasting

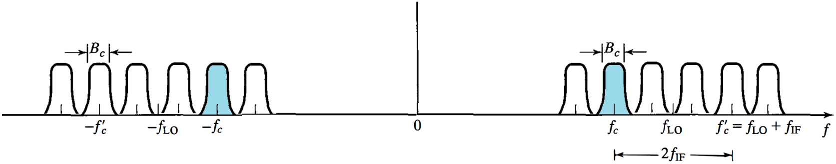
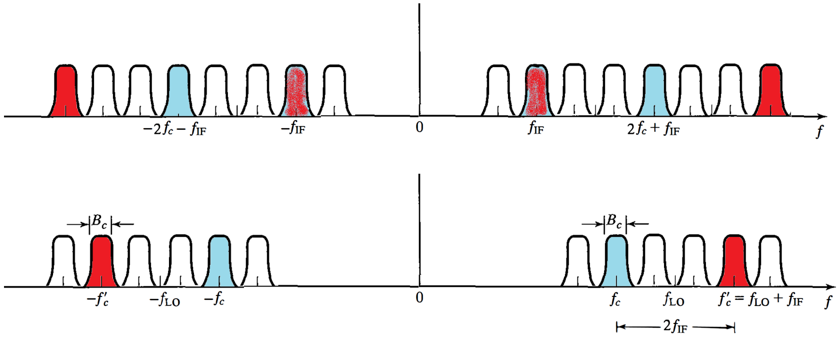


Figure: Sample AM reception scenario.

AM Radio Broadcasting



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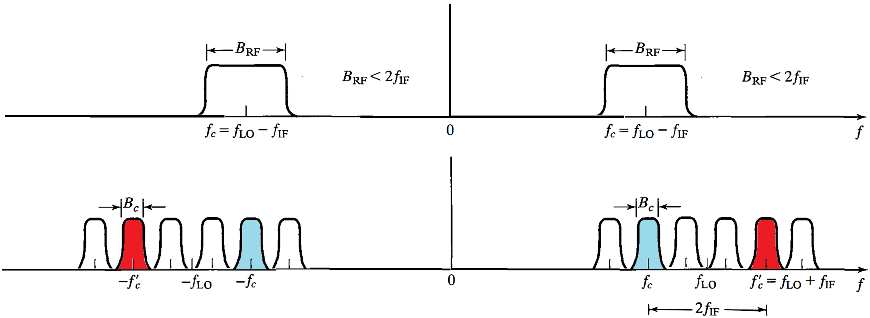
AM Radio Broadcasting



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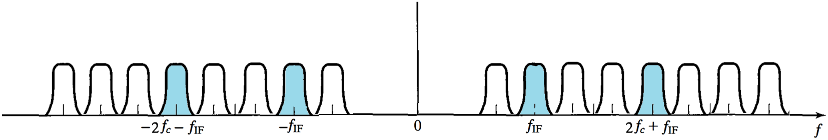
AM Radio Broadcasting



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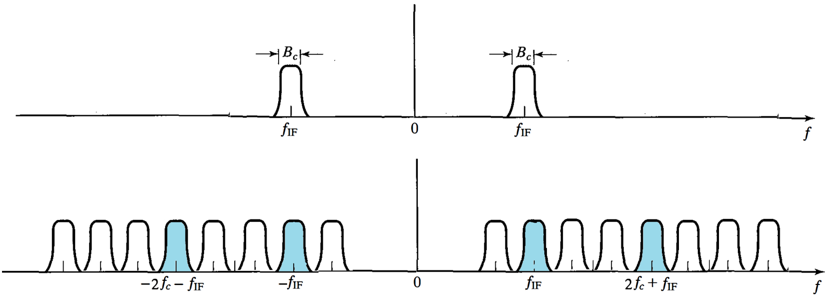

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AM Radio Broadcasting

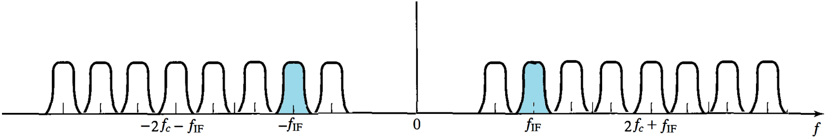

Figure: Sample AM reception scenario.

AM Radio Broadcasting

1. The RF amplifier is tuned to the frequency f_c with the bandwidth B_{RF}.
2. The output of the RF amplifier is mixed with the local oscillator.
3. The mixer output has two signal components.
4. The desired component is centered at the $f_c - f_{LO} = -f_{IF}$ and $-f_c + f_{LO} = f_{IF}$.
5. The adjacent component is centered at $f_c + f_{LO} = 2f_c + f_{IF}$ and $-f_c - f_{LO} = -2f_c - f_{IF}$.
6. Only the component around f_{IF} is passed by the IF amplifier with the bandwidth $B_c = 10$ kHz.

AM Radio Broadcasting

1. The image frequency $f_c' = f_{LO} + f_{IF}$ also creates two components at the output of mixer.
2. The first component is centered at the $f_c' - f_{LO} = f_{IF}$ and $-f_c' + f_{LO} = -f_{IF}$.
3. The second component is centered at $f_c' + f_{LO} = 2f_c + 3f_{IF}$ and $-f_c' - f_{LO} = -2f_c - 3f_{IF}$.
4. The bandwidth of the RF amplifier is chosen to reject the image frequency; so, $B_c = 10 < B_{RF} < 2f_{IF} = 910$ KHz.
5. The bandwidth of the RF amplifier is still considerably wider than the bandwidth of the IF amplifier.

AM Radio Broadcasting

1. The output of the IF amplifier is passed through an envelope detector.
2. The output of the envelope detector is amplified to derive a loudspeaker.
3. Automatic volume control (AVC) is provided by a feedback-control loop, which adjusts the gain of the IF amplifier based on the power level of the signal at the envelope detector.

AM Radio Broadcasting

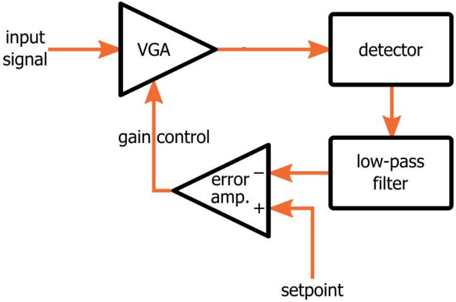

Figure: Automatic volume control (AVC) or automatic gain control unit (AGC).

FM Radio Broadcasting

FM Radio Broadcasting

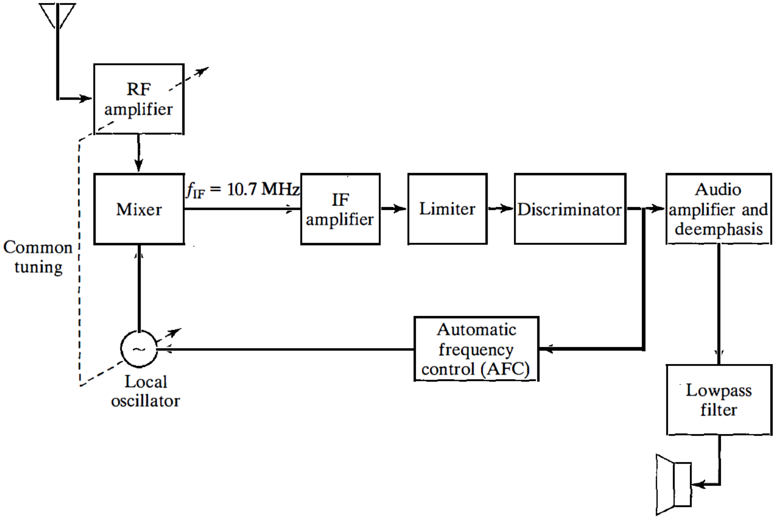

Figure: Block diagram of a superheterodyne FM radio receiver.

FM Radio Broadcasting

1. Commercial FM radio broadcasting utilizes the frequency band 88-108 MHz.
2. The carrier frequencies are separated by 200 kHz and the peak frequency deviation is fixed at 75 kHz.
3. Preemphasis is generally used to improve the demodulator performance in the presence of noise in the received signal.
4. The receiver most commonly used in FM radio broadcasting is a superheterodyne type.

FM Radio Broadcasting

1. Common tuning between the RF amplifier and the local oscillator allows the mixer to bring all FM radio signals to a common IF bandwidth of 200 kHz, centered at $f_{IF} = 10.7$ MHz.
2. The amplitude limiter removes any amplitude variations in the received signal at the output of the IF amplifier by hardlimiting the signal amplitude.
3. A bandpass filter, which is centered at $f_{IF} = 10.7$ MHz with a bandwidth of 200 kHz, is included in the limiter to remove higher-order frequency components introduced by the nonlinearity inherent in the hard limiter.

FM Radio Broadcasting

1. A balanced frequency discriminator is used for frequency demodulation.
2. The message signal is then passed to the audio-frequency amplifier, which performs the functions of deemphasis and amplification.
3. The output of the audio amplifier is further filtered by a lowpass filter to remove out-of-band noise.
4. Automatic frequency control (AFC) is provided by a feedback-control loop adjusting the frequency of the mixer which may drift due to thermal or mechanical change in the values of the electronic components.

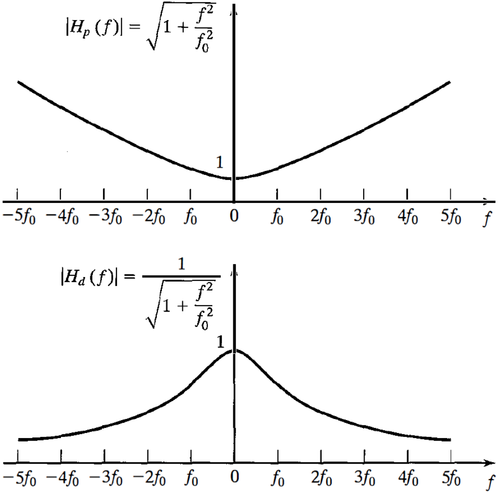

Figure: Preemphasis and deemphasis filter characteristics.

FM Stereo Broadcasting

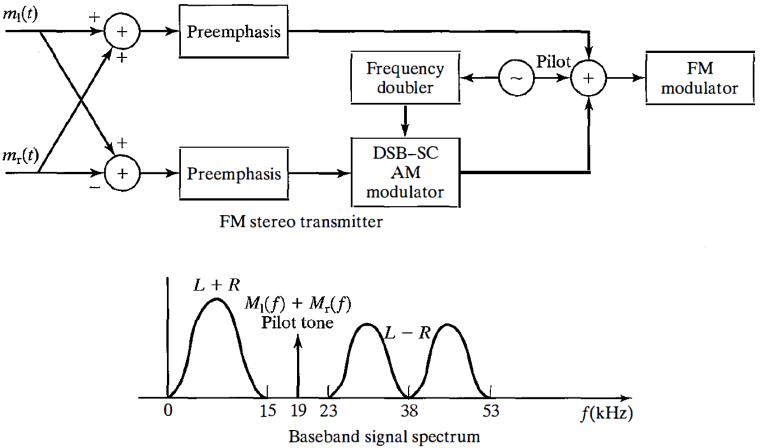

Figure: FM stereo transmitter and signal spacing.

FM Stereo Broadcasting

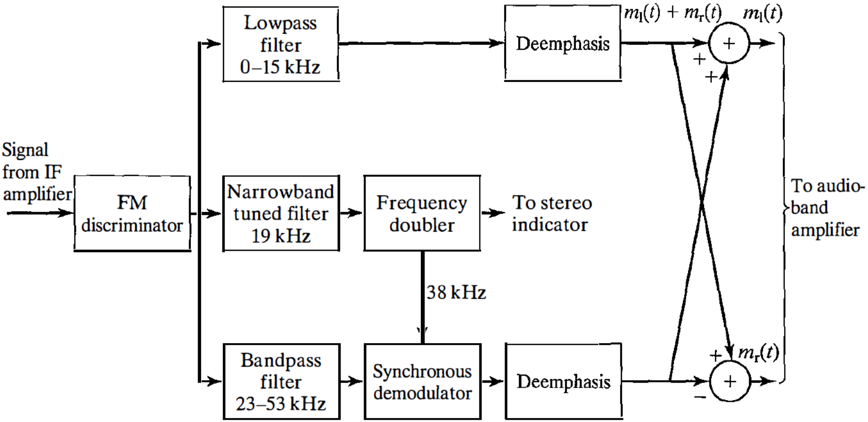

Figure: FM-stereo receiver.

Effective Noise Temperature and Noise Figure

Thermal Noise

Statement (Thermal Noise)

Quantum mechanical analysis of the thermal noise shows that it has a power spectral density given by $S_n(f) = 0.5hf/(e^{\frac{hf}{KT}} - 1)$*, which can be approximated by* $KT/2 = N_0/2$ *for* $f < 2$ *THz, where* $h = 6.6 \times 10^{-34}$ $J \times sec$ *denotes Planck's constan,* $K = 1.38 \times 10^{-23}$ J/K *is Boltzmann's constant, and* T *denotes the temperature in degrees Kelvin. Further, the noise originates from many independent random particle movements.*

Effective Noise Temperature

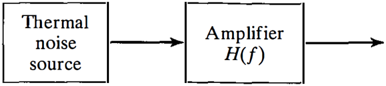

Figure: Thermal noise connected to amplifier.

✓ An amplifier is modeled as a filter with the frequency response $H(f)$ and the maximum available power gain $\mathcal{G} = \max\{|H(f)|^2\}$.

$$P_{n_e} = \int_{-\infty}^{\infty} S_n(f)|H(f)|^2 df = \frac{N_0}{2}\int_{-\infty}^{\infty} |H(f)|^2 df = \mathcal{G}N_0 B_{neq} = \mathcal{G}KTB_{neq}$$

$$P_{n_o} = P_{n_e} + P_{n_a} = \mathcal{G}KB_{neq}(T + \frac{P_{n_a}}{\mathcal{G}KB_{neq}}) = \mathcal{G}KB_{neq}(T + T_e)$$

T_e is called effective noise temperature.

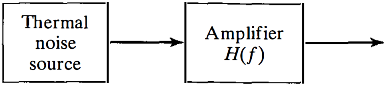

Figure: Thermal noise connected to amplifier.

$$P_{s_o} = \mathcal{G} P_{s_i}$$

$$(\frac{S}{N})_o = \frac{P_{s_o}}{P_{n_o}} = \frac{\mathcal{G} P_{s_i}}{\mathcal{G} K B_{neq}(T + T_e)} = \frac{1}{1 + \frac{T_e}{T}} \frac{P_{s_i}}{N_0 B_{neq}} = \frac{1}{F}(\frac{S}{N})_i$$

$F = 1 + \frac{T_e}{T_0}$ is called noise figure, where $T_0 = 290^\circ$ K is the room temperature.

$$10\log_{10}[(\frac{S}{N})_o] = 10\log_{10}[(\frac{S}{N})_i] - 10\log_{10}[F]$$

$$(\frac{S}{N})_{odB} = (\frac{S}{N})_{idB} - F_{dB}$$

Noise Figure

Statement (Fries' Noise Figure Formula)

The overall noise figure of a cascade of n amplifiers with gains $\mathcal{G}_i$ and noise figures $\mathcal{F}_i$ is

$$F = F_1 + \frac{F_2 - 1}{\mathcal{G}_1} + \frac{F_3 - 1}{\mathcal{G}_1 \mathcal{G}_2} + \cdots + \frac{F_n - 1}{\mathcal{G}_1 \mathcal{G}_2 \cdots \mathcal{G}_{n-1}}$$

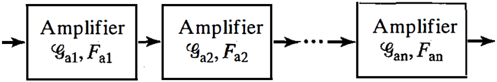

Figure: Cascade of several amplifiers.

✓ The dominant term is F_1, which implies that the front end of the receiver should have a low noise figure and a high gain.

Noise Figure

Example (Fries' Noise Figure Formula)

Suppose an amplifier is designed with three identical stages, each of which has a gain $\mathcal{G}_i = 5$ and a noise figure $F_i = 6$. The overall noise figure of the cascade of the three stages is $F = 7.2 \equiv 8.57$ dB.

$$F = F_1 + \frac{F_2 - 1}{\mathcal{G}_1} + \frac{F_3 - 1}{\mathcal{G}_1 \mathcal{G}_2} = 6 + \frac{6-1}{5} + \frac{6-1}{25} = 7.2$$

Repeaters for Signal Transmission

Transmission Loss

Definition (Transmission Loss)

The loss $\mathcal{L}$ in signal transmission is defined as the ratio of the input (transmit) power to the output (receive) power as

$$\mathcal{L} = \frac{P_T}{P_R} \equiv \mathcal{L}_{dB} = 10\log_{10}(\mathcal{L}) = 10\log_{10}(P_T) - 10\log_{10}(P_R)$$

Transmission Loss

Example (Coaxial cable loss)

If the loss per kilometer is 2 dB at the frequency operation of a coaxial cable, its transmission loss after 10 km is $\mathcal{L} = 100 \equiv 20$ dB.

Example (Free space loss)

The free-space path loss for a signal transmitted at $f = 1$ MHz over distances of $d = 10$ km is

$$\mathcal{L} = (\frac{4\pi d}{\lambda})^2 = (\frac{4\pi df}{c})^2 = (\frac{4\pi \times 10000 \times 10^6}{3 \times 10^8})^2 = 175450 \equiv 52.44 \text{ dB}$$

Transmission Loss

Definition (Analog Repeaters)

Analog repeaters are in-line amplifiers used to boost the signal level and thus, to offset the effect of transmission loss.

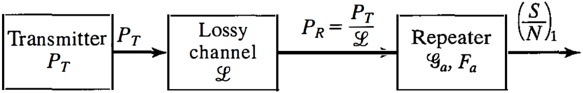

Figure: A communication system employing a repeater to compensate for channel loss.

$$(\frac{S}{N})_1 = \frac{1}{F_a}\frac{P_T/\mathcal{L}}{N_0 B_{neq}} = \frac{1}{F_a\mathcal{L}}\frac{P_T}{N_0 B_{neq}}$$

✓ The cascade of a lossy transmission line and a repeater is equivalent to an amplifier with the noise figure $F_a\mathcal{L}$ and the gain $\mathcal{G}_a/\mathcal{L}$.

Noise Figure

Statement (Cascade of Repeaters and Lossy Lines)

The overall noise figure of a cascade of n segments of lossy lines and repeaters is

$$F = F_{a1}\mathcal{L}_1 + \frac{F_{a2}\mathcal{L}_2 - 1}{\mathcal{G}_{a1}/\mathcal{L}_1} + \cdots + \frac{F_{an}\mathcal{L}_n - 1}{\mathcal{G}_{a1}/\mathcal{L}_1\mathcal{G}_{a2}/\mathcal{L}_2 \cdots \mathcal{G}_{a(n-1)}/\mathcal{L}_{n-1}}$$

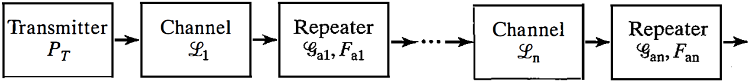

Figure: A communication system employing repeater.

✓ When the segments are identical and the repeaters compensates for transmission losses, $F = nF_a\mathcal{L} - (n-1) \approx nF_a\mathcal{L}$.

Noise Figure

Example (Required transmit power)

A signal with the bandwidth 4 kHz is to be transmitted a distance of 200 km over a wireline channel that has an attenuation of 2 dB/km. $P_T = 5 \times 10^{26}$ W $\equiv 267$ dBW is required to achieve an SNR of $(S/N)_{odB} = 30$ dB at the output of the receiver amplifier that has noise figure $F_{adB} = 5$ dB, where the noise equivalent bandwidth of the repeater is $B_{neq} = 4$ kHz and $N_0 = 4 \times 10^{-21}$ W/Hz.

$$(\frac{S}{N})_o = \frac{1}{F_a \mathcal{L}}(\frac{S}{N})_i = \frac{1}{F_a \mathcal{L}} \frac{P_T}{N_0 B_{neq}} \Rightarrow P_T = F_a \mathcal{L} N_0 B_{neq} (\frac{S}{N})_o$$

$$P_{TdBW} = 10 \log_{10}(N_0 B_{neq}) + F_{adB} + \mathcal{L}_{dB} + (\frac{S}{N})_{odB}$$

$$P_{TdBW} = -168 + 5 + 400 + 30 = 267$$

Noise Figure

Example (Required transmit power)

A signal with the bandwidth 4 kHz is to be transmitted a distance of 200 km over a wireline channel that has an attenuation of 2 dB/km. $P_T = 10^{-10}$ W $\equiv -100$ dBW is required to achieve an SNR of $(S/N)_{odB} = 30$ dB at the output of the receiver amplifier that has noise figure $F_{adB} = 5$ dB, when a repeater with a gain of 20 dB and a noise figure of $F_{adB} = 5$ dB is inserted every 10 km and the noise equivalent bandwidths of the repeaters is $B_{neq} = 4$ kHz and $N_0 = 4 \times 10^{-21}$ W/Hz.

$$(\frac{S}{N})_o \approx \frac{1}{nF_a\mathcal{L}}(\frac{S}{N})_i = \frac{1}{nF_a\mathcal{L}}\frac{P_T}{N_0 B_{neq}} \Rightarrow P_T \approx nF_a\mathcal{L}N_0 B_{neq}(\frac{S}{N})_o$$

$$P_{TdBW} \approx 10\log_{10}(N_0 B_{neq}) + 10\log_{10} n + F_{adB} + \mathcal{L}_{dB} + (\frac{S}{N})_{odB}$$

$$P_{TdBW} \approx -168 + 13 + 5 + 20 + 30 = -100$$

The End