Communication channel model

Goal

The goal of this experiment is to become familiar with the definition of channel model and the effect of the channel model on the transmitted signal both in the time and the frequency domain.

Theory

Communicating data from one location to another requires some form of pathway or medium. These pathways, called communication channels, use two types of media: cable (twisted-pair wire, cable, and fiber-optic cable) and broadcast (microwave, satellite, radio, and infrared). Cable or wire line media use physical wires of cables to transmit data and information. Twisted-pair wire and coaxial cables are made of copper, and fiber-optic cable is made of glass.

The simplified block diagram of any communication system can be presented by Figure 1:

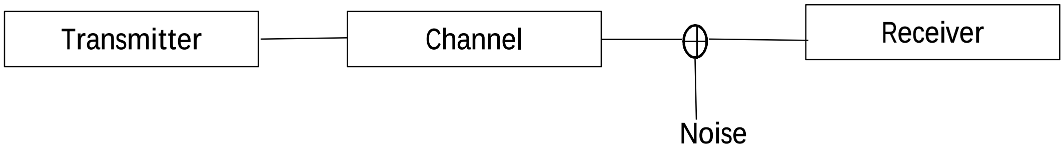

Figure 1. Block diagram of communication systems

As it is seen in Figure 1, in order to model the whole transmission environment, the transmitted signal first passes through the channel and then, noise is added to the signal. In communication systems, noise is an error or undesired random disturbance of a useful information signal in a communication channel. The noise is a summation of unwanted or disturbing energy from natural and sometimes man-made sources. Noise is, however, typically distinguished from interference, for example in the signal-to-noise ratio (SNR), signal-to-interference ratio (SIR) and signal-to-noise plus interference ratio (SNIR) measures. Noise is also typically distinguished from distortion, which is an unwanted systematic alteration of the signal waveform by the communication equipment, for example in the signal-to-noise and distortion ratio (SINAD). Various types of noise are:

1. **Thermal noise**

Johnson–Nyquist noise (sometimes thermal, Johnson or Nyquist noise) is unavoidable, and generated by the random thermal motion of charge carriers (usually electrons), inside an electrical conductor, which happens regardless of any applied voltage.

Thermal noise is approximately white, meaning that its power spectral density is nearly equal throughout the frequency spectrum. The amplitude of the signal has very nearly a Gaussian probability density function. A communication system affected by thermal noise is often modeled as an additive white Gaussian noise (AWGN) channel.

The root mean square (RMS) voltage due to thermal noise ϑ_n, generated in a resistance R (ohms) over bandwidth Δf (hertz), is given by

$$\vartheta_n = \sqrt{4K_BTR\Delta f} \; (1)$$

where K_B is Boltzmann's constant (joules per kelvin) and T is the resistor's absolute temperature (kelvin).

As the amount of thermal noise generated depends upon the temperature of the circuit, very sensitive circuits such as preamplifiers in radio telescopes are sometimes cooled in liquid nitrogen to reduce the noise level.

2. Shot noise

If electrons flow across a barrier, then they have discrete arrival times. Those discrete arrivals exhibit shot noise. The output of a shot noise generator is easily set by the current. Typically, the barrier in a diode is used.

Shot noise in electronic devices results from unavoidable random statistical fluctuations of the electric current when the charge carriers (such as electrons) traverse a gap. The current is a flow of discrete charges, and the fluctuation in the arrivals of those charges creates shot noise. Shot noise is similar to the noise created by rain falling on a tin roof. The flow of rain may be relatively constant, but the raindrops arrive discretely.

The root-mean-square value of the shot noise current i_n is given by the Schottky formula

$$i_n = \sqrt{2I_q\Delta B} \;\; (2)$$

where I is the DC current, q is the charge of an electron, and ΔB is the bandwidth in hertz.

The shot noise assumes independent arrivals. Vacuum tubes have shot noise because the electrons randomly leave the cathode and arrive at the anode (plate). A tube may not exhibit the full shot noise effect: the presence of a space charge tends to smooth out the arrival times (and thus reduce the randomness of the current).

Conductors and resistors typically do not exhibit shot noise because the electrons thermalize and move diffusively within the material; the electrons do not have discrete arrival times. Shot noise has been demonstrated in microscopic resistors when the size of the resistive element becomes shorter than the electron-phonon scattering length.

3. Flicker noise

Flicker noise, also known as 1/f noise, is a signal or process with a frequency spectrum that falls off steadily into the higher frequencies, with a pink spectrum. It occurs in almost all electronic devices, and results from a variety of effects, though always related to a direct current.

4. Burst noise

Burst noise consists of sudden step-like transitions between two or more levels (non-Gaussian), as high as several hundred microvolts, at random and unpredictable times. Each shift in offset voltage or current lasts for several milliseconds, and the intervals between pulses tend to be in the audio range (less than 100 Hz), leading to the term popcorn noise for the popping or crackling sounds it produces in audio circuits.

5. Transit-time noise

If the time taken by the electrons from traveling from emitter to collector becomes comparable to the period of the signal being amplified, that is, at frequencies above VHF and beyond, so-called transit-time effect takes place and noise input admittance of the transistor increases. From the frequency at which this effect becomes significant it goes on increasing with frequency and quickly dominates over other terms.

The noise that is considered to be added to the signal in communication systems is that thermal noise which is modeled as additive white Gaussian noise (AWGN). Since this noise is completely random, it contains all the frequencies as it is indicated in Figure 2.

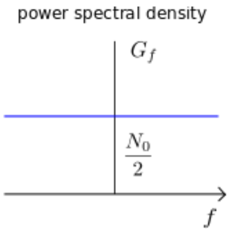

Figure 2. AWGN noise contains all the frequencies

Communication channels can be modeled as various types and each type has its own mathematical model both in the time and frequency domains. In the following, some types of channel models are briefly discussed. In the remainder of this instruction, x(t), y(t), h(t) and n define the transmitted signal, the received signal, channel impulse response and noise all in the time domain. In addition, X(f), Y(f), H(f) and N define the transmitted signal, the received signal, channel impulse response and noise all in the frequency domain.

1. Ideal channel

If signal is passed through an ideal channel, the received signal would be exactly the same as the transmitted signal, y(t)=x(t) and Y(f)=X(f). This scenario is impossible since the transmitted signal needs some time in order to reach to the transmitter. In addition, in wireless communication conditions, the attenuation of the transmitted signal in a loss free environment is proportional to the square of the distance between the transmitter and the receiver. As a result what we mean by an ideal channel is the one that only delays and attenuates the transmitted signal. The delayed and attenuated version of a signal is presented in Figure 3.

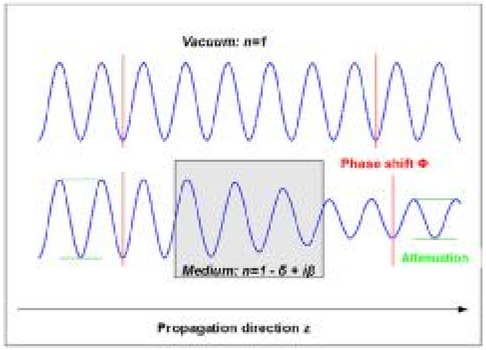

Figure 3. The bottom signal is the delayed and attenuated version of the upper signal after passing through the medium

The relation between the transmitter and the receiver in an ideal channel in the time domain is represented as:

$$y(t) = x(t) * h(t) = kx(t - \tau) \ (3)$$

where k and τ are attenuation and delay of the channel respectively. In the frequency domain we will have:

$$Y(f) = H(f).X(f) = kX(f).e^{j2\pi f\tau} \ (4)$$

Any other type of a channel is a non-ideal channel. In the following, some examples of non-ideal channels are briefly reviewed.

2. Filtering channels

Any environment (like air, cox cables, fiber optics, etc.), would only be able to pass specific frequency band of a signal. Based on the frequency band that the channel can pass, various types of channels would be defined as: Low Pass, High Pass, Band Pass and Band Stop. These types are indicated in Figure 4:

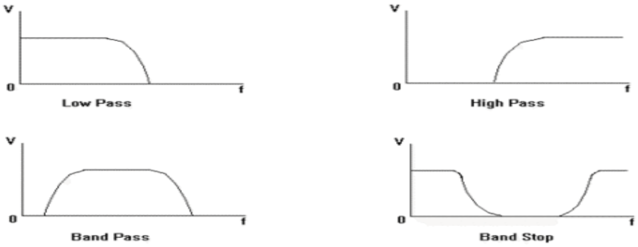

Figure 4. Various types of filtering channels

The effect of low pass and high pass filters on a typical signal are illustrated in Figure 5.

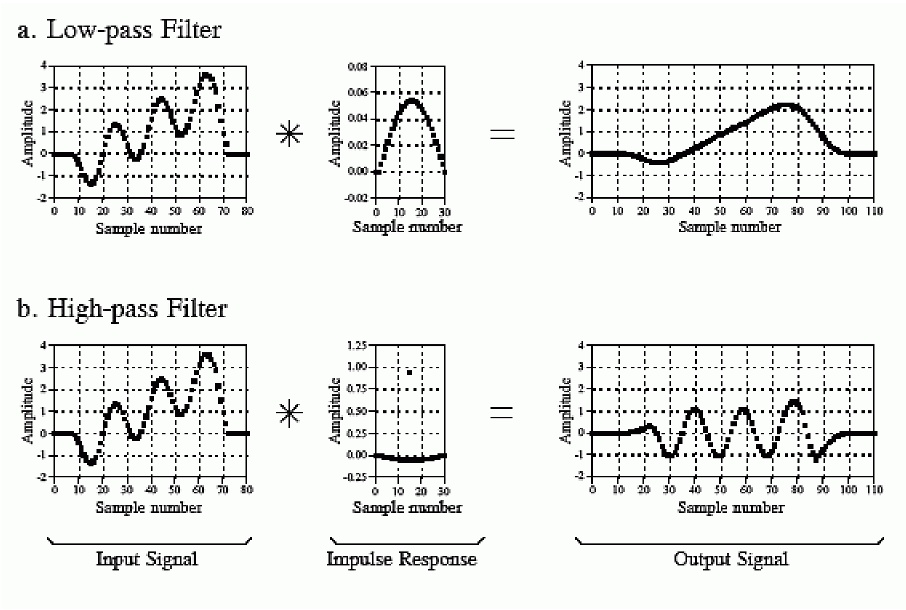

Figure 5. Effect of the low pass and high pass filters on a typical signal

As it is observed in Figure 5, low pass filter omits the fast variations of the signal and keeps the smooth variations. In contrast, high pass filter, keeps the fast variation of the transmitted signal and omits the smooth variation.

Filtering channels can be described in the frequency domain appropriately. Various types of filters can be presented as:

$$H_{low-Pass}(f) = 1 - U(f - f_{low-pass})$$

$$H_{High-Pass}(f) = U(f - f_{High-pass})$$

$$H_{Band-Pass}(f) = U\left(f - f_{low-pass}\right) - U(f - f_{High-pass})$$

$$H_{Band-Stop}(f) = 1 - \left(U\left(f - f_{low-pass}\right) - U\left(f - f_{High-pass}\right)\right)$$

(5)

where U defines the step function, $f_{low-pass}$ is the cutoff frequency for low pass filter and $f_{High-pass}$ is the start frequency for high pass filter.

3. Multipath fading channels

In a crowded environment, the transmitted signal can reach to the receiver from various paths. Therefore, various replicas of the transmitted signal arrives to the receiver and they interfere with each other at the receiver. An example of the multipath environment is indicated in Figure 6.

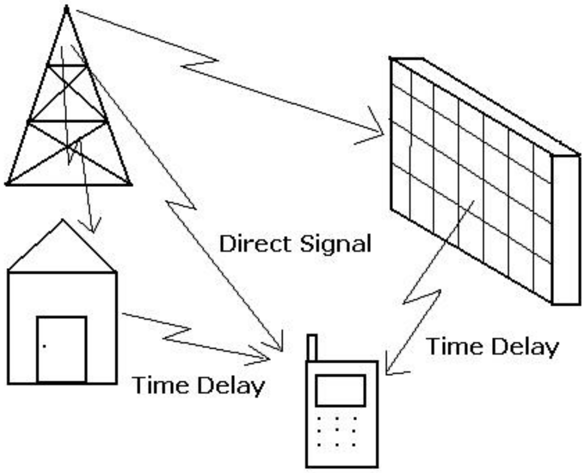

Figure 6. The transmitted signal reach to the receiver from various paths

In Figure 7, it is indicated that how the summation of the shifted version of a signal causes interference at the receiver.

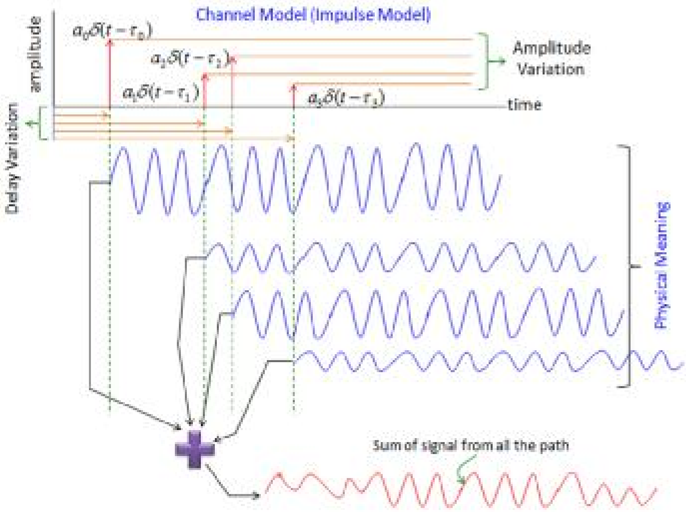

Figure 7. The summation of the shifted version of a signal causes interference

Multipath fading channels can be described in the time domain appropriately. In the time domain, the relation between the transmitted signal and the received signal is described as follows:

$$y(t) = x(t) * h(t) = k_1 x(t-\tau_1) + k_2 x(t-\tau_2) + \cdots k_L x(t-\tau_L) \quad (6)$$

where k_1, k_2, … k_L are the attenuation of each path, τ_1, τ_2, … τ_L are the delay of each path and L is the number of paths.

Equation (6) is defined by using the power delay profile (PDP) of $h(t)$. PDP gives the intensity of a signal received through a multipath channel as a function of time delay. The time delay is the difference in travel time between multipath arrivals. The abscissa is in units of time and the ordinate is usually in decibels. It is easily measured empirically and can be used to extract certain channel's parameters such as the delay spread. Put it in simpler words, PDP defines the power and time distribution of the impulse response of a channel.

Any PDP is defined by the amplitude distribution and the delay distribution of the paths. Usually, time arrival of the paths obey Poisson distribution. The most familiar power distributions are Rician and Rayleigh which are used for line of sight (LOS) and non-line of sight conditions respectively. In LOS scenarios, the signal travels from the transmitter to the receiver directly. As a result, it is more probable that it contains a higher amplitude in comparison to the NLOS scenarios. Therefore, the signal's amplitude is defined by Rician distribution which considers more probability of having a higher amplitude. In contrast, in NLOS scenarios, in which the signal reaches to the receiver after hitting to the obstacles and being attenuated, the power of the signal obeys Rayleigh distribution. It means that the higher amplitude is less probable in NLOS scenarios.

It is important to notice that all the communication channels have filtering characteristics because all the environments are only able to pass specific range of frequencies. As a result, a channel might be multipath fading or not but it is always a filtering channel.

4. Nonlinear channels

All the channels that have been considered up to now, are linear channel. It means that the received signal is a linear combination of the transmitted signal. Nonlinear channel model is also probable in communication systems. One example of a nonlinear channel is the channel that multiply the transmitted signal to itself. In the time domain we have:

$$y(t) = x(t)^2 \quad (7)$$

and in the frequency domain we will have:

$$Y(f) = X(f) * X(f)$$

The nonlinear channels are really undesirable since they make the reconstruction of the transmitted signal challenging.

Pre-lab:

Use LT-Spice for the simulation of the circuits in Figures 7-10.

Experiment

In this section, the generation of the lab model for the discussed channel models is presented. In addition, the effect of the generated channel on a typical signal both in the time domain and the frequency domain is studied.

T1. Generate a 1 KHz 2 V p-p square signal with signal generator. We will call this signal $V_{sig.}$ This would be our input data. Tune the time division of the oscilloscope in order to indicate one period of the signal. Observe the FFT of this signal on oscilloscope.

T2. Generate a 1 MHz 0.2 V p-p sine signal with signal generator. We will call this signal V_{noise}. This will simulate our noise signal.

T3. Settle the following circuit. It simulates the ideal channel.

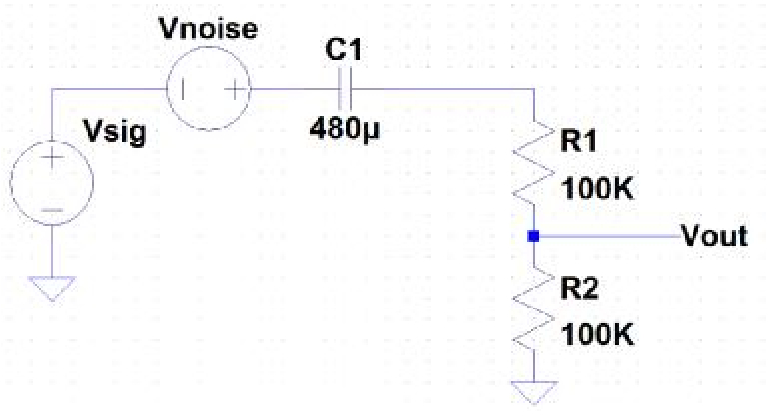

Figure 7. Circuit for the simulation of an ideal channel

T4. Observe V_{out} both in the frequency domain and the time domain.

T5. Change the frequency of the V_{sig} to 100 KHz. Settle the following circuit. It simulates the HPF channel.

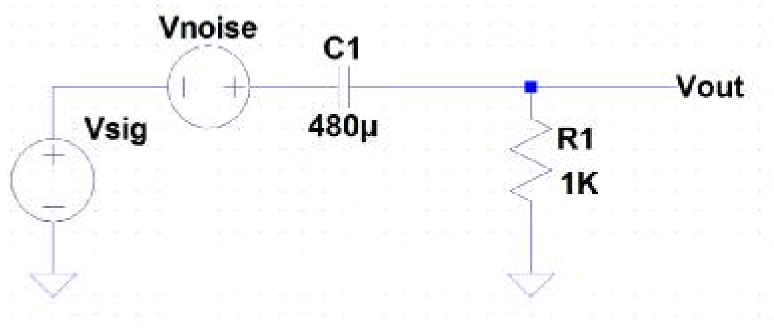

Figure 8. Circuit for the simulation of a HPF channel

T6. Change the value of the resistor, 1KΩ, 10 KΩ, 100 KΩ and 1MΩ. Observe the effect of changing the resistor on V_{out} both in the frequency domain and the time domain.

T7. Settle the following circuit. It simulates the LPF channel.

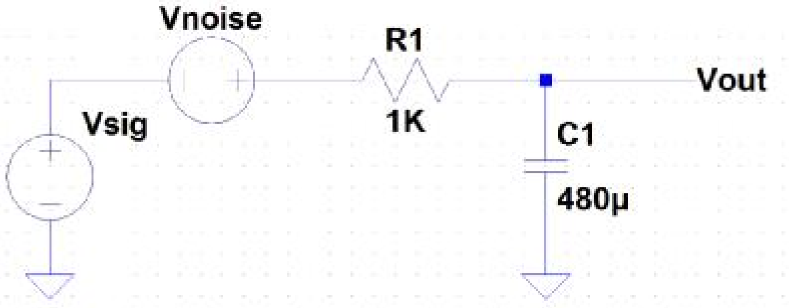

Figure 9. Circuit for the simulation of a LPF channel

T8. Change the value of the resistor, 1KΩ, 10 KΩ, 100 KΩ and 1MΩ. Observe the effect of changing the resistor on V_{out} both in the frequency domain and the time domain.

T9. Settle the following circuit. It simulates the multipath fading channel.

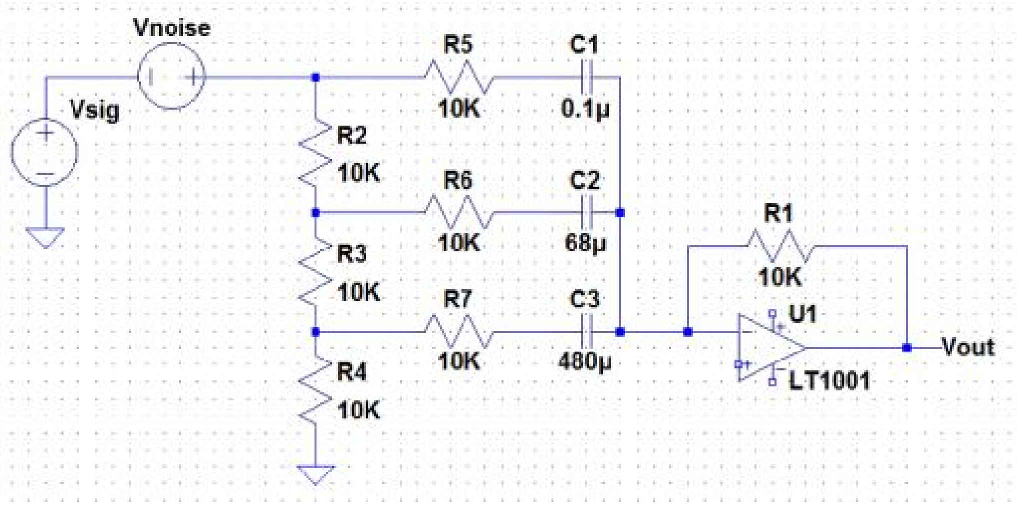

Figure 10. Circuit for the simulation of a multipath fading channel

T10. Observe V_{out} both in the frequency domain and the time domain.

T11. Use TIMS for this task. Make the connections as in Figure 11. This circuit simulates a nonlinear channel.

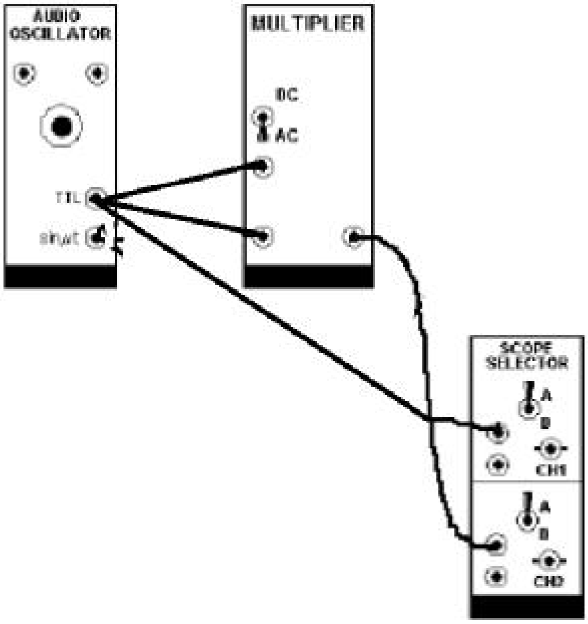

Figure 11. Circuit for the simulation of a nonlinear channel

T12. Observe the output of multiplier both in the frequency domain and the time domain.

Tutorial questions

Q1. Explain how each of the proposed circuit schematics in the experiment section simulates the channel model?

Q2. Why the frequency of the V_{sig} is changed to 100 KHz in T5?

Q3. Can you propose circuits for band pass and band stop channels?

Q4. What is the usage of OP-Amp in Figure 10?

Q5. What is wrong with the noise that we have generated in this experiment?

Q6. Can you propose a circuit for generating appropriate noise?

Q7. Calculate path amplitudes and delays analytically in Figure 10.

Proposed term project:

Design a circuit for the simulation of Rayleigh fading channel with three taps.