Audio Transmission via Digital Modulation

Aim : - the project is to simulate the entire process of audio transmission using Binary Phase-Shift Keying (BPSK) digital modulation over a simulated Additive White Gaussian Noise (AWGN) communication channel.The goal is to demonstrate the fundamental steps of digital communication, including analog-to-digital conversion, modulation, noise contamination, and signal recovery, while quantifying the system's performance using the Bit Error Rate (BER).

Materials Required : -

- Google Collab (for Python execution)
- Python 3.x
- Libraries: numpy, Pillow (PIL), matplotlib, os, random
- Libraries like numpy, scipy.io.wavfile, matplotlib, pydub, tqdm, ffmpeg
- Any Computer/Laptop with a working Microphone (for initial audio recording)

Theory : -

Audio Transmission via Digital Modulation involves converting an analog audio signal into a binary data stream, using digital modulation techniques to map this stream onto a carrier wave, transmitting it over a noisy channel, and finally reconstructing the original audio at the receiver.

The system is fundamentally divided into two major theoretical blocks: **Analog-to-Digital Conversion (ADC)** and **Digital Transmission (Modulation/Demodulation)**.

1. Source Digitization: Pulse Code Modulation (PCM)

The first step is to transform the continuous analog audio signal into a discrete digital bit sequence, a process typically achieved using Pulse Code Modulation (PCM). This process involves three sequential sub-steps:

A. Sampling

The continuous audio signal x(t) is sampled at uniform time intervals, Ts.

- **Principle:** The Nyquist–Shannon Sampling Theorem states that to perfectly reconstruct an analog signal from its samples, the sampling frequency (fs=1/Ts) must be at least twice the maximum frequency component (fmax) of the signal.
- **Formula:** fs≥2fmax.
- **Audio Application:** For high-fidelity audio (audible range up to 20 kHz), the standard CD sampling rate is 44.1 kHz.

B. Quantization

The amplitude of each discrete time sample is mapped to the nearest of a finite set of discrete amplitude levels.

- **Process:** If L is the number of quantization levels (where L=2n and n is the number of bits per sample), the continuous amplitude range is divided into L zones.
- **Error:** This mapping introduces a rounding error called quantization noise (Nq). The quality of the digitized audio is measured by the Signal-to-Quantization Noise Ratio (SQNR), which improves exponentially with the number of bits (n) used.

C. Encoding (Coding)

Each quantized level is converted into a unique n-bit binary code word (e.g., a sample quantized to level 5 might be encoded as 0101 in a 4-bit system). The output is the raw digital bit stream ready for transmission.

2. Digital Modulation and Transmission

The binary stream is converted into an analog waveform suitable for transmission across the communication channel.

A. Digital Modulation

This technique shifts the frequency, phase, or amplitude of a high-frequency carrier signal based on the input digital data.

- **BPSK (Binary Phase Shift Keying):** The simplest form, where a binary '1' is represented by a carrier signal with a 0∘ phase shift and a binary '0' is represented by a 180∘ phase shift.
  - *Mathematical Representation:* A bit bk∈{−1,+1} is mapped to a transmitted signal s(t)=A⋅bk⋅cos(2πfct).
- **QPSK (Quadrature Phase Shift Keying):** This method maps two bits (a 'dibit') simultaneously to one of four possible phase shifts (45∘,135∘,225∘,315∘). QPSK effectively doubles the bit rate for a given bandwidth compared to BPSK.

B. Channel Modeling

The simulated environment for transmission is typically represented by the Additive White Gaussian Noise (AWGN) channel.

- **AWGN:** This model represents thermal noise present in all electronic circuits.
  - **Additive:** The noise is simply added to the transmitted signal.
  - **White:** The noise has uniform power across all frequencies.
  - **Gaussian:** The amplitude of the noise follows a normal (Gaussian) probability distribution.

3. Performance Analysis: BER vs. Eb/N0

The performance of the digital communication system is assessed by measuring how reliably the receiver can recover the transmitted bits.

A. Bit Error Rate (BER)

The BER is the ratio of the number of erroneous bits received (Number of Bit Errors) to the total number of bits transmitted (Total Bits Sent). It is the primary metric for system quality.

BER=Total Bits SentNumber of Bit Errors

B. Energy per Bit to Noise Ratio (Eb/N0)

This ratio, expressed in decibels (dB), is the most fundamental measure of signal quality in a digital link. It represents the ratio of the energy utilized to transmit a single bit (Eb) to the noise power spectral density (N0).

C. Theoretical BER for BPSK

For a coherent BPSK system operating over an AWGN channel, the theoretical BER is given by the Q-function (or Complementary Error Function):

The theoretical benchmark against which the performance of any simulated or practical digital communication system, including audio transmission, is measured. As the Eb/N0 increases (better signal quality), the BER decreases (fewer errors), leading to a higher fidelity audio reconstruction.

Key Features : -

The simulation highlights the core features of digital modulation:

- **Quantifiable Performance (BER)** : The system reports the Bit Error Rate (BER), which is the ratio of incorrectly received bits to the total number of bits transmitted. This is the definitive metric for the reliability of a digital communication link.

- **Robustness to Noise** : The BPSK scheme, demonstrated by the system's ability to maintain a low BER even with moderate noise (low SNR), is one of the most power-efficient forms of digital modulation, meaning it performs well in low-power or high-noise environments.

- **Spectral Efficiency** : The use of a high-frequency Carrier Frequency (4000 Hz in this simulation) allows the low-frequency audio signal to be efficiently transmitted through a specific frequency band, which is a key requirement for multi-user wireless systems.

Application : -

The principles demonstrated are fundamental to any modern system that transmits digitized information over a radio channel:

- **Wireless Data Links**: The underlying technology for digital data and voice transmission in applications like Bluetooth and short-range IoT (Internet of Things) devices.

- **Satellite Communication**: BPSK and its variants are crucial for maintaining links in long-distance satellite systems where the signal power is limited and noise is a significant factor.

- **Digital Telemetry:** Reliable transmission of measurement data (e.g., from scientific sensors) where low power consumption and robust links are essential.

Conclusion : -

The BPSK simulation provides a successful, hands-on model of Audio Transmission via Digital Modulation. It effectively illustrates that by converting an analog signal into a discrete digital format and using phase-shift keying, communication systems gain the ability to quantifiably manage noise and maintain signal quality. The reported Bit Error Rate (BER) serves as a clear indicator of system performance in a noisy environment. Ultimately, the project validates that digital modulation is the indispensable core technology enabling the robust, reliable, and high-quality audio and data transmission that defines all modern communication systems.

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