Information Technology
Inside and Outside
- David Cyganski & John A. Orr

V. Bandwidth and Information Theory

12. Digital Audio

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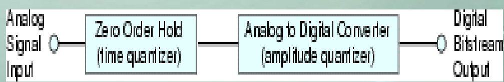
12. Digital Audio

- Objectives:
  - the concept that a digital signal must be represented by a series of integers, each of finite length;
  - the process of quantization by which each sample of an analog signal is approximated by an integer of a given length;
  - the concept of an analog-to-digital converter that performs sampling and quantization;
  - the concept of quantization noise and the trade-off between fidelity ante number of bits used to represent the integer value of each sample; and
  - the process of digital-to-analog conversion by which the digital signal is converted back to analog form for use by humans.

12.2 Digitization of Audio Samples

- **Digitization processes**
  - To be discrete in time by **sampling**
  - To be discrete in amplitude by **quantization**
- **The sampling process**: at a rate equal to or greater than the minimum, or **Nyquist, sampling rate** to retain all of the information in the original signal. For a signal bandlimited to a highest frequency content of ***B* Hz**, this means we must take **at least 2*B* samples per second**.
- ***Quantization*** : be discretized in amplitude to allow a digital representation ➔ ***analog-to-digital converters*** **(ADCs)**
- ***N* bits** can be arranged in $\mathbf{2^N}$ **different patterns**; this means if we use ***N*** bits to represent each audio sample, then each sample can represent any one of 2^N different audio signal amplitudes.

Figure 12.1: The two-step sampling process.



12.3 The Process of Quantization

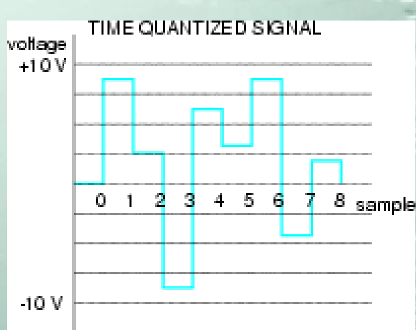
- Some amount of error based on a trade-off, or compromise, between performance (in this case audio quality) and cost (in this case, equipment, storage, and processing speed).

Figure 12.2: A time quantized audio wave form.

- $\mathbf{2^4 = 16}$ **different** binary code words

$$\frac{10-(-10)}{16} = 1.25 \text{ V}.$$

- Assign one of the 16 codewords (0000 through 1111)



12.3 The Process of Quantization(2)

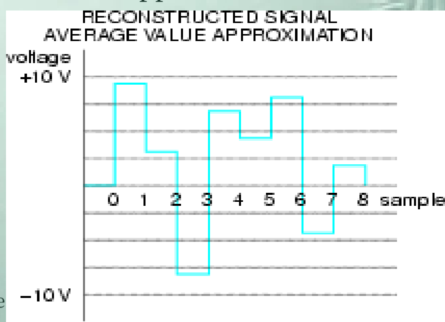
- **Table 12.1:** Quantization Codes and Quantized Values

Range	Code	Range Center
$8.75 \rightarrow 10.0$	1111	9.375
$7.50 \rightarrow 8.75$	1110	8.125
$6.25 \rightarrow 7.50$	1101	6.875
$5.0 \rightarrow 6.25$	1100	5.625
$3.75 \rightarrow 5.0$	1011	4.375
$2.50 \rightarrow 3.75$	1010	3.125
$1.25 \rightarrow 2.50$	1001	1.875
$0.0 \rightarrow 1.25$	1000	0.625
$-1.25 \rightarrow 0.0$	0111	-0.625
$-2.5 \rightarrow -1.25$	0110	-1.875
$-3.75 \rightarrow -2.5$	0101	-3.125
$-5.0 \rightarrow -3.75$	0100	-4.375
$-6.25 \rightarrow -5.0$	0011	-5.625
$-7.5 \rightarrow -6.25$	0010	-6.875
$-8.75 \rightarrow -7.5$	0001	-9.375
$-10.0 \rightarrow -8.75$	0000	9.375

12.4 Quantization Noise

- **Quantization →** each sample value takes on the mean value within its interval. Given this understanding of how we will have to attempt to ``undo" the effects of quantization.
- The difference between the original sample value and this rounded value is called the ***quantization error***
- Quantization error is also referred to as ***quantization noise***
- ***signal-to-noise ratio, or SNR***. The higher the SNR, the smaller the average error is with respect to the signal value, and the better the fidelity of the reconstructed signal can be.

Figure 12.3: The reconstructed sample with average value approximation.



12.5 Adding Up the Bits: Home CD Players

- The **music** created at the recording studio must be **sampled and quantized** according to some standard specifications so that all CDs can be played using the same equipment.
- The standard value within the audio industry for the bandwidth, or highest frequency, of **a high fidelity audio signal is 20 kHz**.
- Thus, **the minimum (Nyquist) sampling rate is 40 kHz**, or 40,000 samples per second.
- Desirable to **over sample :** The standard sampling rate for digital audio is **44.1 kHz, 10% higher.**
- CD systems use 16 bits to represent each sample, meaning that each sample value will be represented by one of $2^{16} = 65,536$ different 16-bit codes. This would suggest that each channel of the audio stream is converted into bits at a rate of.

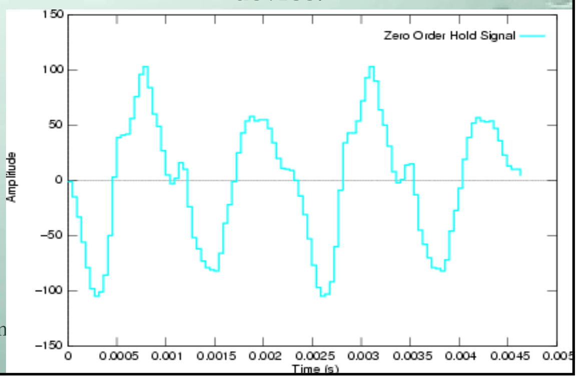
$$44{,}100 \text{ samples/sec} \times 16 \text{ bits/sample} = 705{,}600 \text{ bits/sec;}$$

- **a CD with 60 minutes of music** on it has 60 minutes x 60 seconds/minute x 44,100 samples/second x 16 bits/sample x 2 channels =**5,080,320,000 bits--over 5 billion bits**

12.6 Reconstruction

- Convert binary codewords back into voltage signal samples, using a device called a ***digital-to-analog converter*** **(DAC).** The DAC effectively reverses the process of analog-to-digital conversion performed by the quantization process.
- This process of digital-to-analog conversion is often accompanied by a technique known as a **zero order hold (ZOH),** which creates a **``staircase'' signal** that is continuous in time, but not a good representation of the original, smoother, audio signal.

Figure 12.4: An audio waveform that has been passed through a zero order hold device.

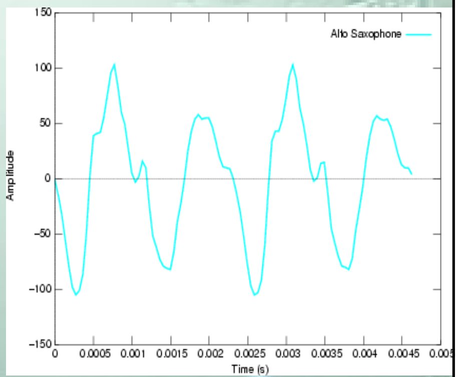


12.6 Reconstruction(2)

- Fortunately,it is a fairly straightforward matter to remove this **unwanted high-frequency information** without destroying the audio signal using a system known as a ***filter***.

- **The filter literally filters out, or removes, the unwanted frequency components from the ZOH signal**, much as an oil filter removes undesirable articles from your engine's lubricants. Moreover, just as the oil filter lets the cleaned oil through to the engine, the audio filter lets the desired audio frequency spectrum through, resulting in a reconstructed signal

Figure 12.5: The reconstructed audio signal.



12.7 Other Applications, and a Few Tricks

- Numerous applications of discretized audio signals
  - **Telephony** : Most telephone calls, including any which use equipment installed recently, are digitized and reconstructed during their transmission
  - **Satellite link** : Because digitized signals make more efficient use of system bandwidth, they are the choice for any application involving an expensive communication resource
  - **Encryption and encoding** : digital audio is used for military and other applications for which security is desired.
  - ***Commanding*** : minimize the effects of quantization noise on audio signals → improve the signal-to-noise ratio of a quantized signal without requiring additional bits for representation. This is accomplished by using non uniformly sized intervals for the voltage ranges, with smaller intervals used for small voltage values, and larger intervals for larger values.
  - ***Predict***