Companding

Sampling

Nyquist showed that a low-pass signal can be reconstructed exactly by low-pass filtering samples of the signal taken at a frequency that is at least twice the bandwidth of the signal.

Quantization Noise

In addition to sampling the signal at discrete time intervals, the voltage of each sample must be converted to a binary number.

Each number corresponds to a different voltage and therefore the continuous signal must be "rounded off" to the nearest discrete voltage level. This quantization operation is equivalent to adding a "quantization noise" signal to the un-quantized signal.

The voltage step between quantization levels for a b-bit A/D converter with input voltage range of $2V$ is $q = \frac{2V}{2^b}$.

The quantization error will be approximately uniformly distributed over the range q. The power (variance) of this uniformly distributed random variable will be $q^2/12$.

Adding one bit of resolution halves the size of the quantization steps and thus reduces the average quantization noise voltage by half and the average quantization noise power by a quarter (6 dB).

The quantization SNR is the ratio of signal power S to quantization noise power. In dB this is:

$$\mathrm{SNR} = \frac{S}{V^2} + 4.8 + 6b$$

.

For random signals such as speech the precise ratio of the signal power to quantization noise power (the quantization SNR) is difficult to calculate because the signal power depends on the probability distribution of the signal and because there is a trade-off between clipping distortion and quantization noise – increasing the signal level increases signal power but also increases clipping noise. In addition, companding (described below) can affect the quantization SNR.

Companding

The quantization noise power is a function of the step size while the signal power is a function of the signal voltage. Thus the quantization SNR is higher at higher input levels and lower at lower input levels. Companding, a combination of the words compressing and expanding, is a way to keep the quantization SNR approximately constant by (effectively) using small quantization steps for low signal levels and large quantization steps at high levels. Companding can be accomplished by using a non-linear amplifier before the A/D converter that has higher gain for low signal levels and less gain for high signal levels. An amplifier with the inverse gain function is then applied after the quantized signal is converted to a continuous signal.

PCM Standards

ITU-T standard G.711 defines defines the sampling rate (8 kHz $\pm$50ppm), signal bandwidth (300 to 3400 Hz), and two types of companding to be used for digital telephony (μ-law and A-law).

The μ-law companding curve is primarily used in North America and A-law is primarily used in Europe. Most hardware and software can be configured to use either.

For historical reasons this method of digitizing signals is called PCM (pulse code modulation). The hardware that converts the analog signal to/from digital format is often called a codec (coder-decoder) and is often integrated into the SLICs used in line cards.