Over the last 40 years, there has been continuous evolution in the design of voice-band modems – starting at a data rate of 300 bits per second in the late 1950s, a rate of 33,600 bits per second has been achieved in 1995. Realising such high data rates over the voice band of 3400 Hz is a remarkable feat, made possible by combining sophisticated techniques from three disciplines, communication theory, signal processing and information theory. In this article, we briefly describe certain advanced ideas, which led to data rates very close to the channel capacity limit, established by Shannon.

Introduction

In Part 1, we gave a brief introduction to voice-band modems and presented basic principles of data transmission. We pointed out that V.34 modems send nearly 10 bps (bits per second) per Hz which is very close to the channel capacity limit, often called the Shannon bound after the founder of information theory. In this article, we introduce the advanced ideas which made possible such high data rates.

Channel Capacity

Given a channel (a communication medium) of bandwidth $W$ Hz, one would like to know the maximum data rate (in bps) the channel can support. Shannon’s capacity formula for an ideal bandlimited, additive white Gaussian noise channel is
where $W$ is the channel bandwidth, $P_{av}$ is the average transmitted signal power and $N_0$ is the noise power spectral density (in Watts/Hz). When we say that the channel is ideal, its frequency transfer function (same as the frequency response), $H(f)$, is given by

\[
H(f) = \begin{cases} 
1 & |f| \leq W \\
0 & |f| > W.
\end{cases}
\] 

Additive white Gaussian noise (AWGN) channel means the noise added by the channel is white and Gaussian. A white Gaussian noise is the noise with uniform power distribution over all frequencies, and the samples of noise are Gaussian random variables. The ratio $\frac{P_{av}}{W N_0}$ is referred to as the signal-to-noise ratio (SNR).

Consider the capacity of an ideal channel given by (1). Though Shannon has established the capacity limit, he has not indicated the coding/modulation scheme which yields the bit rate equal to the capacity. For a given SNR, a practical modulation (i.e., the modulation used in practice) yields bit rates less than the value given by the capacity formula. In other words, with a practical modulation, one needs more SNR (i.e., more power in the signal) than what is specified by the formula to achieve the rate equal to the capacity at an acceptable bit error rate (i.e., fraction of the transmitted bits that are received incorrectly). This additional SNR is the so-called SNR gap, which may also be viewed as the SNR penalty that we have to pay with a practical modulation scheme. Figure 1 provides comparison of the bit rates that are possible with several modulation schemes on an ideal bandlimited AWGN channel at $10^{-5}$ symbol error probability (i.e., probability that a transmitted symbol is received incorrectly), and the channel capacity limit. Here, the channel capacity limit is given in bps/Hz as a