Technology Brief 30
Bandwidth, Data Rate, and Communication

In Section 9-4.1, we defined the ***bandwidth*** B of a resonant circuit as the frequency span over which power transfer through the circuit is greater than half of the maximum level possible. This common half-power (or -3 dB) definition for B can be extended to many devices, circuits, and transmission channels. But how does the everyday use of the word ***bandwidth*** refer to the data rate of a transmission channel, such as the rate at which your internet connection can download data?

Signal and Noise in Communication Channels

Every circuit (including switches, amplifiers, filters, phase shifters, rectifiers, etc.) and every transmission medium (air, wires, and optical fibers) operates with acceptable performance over some specific range of frequencies, outside of which ac signals are severely damped. The actual span of this operational frequency range is dictated by the physical characteristics of the circuit or transmission medium. One such example is the ***coaxial cable*** commonly used to connect a TV to a "cable network" or to an outside antenna. The coaxial cable is a high-fidelity transmission medium—causing negligible distortion or attenuation of the signal passing through it—so long as the carrier frequency of the signal is not much higher than about 10 GHz. The "cutoff" frequency of a typical coaxial cable is determined by the cable's distributed capacitance, inductance, and resistance, which are governed in turn by the geometry of the cable, the conductivity of its inner and outer conductors, and the permittivity of the insulator that separates them.

The ***MOSFET*** offers another example; in Section 5-7 we noted that the switching speed of a MOSFET circuit is limited by parasitic capacitances, setting an upper limit on the switching frequency that a given MOSFET circuit can handle. A circuit with a maximum switching speed of 100 ps, for example, cannot respond to frequencies greater than 1/100 ps (or 10 GHz) without distorting the output waveform in some significant way. Our third example is ***Earth's atmosphere***. According to **Fig. TF20-1** (in Technology Brief 20: The Electromagnetic Spectrum), the transmission spectrum for the atmosphere is characterized by a limited set of ***transmission windows***, with each window extending over a specific range of frequencies.

The overall effective bandwidth B of a communication system is determined by the operational bandwidths of its constituent circuits and the transmission spectra of the cables or other transmission media it uses. As we will see shortly, the channel capacity (or data rate) of the system is directly proportional to B, but it also is influenced by the intensity and character of the ***noise*** in the system. Noise is random power self-generated by all real devices, circuits, and transmission media. In fact, *any material at a temperature greater than* 0 K *(which includes all physical materials, since no material can exist at exactly* 0 K*) emits noise power all of the time.* **Figure TF30-1** illustrates how the noise generated by a circuit modifies the waveform of the signal passing through it. The input is an ideal sine wave, whereas the output consists of the same sine wave but with a fluctuating component added to it. The fluctuating component represents the noise generated by the circuit, which is random in polarity because the voltage associated with the noise fluctuates randomly between positive and negative values.

If we know both the power P_S carried by the signal and the average power P_N associated with the noise, we then can determine the ***signal-to-noise ratio*** (SNR):

$$\text{SNR} = \frac{P_S}{P_N}.$$

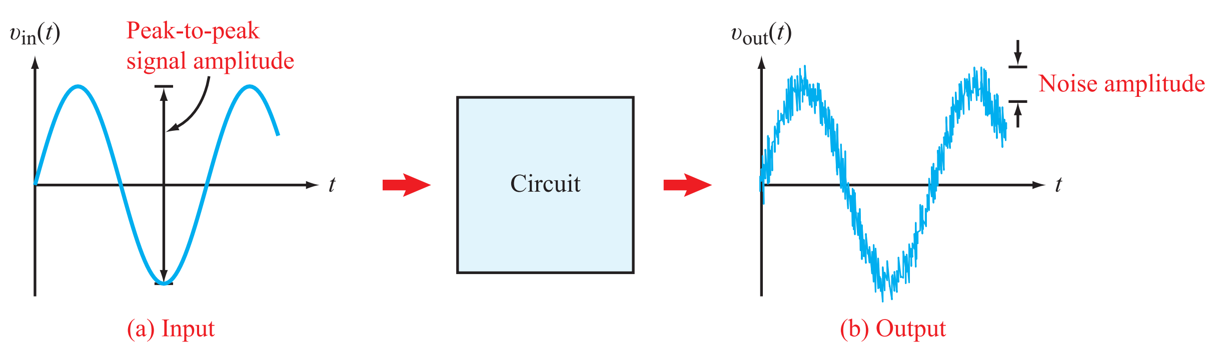

Figure TF30-1: The noise generated by the circuit adds a fluctuating component to the input signal.

Table TT30-1: Theoretical limits for data transmission capacity given typical SNR and channel bandwidth number for several common digital communication layers.

Physical Channel	Channel Capacity (C)	Typical SNR (P_S/P_N)	Bandwidth of Channel (B)
Analog phone line	~30 kbps	10^3	3000 Hz
802.11g Wifi	<60 Mbps	<10	20 MHz
100-BaseT Ethernet	100 Mbps	10^3	100 MHz
10 Gb/s Ethernet	10 Gbps	10^2	1600 MHz

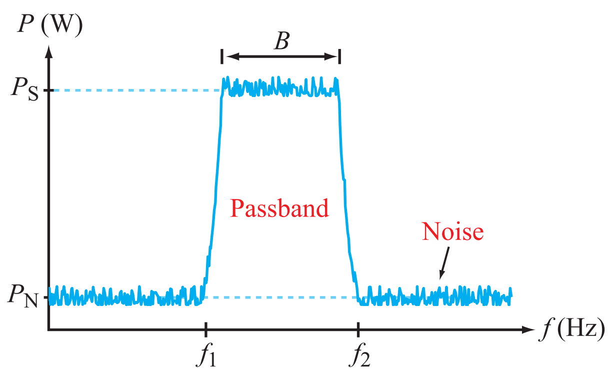

Figure TF30-2: Typical spectral response of a communication system with bandwidth B. The signal-to-noise ratio is given by P_S/P_N, where P_S and P_N are the average power levels of the signal and noise, respectively.

The bandwidth B and the SNR (**Fig. TF30-2**), jointly determine the highest data rate that can be transmitted reliably through a circuit or a communication system.

Shannon-Hartley Theorem

In the late 1940s and early 1950s, ***Claude Shannon***, building on earlier work by ***Harry Nyquist*** and ***Ralph Hartley***, developed a complete theory that established the limits of information transfer in a communication system. This seminal work represents the foundation of ***information theory*** and underlies all of the subsequent developments that shaped today's ***information revolution***, including the Internet, cell phones, satellite communications, and much more. Shannon's foundational work also has impacted the development of many related disciplines, including encryption, encoding, jamming, efficient use of frequency space, and even quantum-level information manipulations.

The ***Shannon-Hartley theorem*** defines how much data can be transferred through a channel (with no error) in terms of the bandwidth B and the SNR. It states that

$$C = B \log_2 \left(1 + \frac{P_S}{P_N}\right),$$

where C is the ***channel capacity*** (or ***data rate***) in bits/second (bps), B is the bandwidth in Hz, and P_S/P_N is the SNR. As an example, let us consider a communication channel with $B = 100$ MHz, $P_S = 1$ mW, and $P_N = 1\ \mu$W. The corresponding SNR is 1000, and the corresponding value of C is 996×10^6 bits/s or ~ 996 Mb/s. By way of comparison, a 100GbE Ethernet connection can operate at 100 Gbps (or approximately two orders of magnitude faster), a 100 Base-T Ethernet connection can manage a maximum rate of only 100 Mbps, 802.11 Wifi networks are rated at 54 Mbps, and the Bluetooth 2.0 protocol used by many portable devices is limited to 2.1 Mbps. The channel capacity of a conventional telephone used to support audio transmissions is only $\sim$33 kbps. **Table TT30-1** provides some theoretical limits for data transmission capacity given typical SNR and channel bandwidth number for several common digital communication layers. We should note that when people use the term "bandwidth" in everyday speech, they really mean channel capacity; B and C are directly proportional to one another, but they obviously are not the same quantity.

According to the expression for C, for a sufficiently high bandwidth, it is possible to achieve reasonably high data-transfer rates even when SNR < 1 ! The implication of this statement is that information can be transmitted reliably on channels whose noise levels exceed that of the signal, provided the signal is spread across a wide frequency spectrum. For example, with a bandwidth of 1 GHz, it is possible to transfer error-free data at a rate of 95 Mbps, even when SNR is only 0.1 (that is, with the signal power an order of magnitude smaller than the noise power). This is (in part) the basis for ***ultra-wideband*** communication schemes used in cell phones and GPS.