# Transmission Rates

DD Owned by David Cherney DISH •••
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## Terminology

**Definition**: The data rate of a transmission pathway is the number of bits sent per unit time.

This is also called bit rate, which makes reference to a particular unit of information.

**Definition:** The modulation rate of a communication pathway is the number of symbols send per unit time, regardless of the symbol sent.

**Definition:** A baud is a unit of modulation rate equal to one symbol per second.

For example, in QPSK one of the four symbols from the set {00,01,10,11} is sent at a rate $R=1/T_b$.

- The data rate is then 2R in dimensions of bits per time. The standard unit is  bits per second
- The modulation rate is R in dimension of symbols per second. The standard unit is called a baud, which is one symbol per second.

**Definition:** The bandwidth of a communication pathway is the range of frequencies used in that pathway.

For example, if a binary frequency modulation scheme uses the two frequencies 12kHz and 14kHz then the bandwidth of communication in that modulation scheme is 14kHz-12kHz = 2kHz.

The mathematician Claude Shannon proved that there is an upper limit to the data rate that can be transmitted using a bandwidth B. This upper limit is called the channel capacity, C. The limit depends on the ratio of the power of the signal S to the power of the noise N.

**Theorem:** The data rate without error for a communication pathway of bandwidth B with modulation scheme that has M symbols, given that the power of the signal is S and the power of the noise is N is, can not exceed

$$C:=B \log_2(1+S/N)\log_2(M).$$

**Definition:** The theoretical upper limit of data rate in Shannon's theorem is called error free channel capacity.

**Definition:** The maximum data rate that can be transmitted through a communication pathway is the throughput of that pathway.

Shannon's theorem states that the throughput of a communication pathway is always less than or equal to the error free channel capacity.

While Shannon's theorem on error free channel capacity makes a statement about theoretically maximum data rates, it gives no indication of how to build physical systems that meet these limits, and in practice data rates are much lower than this upper limit.

Note that a naive interpretation of Shannon's theorem is that channel capacity can be increased indefinitely by increasing signal strength S. However, in practice increasing signal strength also increases noise due to non-linearities in physical systems.  Another naive interpretation is that channel capacity increases indefinitely with number of symbols M. However, as modulation schemes become more complex, transmission without error becomes more difficult.

Nevertheless, Shannon's theorem makes clear the requirements of high bitrate communication: large bandwidth, large signal to noise ratio, and a modulation scheme with many symbols.

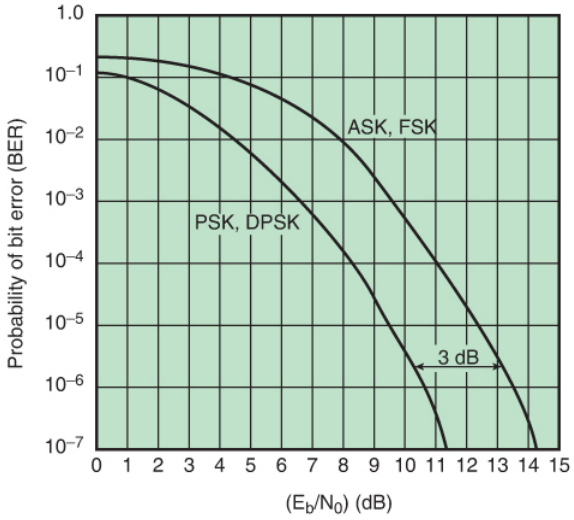
## Error Rates

While error free channel capacity is nicely characterized by signal to noise ratio, error rates are not. Another ratio allows more concise statements about error rates.

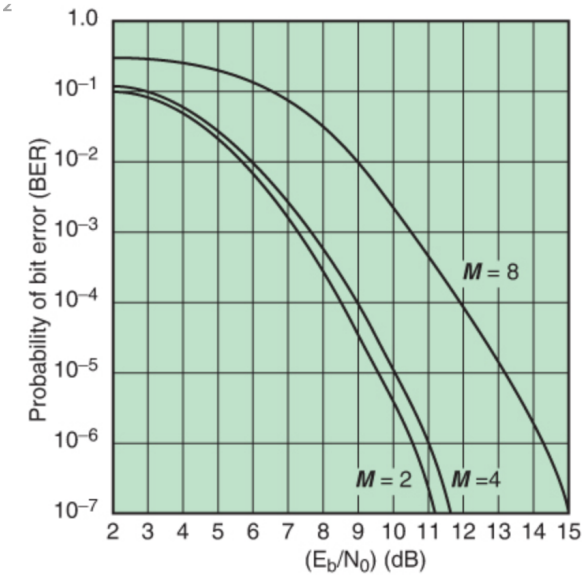
Let $E_b$ be the signal energy transmitted per bit transmitted. In terms of previously introduced signal power S, bit transmission period $T_b$, and its associated rate R=1/Tb, this new quantity $E_b=ST_b=S/R$.

Let $N_0$ be the noise energy per second time per frequency. In terms of the previously introduced noise power N, and bandwidth B, this new quantity $N_0=N/B$.

It is common to compare error rates in log scale to the log of the ratio Eb/N0 as in the diagram below. Note that a line on such a plot would indicate a power function relationship. The diagram shows that phase shift keying tends to have lower error rates at fixed values of the ratio than shift keying by amplitude or frequency.




Comparing the number of symbols used, the diagram shows that phase modulation schemes with more symbols have greater error rates.




## Supplementary Uplink

5G has a new feature; when additional uplink data rate capacity is needed, a supplementary uplink channel at a high frequency can be added. There are a few mechanisms for this, but carrier aggregation is the name of one mechanism to provide a supplementary uplink (SUL) channel.

## Pedantics

Reviewing definitions above:

- The term data rate describes the actual (recorded) rate of transmission.
- The term throughput refers to maximum (physically) possible data rate.
- The term error free channel capacity refers to maximum (theoretical) possible data rate.
- The term bandwidth refers to a range of frequencies.

Unfortunately, people sometimes use these terms interchangeably.

- use the term “bandwidth” to refer to the concept of ‘data rate’ .
- use the term “throughput” to refer to the concept of ‘data rate’.

Please avoid these confusing usages.