Computer Networks
Handout—Class 2

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1 Class Overview

- Representing digital data using EM signals.
- Spectrum, bandwidth, data-rate.
- Encoding: NRZ, NRZI.

2 Digital Signals and EM Signals

2.1 Approximation of digital signals as EM signals

Let $s_1(t) = \sin t$, $s_2(t) = \frac{1}{3}\sin 3t$, and $s_3(t) = \frac{1}{5}\sin 5t$. Now, consider:

$$\begin{aligned} s(t) &= s_1(t) + s_2(t) + s_3(t) \\ &= \sin t + \frac{1}{3}\sin 3t + \frac{1}{5}\sin 5t \end{aligned} \tag{1}$$

This function is plotted below.

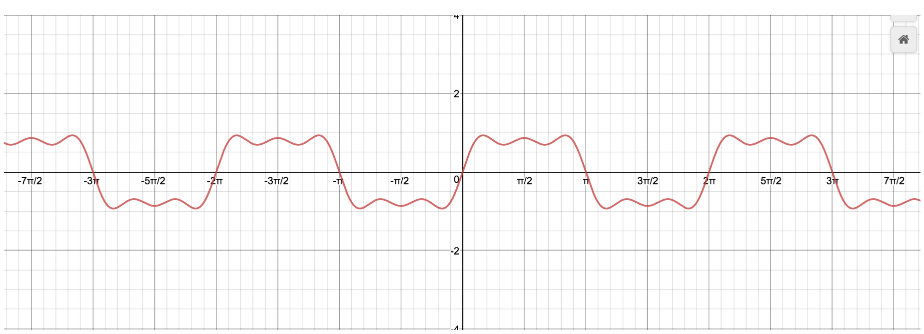

Figure 1: Plot of $s(t)$ from equation 1

If we keep on adding more and more similar terms (like $s_4(t) = \frac{1}{7}\sin 7t$) to the expression given in equation 1, **we get a better and better approximation** of periodic data (i.e. alternating 1s and 0s). This can be seen in figure 2 and can be compared with the plot in figure 1. The "higher" parts of the graph can be thought of as representing 1, and the "lower" parts 0.

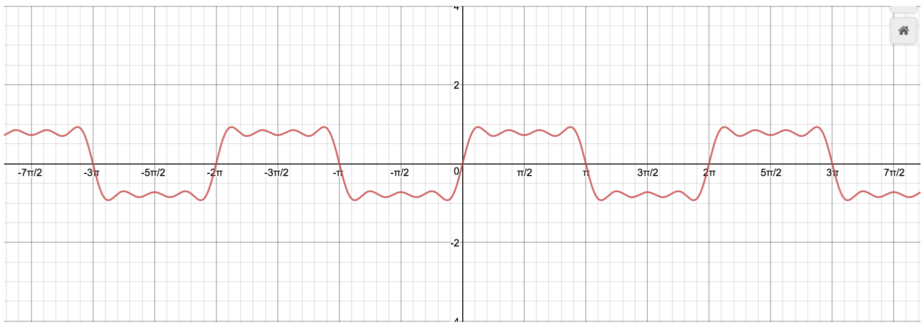

Figure 2: Wave with a higher bandwidth

It also is worth noting that although s_1, s_2 and s_3 have different frequencies individually ($f_1 = \frac{1}{2\pi}$, $f_2 = \frac{3}{2\pi}$, $f_3 = \frac{5}{2\pi}$ respectively), their sum s has $f = \frac{1}{2\pi}$, as can be seen in the plot in figure 1.

But how do we encode non-period non-trivial data like 0111001 **in this manner?** That requires more complex summations of sinusoids, which is explained by the Fourier theory.

3 Spectrum, Bandwidth, Data-rate

3.1 Spectrum of an EM signal

The spectrum of an EM signal is the set of frequencies of the sinusoids that make up the signal.

Example Suppose $s(t) = \sin t + \frac{1}{3}\sin 3t + \frac{1}{5}\sin 5t + \frac{1}{7}\sin 7t$ is the EM signal in consideration. Then:

$$S(s(t)) = \{f, 3f, 5f, 7f\} \qquad \text{where } f = \frac{1}{2\pi}$$

3.2 Bandwidth of an EM signal

The bandwidth is the difference between the highest and lowest frequencies of the sinusoids that make up the signal.

Example Consider the same example as in the previous section. $S(s(t)) = \{f, 3f, 5f, 7f\}$. Then:

$$\begin{aligned}\text{Bandwidth}\,(s(t)) &= 7f - f \\ &= 6f\end{aligned}$$

Larger the spectrum of an EM signal, larger is the bandwidth, and better is the approximation of the digital signal.

3.3 Bandwidth vs Data-rate

Consider an EM signal defined as follows:

$$s(t) = \sin 2\pi ft + \frac{1}{3}\sin 2\pi \cdot 3ft + \frac{1}{5}\sin 2\pi \cdot 5ft$$

Now, let $f = 1$ MHz $= 10^6 c/s$. Then,

$$\begin{aligned}B\,(s(t)) &= 4f && \text{and} \\ T &= \frac{1}{f} = \frac{1}{10^6}s \\ &= 1\mu s\end{aligned}$$

The situation is represented graphically in figure 3.

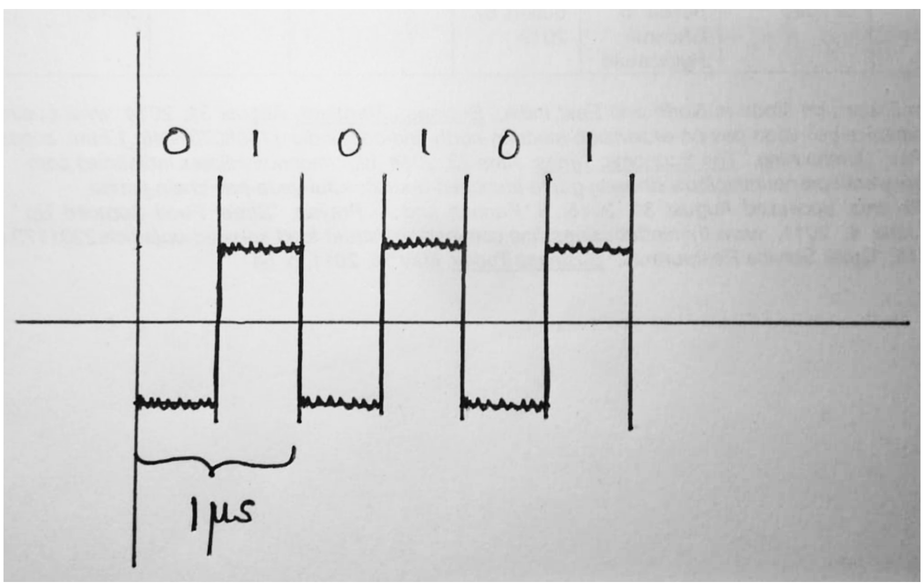

Figure 3: Graphical representation of the EM signal

Since $T = 1\mu s$, two pulses will last $1\mu s$ and one pulse will last $0.5\mu s$. This means that in $1s$, we can transfer 2×10^6 bits. That is, the **data-rate of this EM signal is 2 Mbps**.

3.4 Importance of these terms

Consider two EM signals as defined below:

$$s_1(t) = \sin 2\pi ft + \frac{1}{3}\sin 2\pi \cdot 3ft + \frac{1}{5}\sin 2\pi \cdot 5ft$$
$$s_2(t) = \sin 2\pi ft + \frac{1}{3}\sin 2\pi \cdot 3ft + \frac{1}{5}\sin 2\pi \cdot 5ft + \frac{1}{7}\sin 2\pi \cdot 7ft$$

Let us make the following comparisons to draw some conclusions in the next paragraph. Here, f = frequency, B = bandwidth, D = data-rate.

f	B	D	Signal
1 MHz	4 MHz	2 Mbps	s_1
1 MHz	6 MHz	2 Mbps	s_2
2 MHz	8 MHz	4 Mbps	s_1

Table 1: Effect of changing bandwidth on data-rate

Conclusions from table 1 Higher bandwidth is desirable because of the following reasons:

1. Either it gives us a better approximation of the digital signal (when we increase the spectrum—as in case 2 in table 1).

2. Or, it translates to a higher data-rate (when we increase the frequency of the signal—as in case 3 in table 1).

However, we cannot keep on increasing the bandwidth indefinitely to reap these benefits due to physical constraints.

- Increasing the spectrum would mean adding more sinusoids with $A = \frac{1}{x}$. Eventually, $\frac{1}{x}$ will start tending to 0, and the sinusoid will stop affecting the construction of the EM signal.

- Increasing the frequency beyond a certain point will lead to 'mixing' of the highs and lows (1s and 0s) of the signal, and hence increase the chances of erroneous data.

4 Encoding bits to digital signals

Our data is originally in the form of bits (1s and 0s). We first need to encode this data into digital signals (let's call this ENC_1), which is then further encoded

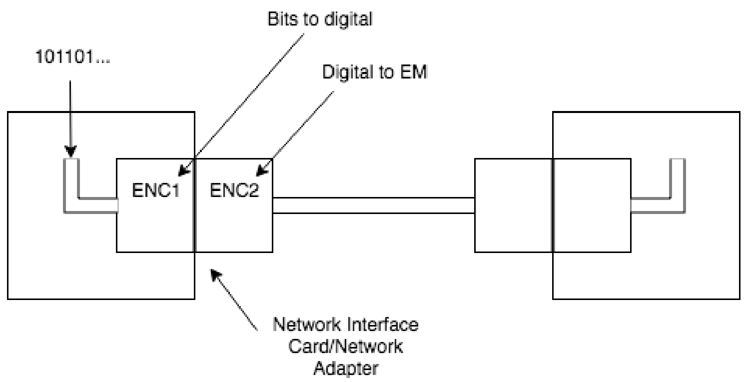

Figure 4: Network Interface Card or Network Adapter

into EM signals (say, ENC_2) as explained in previous sections. All this happens in the Network Interface Card as shown in figure 4. There are various protocols for ENC_1: NRZ, NRZI, Manchester, 4B/5B.

4.1 NRZ: Non-Return to Zero

This is the most natural encoding: higher amplitudes represent 1s and lower amplitudes represent 0s. An example is given in image 5.

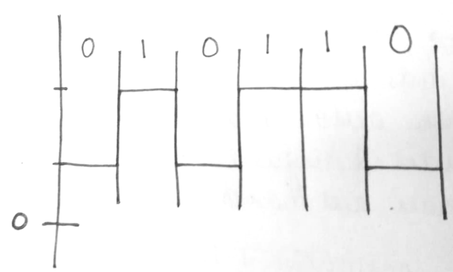

Figure 5: NRZ Encoding Protocol

4.2 Problems with using NRZ

- Unless the clocks of the receiver and the sender are perfectly synchronized, NRZ cannot handle too many consecutive 1s or 0s being transmitted. This is because one clock may drift relative to the other, and as soon as this happens, a bit may be lost. For example: data-rate being 1 Mbps means that the receiver should sense the channel 10^6 times per second—one more or one less will result in an error. Refer image 6 taken from this source.

However, if the data is changing often, then the receiver can re-sync its clock with the changing data.

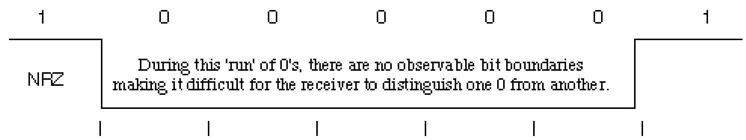

Figure 6: NRZ Clock Synchronization Problem

- The receiver keeps an average of the signal it has seen so far and then uses this average to distinguish between low and high signals. Whenever the signal is significantly lower than this average, the receiver concludes that it has just seen a 0, and conversely for 1. Too many consecutive 1s or 0s cause this average to change, making it more difficult to detect a significant change in the signal. This situation is called *baseline wander*. This problem becomes more troublesome because the signal gets attenuated in the medium by the time it reaches the receiver.

These **clock synchronization** problems mean that we would like to avoid using NRZ protocol, and look at other protocols that avoid long periods of 1s or 0s.

4.3 NRZI: Non-Return to Zero Inverted

If the bit is 0, stay at the same level. If the bit is 1, change level (irrespective of whether it's from low-to-high or high-to-low). In this encoding, the **change** of level is what is measure, and not the level itself. An example is given in image 7.

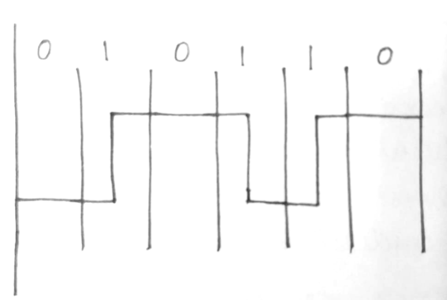

Figure 7: NRZI Encoding Protocol

NRZI protocol solves the problem of consecutive 1s (by changing level every time it encounters a 1). However, there is still a problem of consecutive 0s. Hence there may still be a clock synchronization problem.