Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

EEU44C18 / EEP55C28
Digital Wireless Communications

Lecture 1: Introduction

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Course Outline

- Scope
  - An introduction to the area of digital communications, with specific emphasis on its use in wireless environments.
- Structure
  - 8 set of lecture notes and 8 tutorials
  - 2 x 2 hrs Lab Sessions - Teaching Weeks 9 and 10
  - This is a shared module
    - The content until the Reading Week is covered by **Prof Arman Farhang**
    - The rest of the content is covered by **Prof Libin Mathew**
    - There are guest lectures by head of CONNECT research centre **Prof Dan Kilper** on energy efficiency of communication networks.

Assessment Details

- **Evaluation**
  - 75% Final Examination
  - 25% Written report based on two 2 hrs lab sessions
- **Lab Reports**
  - Corrected within two weeks

Course Texts

- Simon Haykin, Communication Systems (5th ed.), Wiley, 2010.
- “Communication Systems”, Simon Haykin
- John Proakis, and Masoud Salehi, Digital Communications (5th ed.), McGraw-Hill, 2008.
- Michael Rice, Digital Communications: A Discrete-Time Approach, Prentice Hall, 2009.
- Michel C. Jeruchim, Philip Balaban, and K. Sam Shanmugan, Simulation of Communication Systems (2nd ed.), Springer Science & Business Media, 2006.
- Bernard Sklar, Digital Communications: Fundamentals and Applications (2nd ed.), Prentice Hall, 2001.

Module Syllabus

- Introduction to basic digital communication theory
  - Basic terms and concepts
  - Components of a digital communications system
- Analog modulation of digital signals and complex baseband representation of the communication channel
- Digital modulation and pulse-shaping
- Orthogonal signalling; multi-tone modulation
- Wireless channel modelling and signal propagation in wireless environment
- Diversity reception
- Spread spectrum communications
- Channel capacity and multiuser detection
- Energy efficiency of selected digital communication technologies

Lecture 1: Introduction to Digital Communications

- Name advantages and disadvantages of digital systems versus analogue ones
- Describe the relationship between the spectrum of an analogue signal and its digital version
- Describe why wireless communications represent a bigger challenge than wired communications
- Name the basic components of a digital communication system

Introduction

- Modern wireless communication systems such as mobile and satellite are digital.
- It is necessary to study digital communications theory before looking at mobile/satellite specifics.
- General modelling of communication systems is the same whether over a piece of wire or over a wireless link.
- Wireless versus wired systems.
  - Landline: The characteristics of a piece of wire change only slowly over time.
  - Wireless: The characteristics of the interface are random depending on different factors such as the position of the person, obstacles, mobility and weather conditions. These characteristics are also prone to very rapid changes, e.g. when the user turns a corner.
- However, most signals of interest are continuous time, which is how they almost always appear in nature.

Why Wireless Communications

- Freedom from wires
  - No cost of installing wires or rewiring
  - No bunches of wires running here and there
- Global Coverage
  - Communications can reach where wiring is infeasible or costly, e.g., rural areas, old buildings, battlefield, vehicles, outer space
- Stay Connected
  - Roaming allows flexibility to stay connected anywhere and any time
  - Rapidly growing market attests to public need for mobility and uninterrupted access, necessitating ultra-reliability and low latency
- Flexibility
  - Services reach you wherever you go (Mobility). E.g, you don't have to go to your lab to check your mail
  - Connect to multiple devices simultaneously (no physical connection required)

Quick Review

- Complex number
  - Complex numbers have two parts: real and imaginary.
  - You can also think of it as magnitude and phase.
  - Euler's equation:

$$e^{j\phi} = \cos(\phi) + j\sin(\phi) \tag{1}$$

- Negative frequencies
  - Electrical Engineers often refer to negative frequencies.
  - Negative frequencies are a mathematical construct and do not exist in the physical world we live in.
  - They are useful, however, for analyzing radio-frequency problems and naturally occur as a result of the math.
  - In all cases where negative frequencies appear to exist, there is a physical explanation for them.

Quick Review - Fourier transform

- The Fourier transform calculates the dual frequency representation of a time domain signal. The inverse Fourier transform carries out the opposite operation

$$X(f) = \mathcal{F}[x(t)] = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \quad (2)$$

$$x(t) = \mathcal{F}^{-1}[X(f)] = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(f) e^{j2\pi ft} df \quad (3)$$

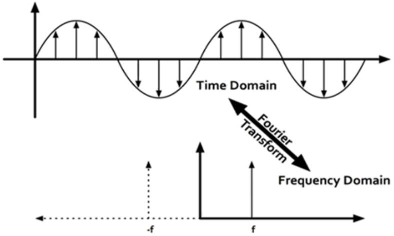

Figure: Dual-relation between time-frequency signal representation

Quick Review - Fourier Transform Table

$$
\begin{aligned}
f(t) &\leftrightarrow F(\omega) \\
\delta(t) &\leftrightarrow 1 \\
1 &\leftrightarrow 2\pi\delta(\omega) \\
e^{\pm j\omega_0 t} &\leftrightarrow 2\pi\delta(\omega \mp \omega_0) \\
\cos\omega_0 t &\leftrightarrow \pi\left[\delta(\omega-\omega_0)+\delta(\omega+\omega_0)\right] \\
\sin\omega_0 t &\leftrightarrow -j\pi\left[\delta(\omega-\omega_0)-\delta(\omega+\omega_0)\right] \\
rect(t/\tau) &\leftrightarrow \tau\,\mathrm{sinc}(\omega\tau/2) \\
\frac{W}{\pi}\mathrm{sinc}(Wt) &\leftrightarrow rect(\omega/(2W))
\end{aligned}
$$

Quick Review - Bandwidth

- The bandwidth of a signal is the width of the frequency band that contains a sufficient number of the signal's frequency components to reproduce the signal without unacceptable amount of distortion.
- For analogue signals, a common criterion for measuring the signal bandwidth is to consider the range of frequencies over which the spectral power or energy density does not drop to less than half of its peak level. In dB, half power corresponds to 3 dB below the peak.
- For digital signals, two common criteria for measuring the signal bandwidth are to consider the range of frequencies over which 90% or 99% of the power of the signal is contained.

Quick Review - Bandwidth

- The bandwidth of a signal is always measured on the positive side of the frequency axis. Remember that negative frequencies are only a mathematical tool and do not exist in reality. For example, the spectrum of real valued signals is symmetrical with respect to DC.

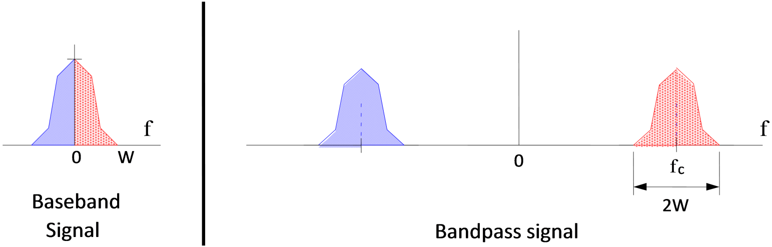

Figure: Example of bandwidth of a real-valued baseband signal and real valued bandpass signal

Quick Review - Noise

- In communications systems, noise represents some unwanted variation in the communicated signal. Regardless of where the noise originates from, the net effect is some corruption of the signal.
- In previous modules you have studied some sources of noise in communication systems, such as thermal noise. This noise is produced by the components which form the transmitter and receiver, with much more importance on the receiver side. There are also external sources of noise such as high power lines, atmospheric noise and space noise which get added to the signal during transmission.
- In general, to model the noise, all the noise components are considered together as a unique noise component. This noise signal is considered to have a 'flat' power spectral density (F), in other words, the same power density for all frequencies, for this reason it is called 'white noise' .

Quick Review - Noise

- Since the wireless channel is considered a random process, the noise introduced by the wireless channel is also considered to be a random process with zero mean (Gaussian process). Therefore, the white noise introduced by the wireless channel is generally known as Additive White Gaussian Noise (AWGN).

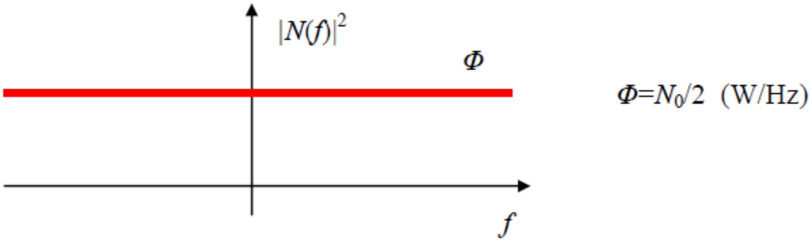

Figure: Additive White Gaussian Noise (AWGN)

Quick Review - Signal to Noise Ratio (SNR)

- The effect of noise on the signal quality depends on the relative power of the signal and noise. This is expressed as the signal to noise ratio (SNR) which may be expressed as a linear ratio or in dB.

$$
\begin{aligned}
SNR &= \frac{E\{s^2(t)\}}{E\{n^2(t)\}} && (4) \\
&= \frac{E\{s^2(t)\}}{\sigma_n^2} && (5)
\end{aligned}
$$

- In dB scale,

$$
\begin{aligned}
SNR(dB) &= 10\log_{10}(SNR) && (6) \\
&= P_{signal}(\mathrm{dBm\ or\ dBW}) - P_{noise}(\mathrm{dBm\ or\ dBW}) && (7)
\end{aligned}
$$

Electromagnetic spectrum

- Wireless communications is possible thanks to the propagation of electromagnetic waves.
- These electromagnetic waves have a physical dimension called frequency (f) which is related to their wavelength (λ).
- The speed that waves travel at, and hence their physical wavelength, is a function of the material the wave is travelling in.
- Single frequency (monochromatic) waves do not convey information aside from their existence.
- Wireless communication systems modulate the wave with an information signal of some kind. A modulated wave is no longer monochromatic and may have a finite or infinite bandwidth.
- Modulation means that one of the properties of the electromagnetic wave (amplitude, frequency or phase) is changed according to an information message.

Electromagnetic spectrum

- Wireless communications signals generally employ frequencies allocated in well-defined frequency bands.

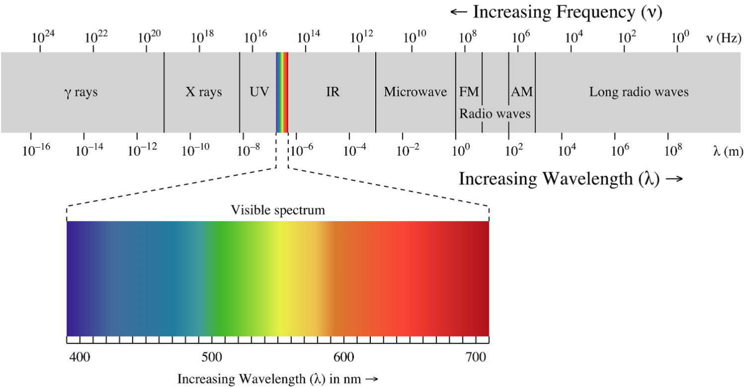

Figure: Electromagnetic frequency spectrum

Digital vs. Analogue Technology - Advantages

- Guaranteed accuracy. How accurate a digital signal is gets determined by how many bits are used to represent it.
- Perfect duplication. The performance of a unit can be identical to another one since tolerance variations do not exist.
- There are no changes in the performance due to temperature changes or components damaged caused by time.
- Flexibility. A digital system can be reprogrammed over the same hardware to carry out different tasks.
- Performance. Digital signal processing can perform operations that are not possible in the analogue domain, i.e. designing filters with perfect linear phase response.
- A digital computer can process and store discrete time signals using extremely flexible and powerful algorithms.
- Signal theory. Use of error correction techniques (channel coding) and compression techniques (source coding).

Digital vs. Analogue Technology - Disadvantages

- Bandwidth resolution limitations due to analogue-to-digital converters (ADCs) and digital-to-analogue converters (DACs).
- Finite length word limitations. In applications where not enough number of bits are used to represent the signal, information can be lost.

Analogue to digital

- In electronic engineering, we usually refer to continuous time signals as analogue signals and to discrete time signals as digital signals.
- A continuous time signal can be converted into a discrete time signal using sampling and analogue-to-digital converter.
- A digital signal $x[n]$ is a sampled version of an analogue signal $x_{\mathrm{a}}(t)$ in the way

$$x[n] \;=\; x_{\mathrm{a}}(nT), \;\text{for}\; T > 0 \qquad (8)$$

where T is known as "sampling period", and $2\pi/T$ is the "sampling frequency or rate".

Analogue to digital

- Nyquist or Shannon Sampling Theorem
  - A band-limited signal of finite energy, which has no frequency components higher than W Hz, is completely described by samples taken at any rate above $2W$ samples/second.
- Examples
  - Human ear hears frequencies up to 20 kHz $\rightarrow$CD sample rate is 44.1 kHz.
  - Phone line passes frequencies up to 4 kHz $\rightarrow$phone company samples at 8 kHz.

Spectrum of Digital Signals

Relationship between FT of an analogue signal and its sampled version

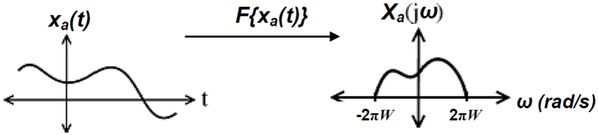

Figure: Fourier transform of a continuous time signal

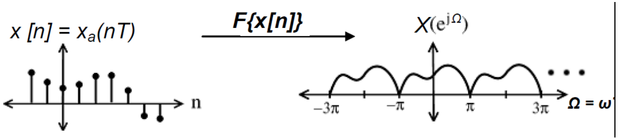

Figure: Fourier transform of a discrete time signal

Spectrum of Digital Signals

- Mathematically, the relationship is given by

$$X(e^{j\Omega}) = \frac{1}{T} \sum_{k=-\infty}^{\infty} X_{\mathrm{a}} \left(j \left(\Omega - \frac{2\pi k}{T} \right) \Big|_{\Omega=\omega T} \right) \tag{9}$$

- Given FT of an analogue signal, how to find FT of its discrete version
  - Creating copies of signal separated by uniform intervals $2\pi/T$ known as "aliases".
  - Dividing all these copies by a factor T.
  - Substituting ωT by Ω.
- Expressing the sample rate in Hertz as $f_{\mathrm{s}} = 1/T$, a baseband digital signal has unique frequency components up to $f_{\mathrm{s}}/2$.
- If there is no overlap between different copies of the original signal (aliasing) the analogue signal can be recovered from its digital version by filtering one of the copies (i.e. with a low-pass filter). If aliasing is produced, the original signal will be distorted.

Spectrum of Digital Signals

Futher observations (cont):

- The aliases overlap can be avoided by applying the Shannon or Nyquist Sampling Theorem.

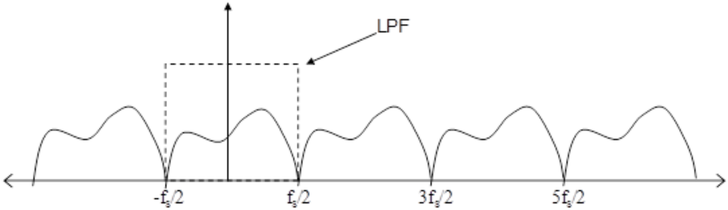

Figure: Low-pass filtering of sampled signal spectrum

- Low-pass filter (LPF) in the above figure is ideal. In practise, low-pass filtering introduces some distortion (mainly at the edges of its response), since the ideal “brick wall” response is unrealisable.

Spectrum of Digital Signals

Further observations (cont):

- Thus the sampling frequency will be chosen slightly higher than the Nyquist theorem limit ($f_\mathrm{s} > 2W$).
- Wireless digital communications transmits digital data by modulating and demodulating an analogue carrier signal.

Modelling a Digital Communication System

- The goal in modelling a real digital communication system is to create a discrete model for the entire system, since:
  - Digital data is inherently discrete.
  - Digital data only exists at the sampling instant, thus only the value of the signal at the sampling instant is important.
  - A discrete model is much easier to analyse than a continuous one.
- A typical digital communication system may be split into three distinct parts, i.e. information source and transmitter, the receiver and the channel, where each component needs to be expressed as a discrete model.

Figure: Communications system blocks

Components of a Wireless Digital Commun. System

The information source:

- The source corresponds to any data which we choose to represent digitally, e.g.
  - True digital signals:
    - Documents, spreadsheet, databases.
    - Photos from a digital camera.
    - Text messages.
  - Signals converted to digital form for robust transmission:
    - Scanned photographs.
    - A voice signal for mobile phone transmission.

Components of a Wireless Digital Commun. System

Main operations of digital source processing at a transmitter

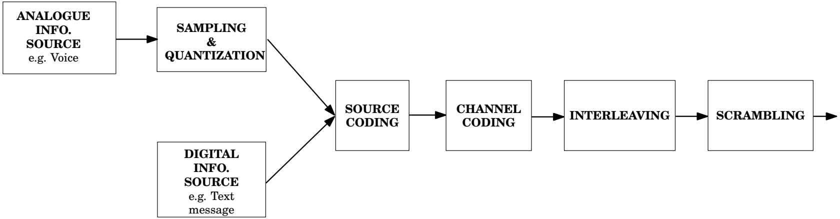

Figure: Digital source processing

- If the source signal is analogue, first the **sampling and quantisation process** is carried out to convert it to digital.
  - Source coding is the lossless compression of data before transmission.
- **Channel coding** is coding introduced to mitigate the effect of receive errors by allowing for the detection and/or correction of errors during detection at the receiver.

Components of a Wireless Digital Commun. System

- **Interleaving** is the reordering of the data to be transmitted so that a burst of errors occurring in close succession will not affect consecutive pieces of the data stream and so the sequence can be effectively error corrected after de-interleaving at the receiver.
- **Scrambling** is the randomizing of the transmit data:
  - This reduces the risk of Rx/Tx synchronization being lost if a bit pattern of all ones, or zero, is transmitted for a prolonged period of time.
  - This bit pattern is avoided by scrambling the data stream using a defined mathematical algorithm.
  - Random data may be transmitted over the channel at a higher rate than highly ordered data.

Components of a Wireless Digital Commun. System

Transmitter

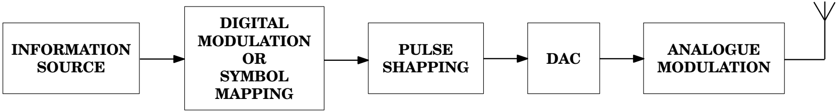

Figure: Wireless digital transmitter structure

- The wireless digital transmitter typically consists of the following components:
  - Data source
  - Digital Modulation or symbol mapping
  - Pulse-shaping
  - Digital-to-analogue conversion
  - Analogue Modulation
  - Antenna

Components of a Wireless Digital Commun. System

The transmitter

- The transmitter converts the digital source into a continuous time signal which we can apply to our channel (e.g. as a voltage to one end of a piece of wire).
- The signal transmitted must occupy a limited bandwidth:
  - Physical bandwidth constraints, e.g.
    - A piece of wire does not support transmission of data at high frequencies, since the attenuation is too high.
    - Channel distortion may be less severe at some frequencies than at others.
  - Bandwidth allocated by some national body (e.g. ECC (Europe)), e.g.
    - GSM bands allocated at 900 and 1800 MHz.
- The source is mapped onto digital values before the digital-to-analogue converter (DAC), i.e. digital modulation.

Components of a Wireless Digital Commun. System

The transmitter

- We ensure that the signal occupies only a limited bandwidth by including a low-pass filter, either implicitly (by appropriate modulation) or explicitly by incorporating a low-pass filter with desirable characteristics, i.e. pulse-shaping.
- The signal is passed through a DAC.
- The signal is shifted to a frequency appropriate for transmission, e.g. analogue modulation.
- The antenna converts the electrical voltage and current in its terminals into an electromagnetic wave which is radiated in the air.

Components of a Wireless Digital Commun. System

The channel

- The channel corresponds to all distortion/filtering which occurs between transmitter and receiver:
  - A piece of wire will induce different attenuation and phase shifts at different frequencies.
  - The multiple paths and randomness of reception time/angle of wireless systems leads to distortion.
  - The physical channel has a frequency response and can thus be represented as a linear filter.
  - Often, the channel corresponds to the effect of both the physical channel and transmit/receive filters.
  - Channels are affected by noise.

Components of a Wireless Digital Commun. System

The receiver

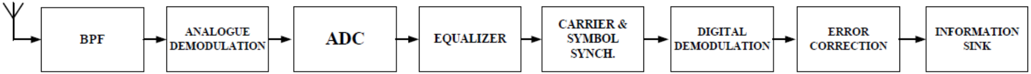

Figure: Receiver structure

- As it is usual in communications, both wired and wireless, the complexity of the receiver is larger than the transmitter.
- The receiver typically consists of the following components:
  - Antenna
  - Bandpass filtering
  - Analogue demodulation
  - Analogue-to-digital conversion
  - Equalization

Components of a Wireless Digital Commun. System

The receiver

- The receiver typically consists of the following components:...
    - Carrier and symbol synchronisation
    - Digital demodulation or symbol demapping
    - Error correction
- The receiver antenna performs the opposite action to the transmitter antenna, it converts an electromagnetic wave into an analogue signal in its terminals with a particular voltage and current.
- After, the rest of the receiver components convert the incoming modulated analogue signal into digital data.

Components of a Wireless Digital Commun. System

The receiver

- A typical receiver:
  - Selects the frequency range of the signal using a BPF.
  - Demodulates the signal.
  - Samples the signal (ADC).
  - Filters the signal, using an equalizer, to attempt to mitigate the effect of distortion/noise in the channel.
  - Estimates the carrier phase and symbol timing prior to the digital demodulation for correct symbol detection.
  - Performs the digital demodulation or symbol demapping.
  - Applies the error correction algorithm on the error information bits.
  - The digital data is stored (memory), played (music), processed (data mining), etc.