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WIRELESS RADIO CHANNELS CHARACTERISTICS

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Wireless Signal Transmission

- The propagation path of wireless signals can vary significantly from line-of-sight (LOS) to obstructed indoor space (OBS)
- The path is not stationary and changes with receiver's motion
  - Rather stochastic in nature
- EM waves exhibit several propagation mechanisms
  - Reflection
  - Diffraction
  - Scattering

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- The material in the next several slides relates closely to the field of communications, which is essentially a discipline in its own right. The objective of these lectures is to familiarize you with the principles and concepts underpinning wireless communications, which is an indispensable part of IoT systems. The interested reader can delve more into the covered topics using the provided or other sources and references.
- A. F. Molisch, *Wireless Communications,* 2nd Edition, Wiley-IEEE Press, 2011.
- A. Goldsmith, *Wireless Communications,* Cambridge University Press, ISBN: 9780511841224, 2005.
- K. Q. T. Zhang, *Wireless Communications: Principles, Theory, and Methodology,* Wiley, ISBN : 9781119978671 (hardback), 2016 (e-book also available).

Generic Log-Distance Path Loss Model

- Both indoor and outdoor radio channels, the signal strength drops logarithmically with distance
  - $\overline{PL}(d) \propto \left(\frac{d}{d_0}\right)^n$ or $\overline{PL}(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$
  - where n is the **path loss exponent**, which indicates the rate at which the path loss increases with distance
  - For free space $n = 2$ and increases when obstructions are included
  - d_0 is the minimum distance from the transmitter that is considered to be in the far-field of transmitter antenna
  - d is the distance between the transmitter and the receiver

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- Path loss exponent, *n* for different environments (from Wireless Communications: Principles and Practice, T. Rappaport)
- The reference distance d_0 should always be in the far-field of the antenna to avoid near-field effects. The reference path loss (at the reference distance) can be determined either through the free space model (see following slides) or field measurements at the reference distance.

Environment	Path loss exponent
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
Obstructed in building	4 to 6
Obstructed in factories	2 to 3
In building line-of-sight	1.6 to 1.8

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Free Space Propagation – The Ideal Case

- Unobstructed LOS path between Tx and Rx

$$P_{R_x}(d) = \frac{P_{T_x} G_{T_x} G_{R_x} \lambda^2}{(4\pi)^2 d^2 L} \qquad (1)$$

- Power falls off based on a power law function
  - Power of two for the Friis free space model
  - Implies a 20dB/loss per decade
- Path loss in dB for free space model and unity gain for the antennas

$$PL(dB) = 10 \log \frac{P_{T_x}}{P_{R_x}} = -10 \log \left[\frac{\lambda^2}{(4\pi)^2 d^2} \right]$$

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- In (1), P_{Tx} is the transmitted power, $P_{Rx}(d)$ is the received power at distance d from the transmitter (Tx), λ is the wavelength (in meters), G_{Tx} is the gain of the transmitter antenna, G_{Rx} is the gain of the receiver antenna, and L is the system loss factor not related to propagation.
- The system (hardware) losses $L \geq 1$ are typically due to transmission line attenuation, filter losses, and antenna losses in the communication system. If L equals one, no hardware losses are assumed.
- The free space model is applicable for such distances where the receiver is in the **far-field** of the transmitting antenna. The far-field is denoted as d_f and is determined as

$$d_f = \frac{2D^2}{\lambda},$$

where $d_f >> D$ and $d_f >> \lambda$. The largest physical dimension of the antenna is denoted as D.

- Often the power at the receiver is related to the receiving power at a reference distance d_0 which should be greater than d_f. In this case, the received power in free space at a distance greater than d_0 is

$$P_{R_x}(d) = P_{R_x}(d_0)\left(\frac{d_0}{d}\right)^2, \qquad d \geq d_0 \geq d_f.$$

Signal Losses for Propagation Indoors

Building	Frequency (MHZ)	*n*	σ (dB)
Retail store	914	2.2	8.7
Grocery store	914	1.8	5.2
Office (hard partitions)	1500	3.0	7.0
Office (soft partitions)	900	2.4	9.6
Office (hard partitions)	1900	2.6	14.1
Factory (LOS) Textile/Chemical	1300	2.0	3.0
Factory (LOS) Textile/Chemical	4000	2.1	7.0
Factory (LOS) Paper/Cereals	1300	1.8	6.0
Factory (LOS) Metalworking	1300	1.6	5.8
Factory (LOS) Textile/Chemical	4000	2.1	9.7
Factory (OBS) Metalworking	1300	3.3	6.8
Suburban home - Corridor	900	3.0	7.0

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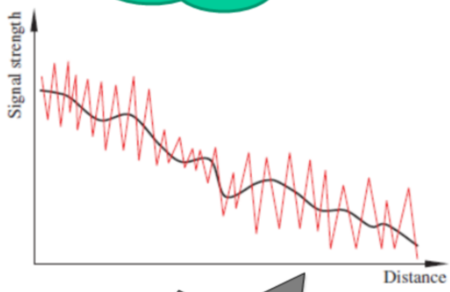
Signal Propagation Losses

- Signal energy decreases due to several sources of losses
  - A plethora of models exists to describe those
    - Large-scale (outdoor) and small-scale (indoor) or fading models
- The received signal of a wireless mobile device is a sum of waves with different amplitudes and phases as each wave traverses different paths
  - 30dB to 40dB power loss are expected when the receiver moves away by few meters
  - IoT stationary wireless devices may suffer lower losses
    - Heavily depends on the system and/or application

Illustration of Different Losses

- Signal fades with distance
  - Log-distance path loss model
  - A slow smooth drop over distance due to diffraction (secondary waves) from large objects
- Local and rapid fluctuations due to local multipath propagation
  - Scattering from small objects

So, is a free-space model useful?



Yes, can be used to set the minimum power required

Radio Channel Capacity

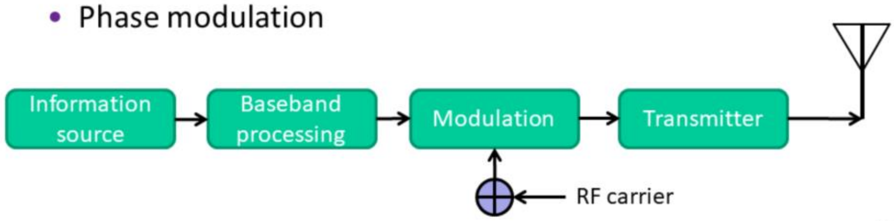
- Shannon's theorem on channel capacity

$$C = Blog_2\left(1 + \frac{S}{N}\right)$$

- where *C* is measured in bps
- *B* is the RF bandwidth
- and *S/N* is the signal to noise ratio
- Non-fading channels with Additive White Gaussian Noise (AWGN) are assumed

Modulating Mechanisms

- To allow higher bandwidth, longer transmission distances and manage noise, interference, and losses signals are modulated
- Modulation techniques vary the following characteristics of a high frequency signal
  - Amplitude modulation (AM)
  - Frequency modulation (FM)
  - Phase modulation



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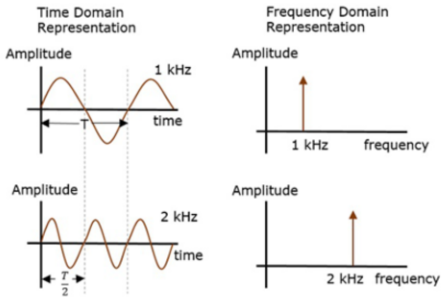
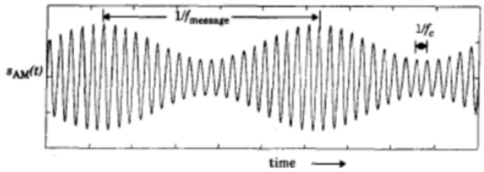
Very Basics of Modulation

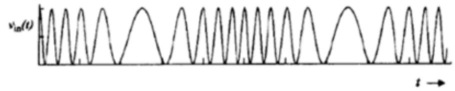
- $s(t) = A_c \cos(2\pi f_c t + \theta(t))$



- Amplitude modulation (AM)



- Frequency modulation (AM)



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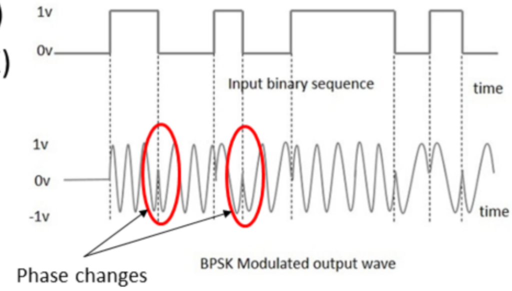
Phase Shift Keying (PSK)

- In PSK, the phase of a constant amplitude carrier is modified to represent different binary symbols
- For binary PSK two phase values encode the 1 and 0 logic values. Typically, the phase difference is 180 °C
- Other more complex PSK techniques exist
  - Differential PSK (DPSK)
  - Quadrature PSK (QPSK)
  - π/4 QPSK.....



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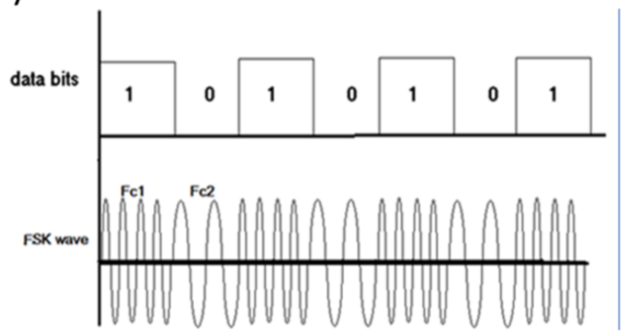
Frequency Shift Keying (FSK)

- In FSK, the frequency of a constant amplitude carrier signal is varied to represent different binary symbols
- For binary FSK, the frequency changes between two values (high (Fc1) and low (Fc2) tones) corresponding to binary 1 and 0



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Spread Spectrum (SS) Modulation Techniques

- SS methods require bandwidth which is orders of magnitude greater than other modulation techniques
  - They spread the signal onto many frequencies
  - Ideal for multiple users
  - Spread spectrum signals are *pseudorandom* and exhibit noise like properties
- SS techniques utilize pseudo-noise sequences produced by appropriate circuits
  - The pseudo-noise codes are also available to the receiver to demodulate the spread spectrum signal

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- Signal recovery is performed by cross-correlation with a locally generated version of the pseudorandom carrier with which the signal was modulated.
- Cross-correlation with the pseudorandom sequence of the user for which the message was destined, despreads the spread spectrum signal and recovers the original message.
- Cross-correlation with the local pseudorandom sequence of an unintended user yields a very weak wideband noise at that receiver.
- Spread spectrum signals have uniform energy over a very large bandwidth and thus at any given time only a small portion of the spectrum will suffer from fading.

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Pseudo-Noise (PN) Sequences

- Binary sequences that have an autocorrelation that over a period of time resembles the autocorrelation of random binary sequence
  - Has approximately equal number of 1's and 0's
  - Very low correlation between shifted versions of the sequence
  - Very low cross-correlation between any two sequences

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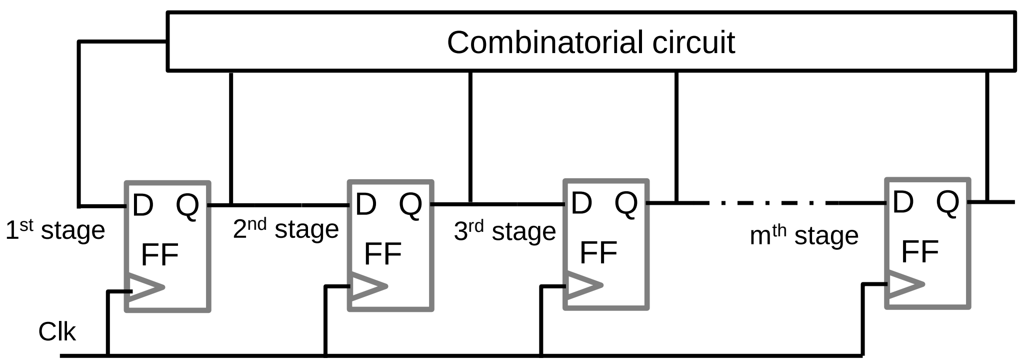
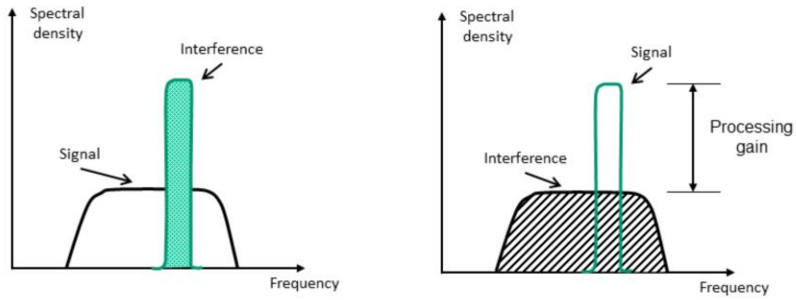
- PN binary sequences are typically generated by feedback shift registers (as shown below)
- A feedback shift register consists of a number of FFs equal to number of the bits of the sequence, say *m*-bits and combinatorial components, usually implementing a high order polynomial using XOR-gates (linear feedback shift register (LFSR)).
- The period of an *m*-bit shift register is 2^m-1 symbols. That is a sequence may be repeated after 2^m-1 symbols.



Direct Sequence Spread Spectrum (DS-SS)

- DS-SS systems spread the baseband data by directly multiplying the baseband data pulses with a PN sequence produced by a PN sequence generator
- At the receiver the narrowband signal is recovered by correlating the wideband signal with the appropriate PN



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Frequency Hopped Spread Spectrum (FHSS)

- Frequency hopping involves a periodic change of transmission frequency
- A frequency hopping signal may be seen as a sequence of modulated bursts of data with time-varying, pseudorandom carrier frequencies (hopset)
- The hopping sequence of frequencies is only known to the desired receiver
  - The time between hops is called *hop duration or hopping period*
  - The total BW of the hopset and the instantaneous BW of each frequency are notated as B_{SS} and B
  - The processing gain is B_{SS} / B for FH systems

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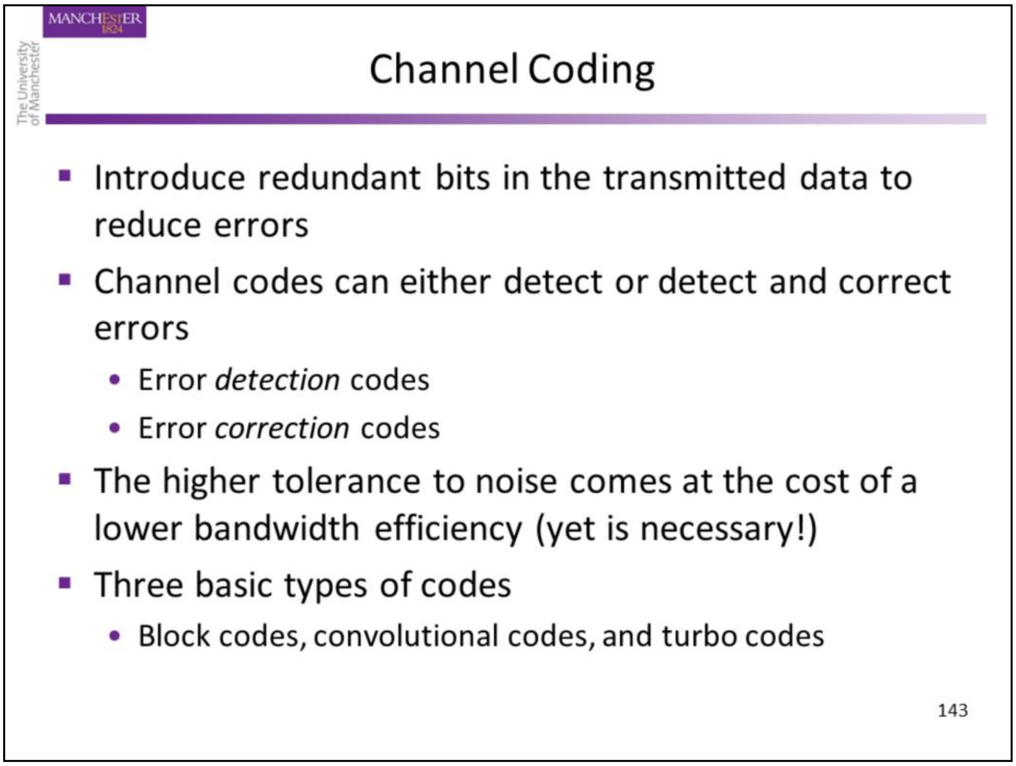
*The concept of frequency hopping was invented during World War II by film star Hedy Lamarr and composer George Antheil. Their patent for a "secret communications system" used a chip sequence generated by a player piano roll to hop between 88 frequencies. The design was intended to make radio-guided torpedos hard to detect or jam.



Error detection and correction codes are extensively used in wireless communications.

- **Block codes** are forward error codes that can detect a specific number of errors depending on the complexity of the code and correct these errors, without the need to retransmit the message. In block codes, parity bits are added to the bits of the message forming codewords or code blocks. In general, a block coder, k data bits are encoded into n code bits. Thus, the redundant bits are $n - k$ and the code is usually referred to as an (n,k) code. Examples of block codes include Hamming, Hadamard, and Cyclic codes.
- Differently from block codes, **convolutional codes** map a continuous sequence of information bits into a continuous sequence of encoder output bits. A convolutional code can demonstrate a higher coding gain as compared to block codes with the same level of complexity. To produce a convolutional code, the information sequence is shifted in through a shift register. Typically, the shift register contains N k-bit stages and m linear algebraic function generators.
- **Turbo codes** have been invented more recently and are integrated with 3G wireless standards. This type of codes combines the capabilities of convolutional codes with channel estimation theory and can be described as nested or parallel convolutional codes. Their coding gains are much higher than the other types of codes allowing the capacity of a wireless channel to reach the Shannon capacity bound (see previous slides).