Advance Digital Radio

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1. Introduction

Modern Communication Standards

<1940s Morse AM FSK
1950s FM appeared
1978 Military GPS (CDMA)

Since 1991, an explosion of Radio Standards, many are GMSK, CDMA and OFDM based

WiFi 802.11a-z
BlueTooth
LoRa
ZigBee
IOT 5G
WiMAX WiBro
GSM/EDGE 2G
LTE 4G
W-CDMA 3G
Morse Code
DVB-T
DVB-S
Chirp RADAR
OFDM
QAM
APSK
Thuraya
TETRA
PSK
GNSS Bidou
GNSS GPS
GNSS Galileo
FM
DVB-T2
DVB-S2
AM
DAB

Lets make it a bit more manageable

Focus on
DSSS/CDMA
OFDM

WiFi
802.11a-z

BlueTooth

LoRa

ZigBee

IOT
5G

WiMAX
WiBro

GSM/EDGE
2G

LTE
4G

W-CDMA
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Morse
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Bidou

GNSS
GPS

GNSS
Galileo

FM

DVB-T2

DVB-S2

AM

DAB

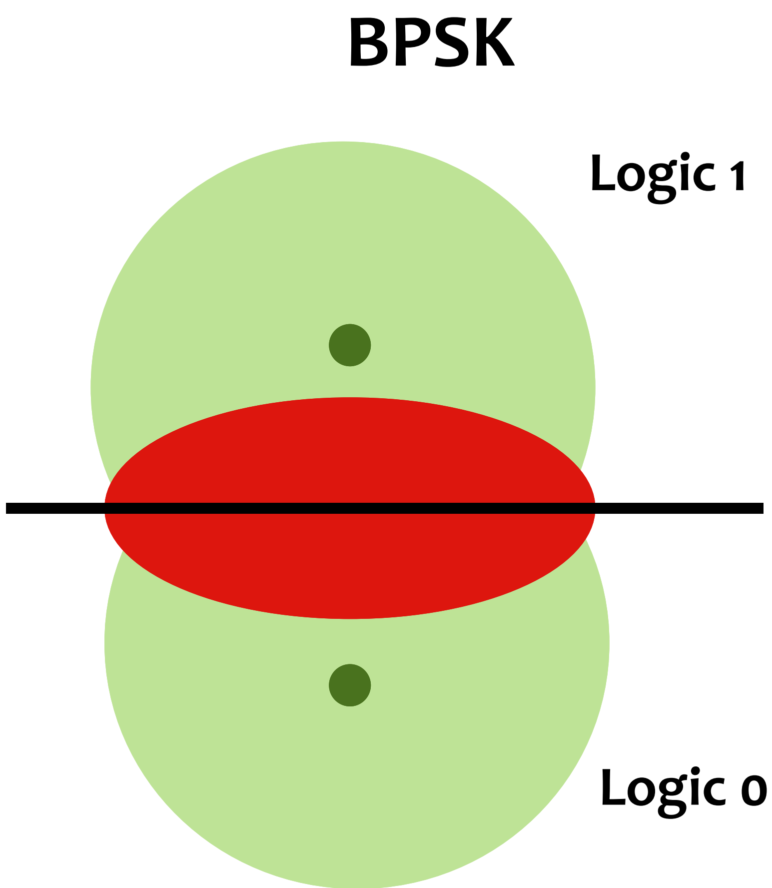
Introduction

- **Bit Errors**
  - Effect of Bit Errors on Encryption and Data Compression
  - The need for Error Detection
  - The use of Error Correction Codes
  - The need for reconfigurable Error Correction
- **Direct Sequence Spread Spectrum**
  - Develop this as an extreme case of Error Correction Coding.
- **OFDM Coding**

2. Reducing Data Loss

Noise and Symbol error

- **Ideal systems have pin point constellation diagrams**
  - Precisely defined locations
- **Real systems have noise.**
  - Random positions defined by probability.
  - If noise too large, decision threshold crossed for some of the bits.
  - Data is partially damaged



Has Data been corrupted? CRC Checks

- **Simplest error detect code**
  - Parity bits
- **More sophisticated codes**
  - Cyclic Redundancy Codes
- **Many systems use a handshaking procedure**
  - for requesting a message be repeated
  - for checking quality of reception

- **8 bit Parity check**
- **Parity=mod(sum(bits),2)**
  - 1111 0000 P=0
  - 1111 0001 P=1
  - Detects single error ok
  - Can be fooled by multiple errors

Bit Errors and Encryption

- **Example Block Encryption**
- **Alphabetical Encryption**
  - Magic Square type
  - No Q
- **Only one bit error in encrypted letter.**
  - 5 bit errors in decrypted letter.
- **Encryption can multiply bit errors**

$$\begin{pmatrix} A & B & C & D & E \\ F & G & H & I & J \\ K & L & M & N & O \\ P & R & S & T & U \\ V & W & X & Y & Z \end{pmatrix} \leftrightarrow \begin{pmatrix} C & H & M & S & X \\ D & I & N & T & Y \\ E & J & O & U & Z \\ A & F & K & P & V \\ B & G & L & R & W \end{pmatrix}$$

L=1001100
J=1001010
K=1001011
S=1010011

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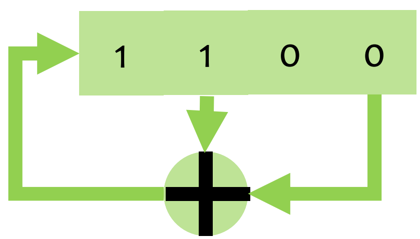
Bit Errors and Scramble Codes

- **Alternative to Block Encryption is a Running Cipher.**
  - XOR (mod2) with PRS/Gold
  - Gives data privacy if PRS is user and cell dependent.
  - PRS can cycle over several frames or subframes.
  - Randomness also improves behaviour of radio links.
    - Real time Calibration
    - Reduced peak to average.

- **Pseudo Random Sequences**
  - Generated by shift registers with feedback
- **Gold Codes**
  - Generated by combining several PRSs of different length and phase via XOR



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Bit Errors and Data Compression

- **Data compression**
  - widely used to reduce size of data.
  - E.g. mp3, mpg, zip etc.
  - FFT and Huffman codes
- **Language consists of words**
  - around 400 commonly used.
  - 10,000 used occasionally
- **AsciiZip**
  - Ascii 7 bit code, usually stored in 8 bits. 128 spare codes.
  - Lets use 128 codes for commonly used words…
- **Dictionary**
  - 128 The
  - 129 And
  - 130 Now
  - 131 Don't
  - 132 Feed
  - 133 Kill
  - 134 Cat
- **Sentence**
  - **"And feed the cat."** 129,132,128,134
  - 15 characters → 4 bytes
  - Compression nearly 400%
- **1 bit errors**
  - **"Don't feed the cat."** 131,133,128,134
  - **"And kill the cat."** 129,134,128,134
  - Life changing consequences!
    - No cats were harmed making this slide

Error Correction Codes

- **Example Hamming 7-4 Code**
  - 4 Data bits
  - 3 Parity bits
  - 7 Transmitted bits
- **Encoded and Uncoded data related by Mathematical transformations.**
- **Error correction codes can correct 1 or more bits depending on type.**
- **Many FEC techniques.**
  - Viterbi codes are widely used in Radio links

$$\begin{pmatrix} E_6 \\ E_5 \\ E_4 \\ E_3 \\ E_2 \\ E_1 \\ E_0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \end{pmatrix} \begin{pmatrix} D_3 \\ D_2 \\ D_1 \\ D_0 \end{pmatrix}$$

Error Correction and Data Efficiency

- **Mobile radio**
  - Reception quality varies with location.
  - Strong error correction codes reduces data transmission rate,
    - Typically 200-300%
  - Weakest error correction
    - Typically 20-40%
  - Need adaptive error correction
- **Hardware often used to implement error correction coding.**
  - **Puncturing**, discarding known bits at known places.
  - E.g. 5/6 rate codes

Burst Errors and Interleaving

- **Forward Error Correction is good at correcting occasional errors.**
- **But fails if a burst of errors occurs.**
- **By interleaving data**
  - E.g. Matrix transpose
- **Burst of errors can be spread over several encoded words, or even entire frames.**
- **So looks like single bit errors in several encoded words.**

$$\begin{pmatrix} D_0 & D_1 & D_2 \\ D_3 & D_4 & D_5 \\ D_6 & D_7 & D_8 \end{pmatrix} \leftrightarrow \begin{pmatrix} D_0 & D_3 & D_6 \\ D_1 & D_4 & D_7 \\ D_2 & D_5 & D_8 \end{pmatrix}$$

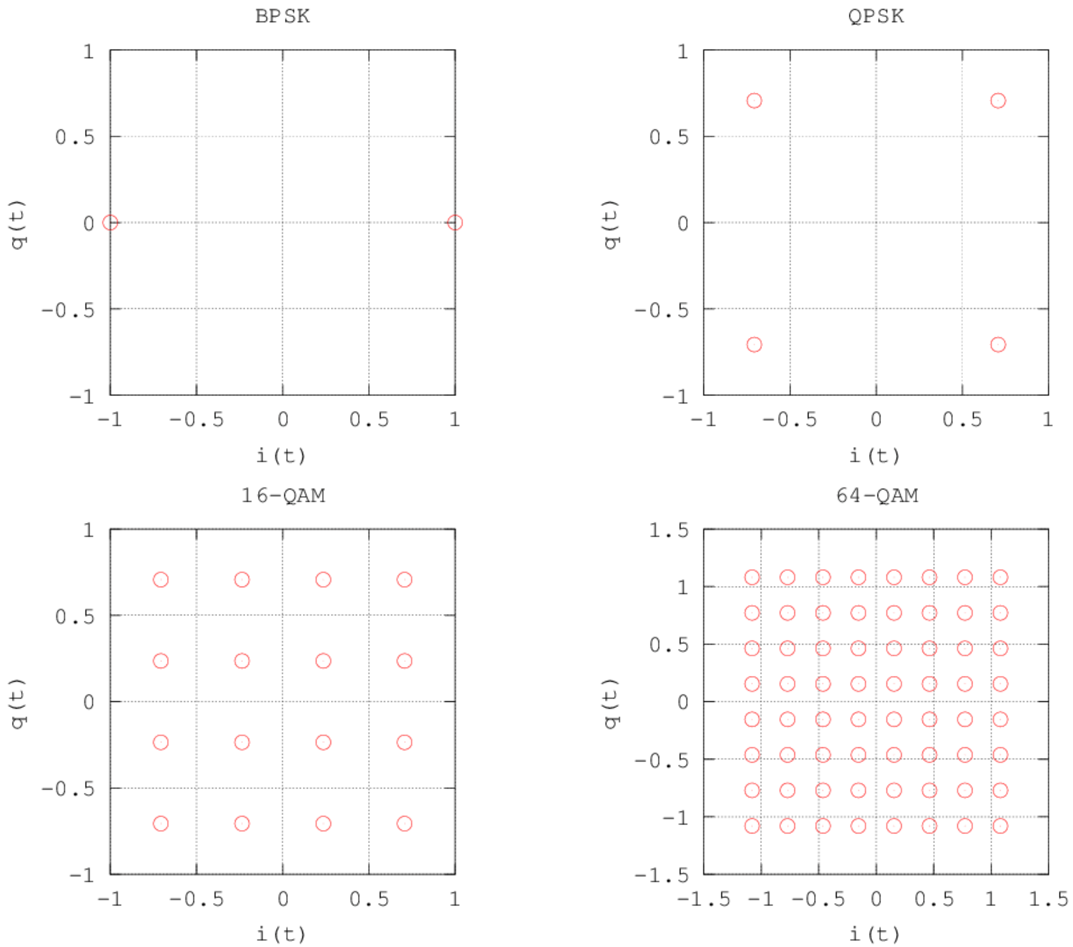
QAM and Bit Error Multiplication

- **Example QAM16**
  - Noise leads to adjacent symbol being chosen
- **Straight binary encoded**
  - Horizontal or Vertical 1-2 errors
  - Diagonal 1-3 bits error
- **Grey encoded**
  - Horizontal or Vertical 1 error
  - Diagonal 2 bit errors
  - Diagonal error less probable than horizontal or vertical due to distance

0000	0001	0010	0011
0100	0101	0110	0111
1000	1001	1010	1011
1100	1101	1110	1111

0000	0001	0011	0010
0100	0101	0111	0110
1100	1101	1111	1110
1000	1001	1011	1010

Bit Errors and QAM Density



- **Lower QAM Density the more resilient to bit errors.**
  - BPSK and QPSK have similar noise performance.
  - Many mobile systems will use adaptive modulation to make best use of propagation conditions.

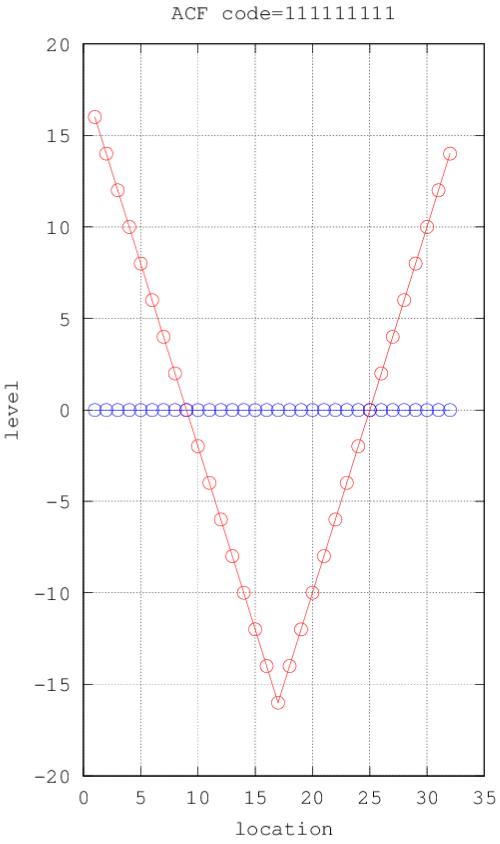
3. Direct Sequence Spread Spectrum Signals

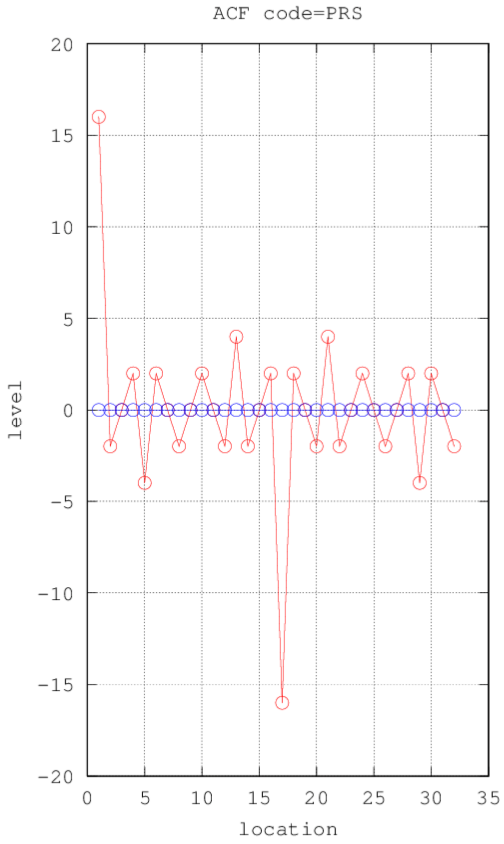
Spread Spectrum and Error Correction

- **Error correction increase number of transmitted bits.**
  - Imagine we can keep increasing the transmission rate, but keeping the information rate the same.
  - Leads to an increase in bandwidth
  - Called spread spectrum
- **What happens if I keep increasing the bandwidth?**
  - Signal can be decoded even if below the noise floor of the system.
- **E.g. BCH(63,7) code**
  - 63 transmitted bits
  - 7 information bits
  - Corrects any combination of 15 bit errors.
  - Spectrum spread by a factor 9!
- **What if I forget FEC coding, and just send message 9 times instead!**
  - Replace 1 bit, by 9 bits (Spreading Code)
  - 1 -> 111 111 111
  - 0 -> 000 000 000
  - Can correct up to 28 bit errors at a rate of 4 bits per symbol.
  - Code gain 9.5dB (Eb/N0 7dB for BPSK)

Spread Spectrum – The ACF

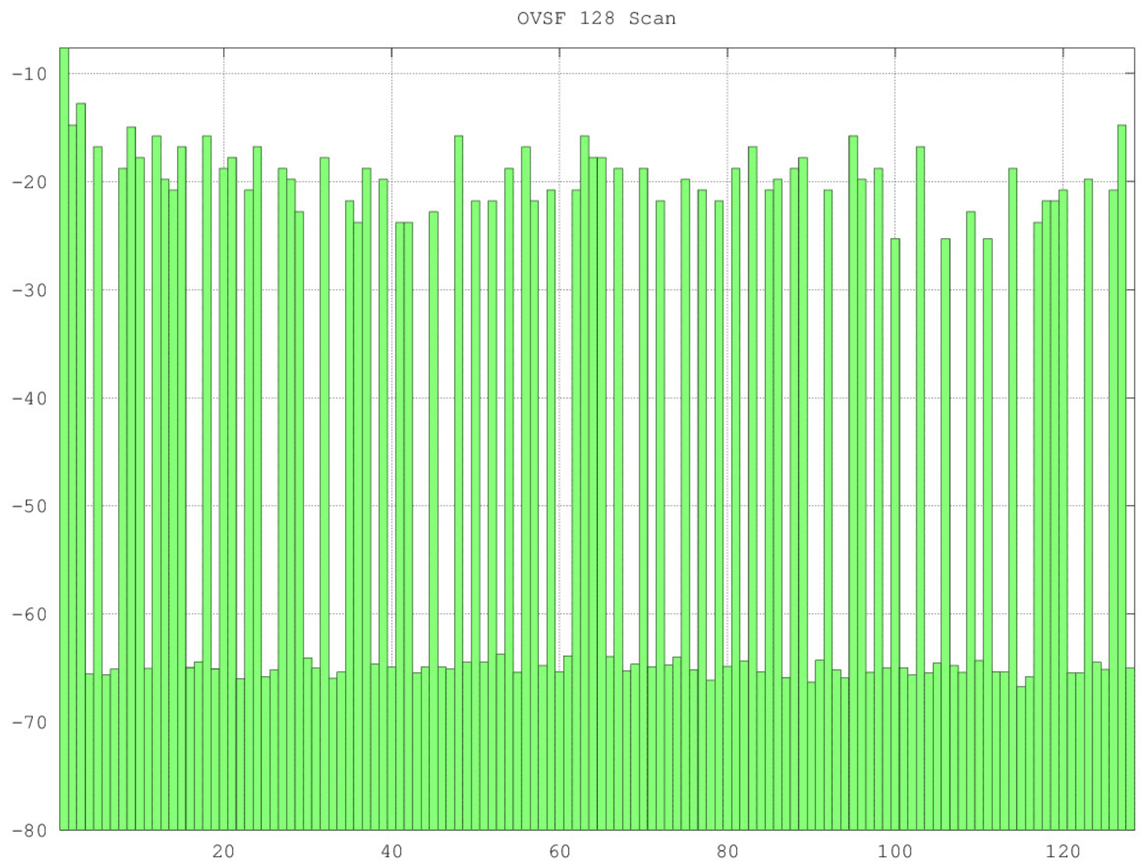
- **Alternative binary representation**
  - {1,0}→{1,-1}
- **Decoding is now pattern recognition.**
  - Auto Correlation Function.
- **Use PRS instead of all '1's to spread signal, has better ACF.**
  - Can measure phase shift and small Doppler shifts.
  - Can detect the presence of echos a help construct echo cancel FIR filte





Code Domain Multiple Access (CDMA)

- **Spread spectrum can see below noise**
  - What if noise floor was other signals?
  - Transmit several orthogonal signals overlapping in time and frequency.
  - Each signal uniquely identified by a unique spreading code.
    - Code Domain "spectrums"
  - Used in W-CDMA (3G) and GPS
  - W-CDMA uses a mix of Walsh functions and PRS to minimise interaction of other codes.



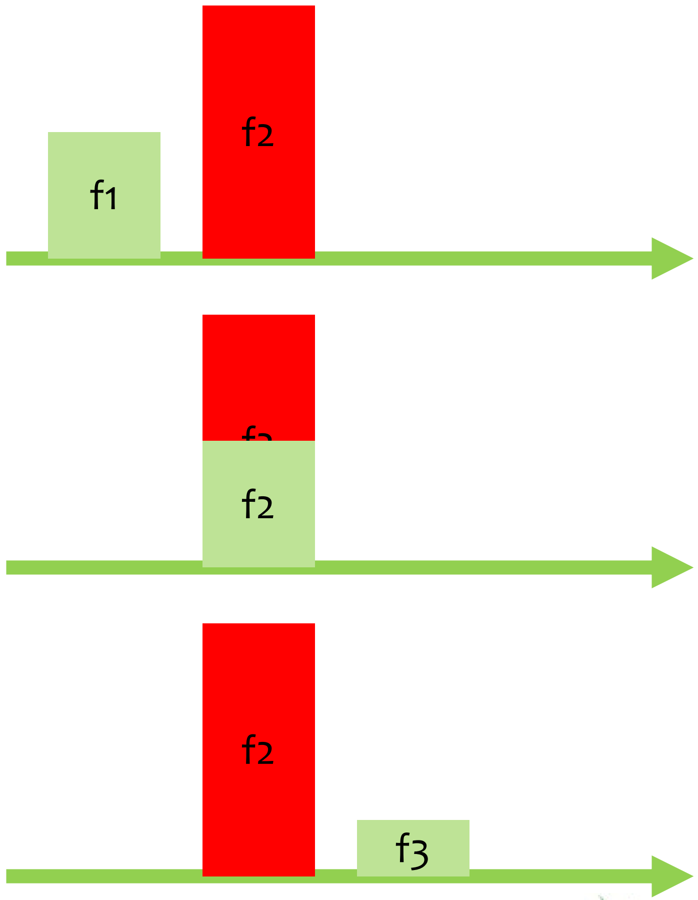
DSSS and Long Range Communications

- **Satellite or probe has limited RF output power and antenna size.**
  - Trade spreading factor for range.
- **Mobile phone has limited battery power and small antenna size.**

- **W-CDMA UL 0.25W (average)**
  - Code gain 24dB (15kb/s)
  - Over 20km range
    - With 30dB margin
  - Receiver sensitivity
  - -120dBm
- **GPS 20W Transmitter**
  - Code gain 43dB (50b/s)
  - Over 25,000km range.
  - Receiver Sensitivity
  - -130dBm

Frequency Hopping

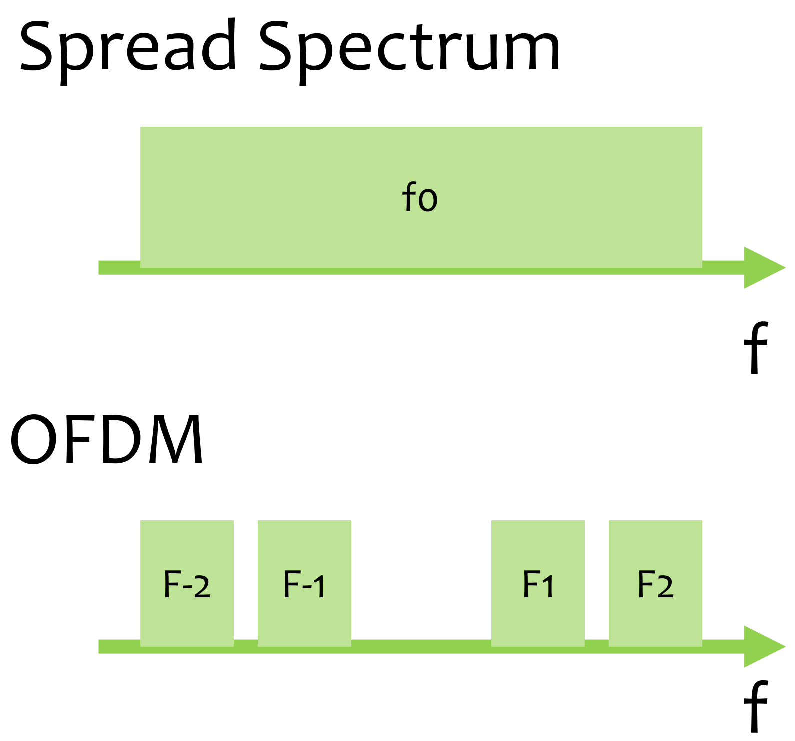
- **Technique to reduce effect of random interference and fading.**
  - Data interleaving spreads over the hopping sequence.
  - Error correction will recover data.
  - A known random hop sequence can also improve privacy.



2. OFDM

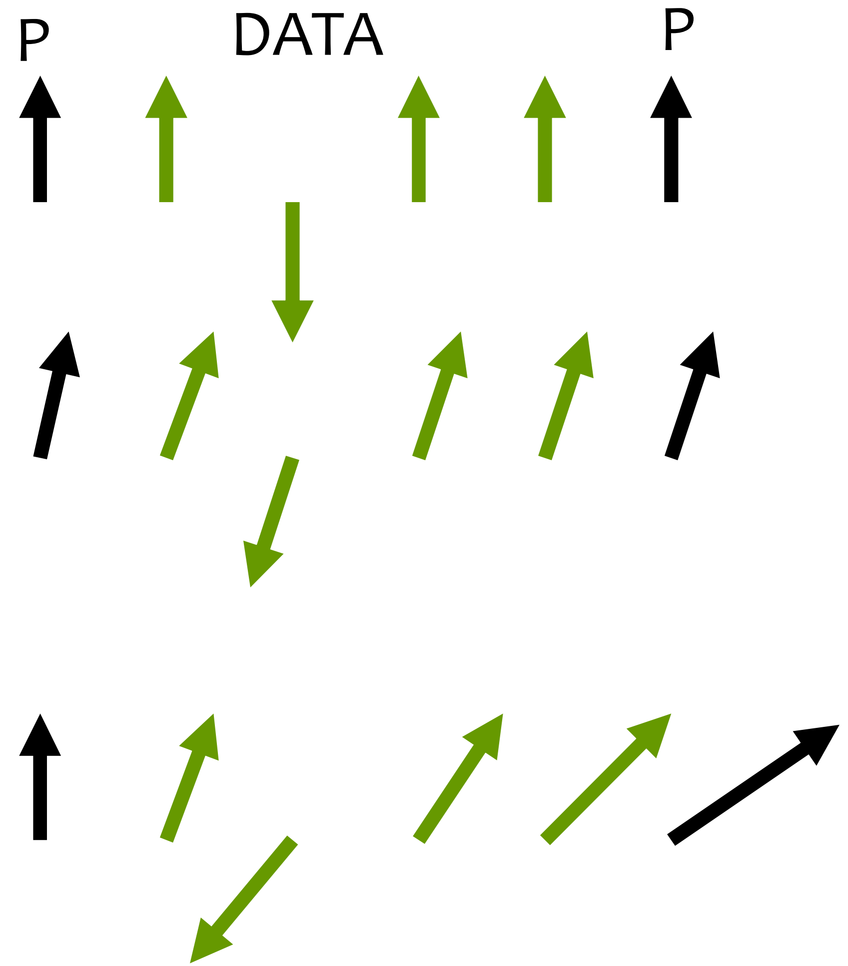
OFDM as a Signal Spectrum

- **Signal spectrum can be**
  - One wide band signal
  - Many narrow band signals
- **OFDM**
  - Many subcarriers regularly spaced
  - Some subcarriers missing e.g. F0
    - Much less sensitive to DC offset.
  - Some subcarriers reserved for special purpose
    - Synchronisation and pilot tones
  - Subcarriers modulated with QAM
  - Generated by iFFT.



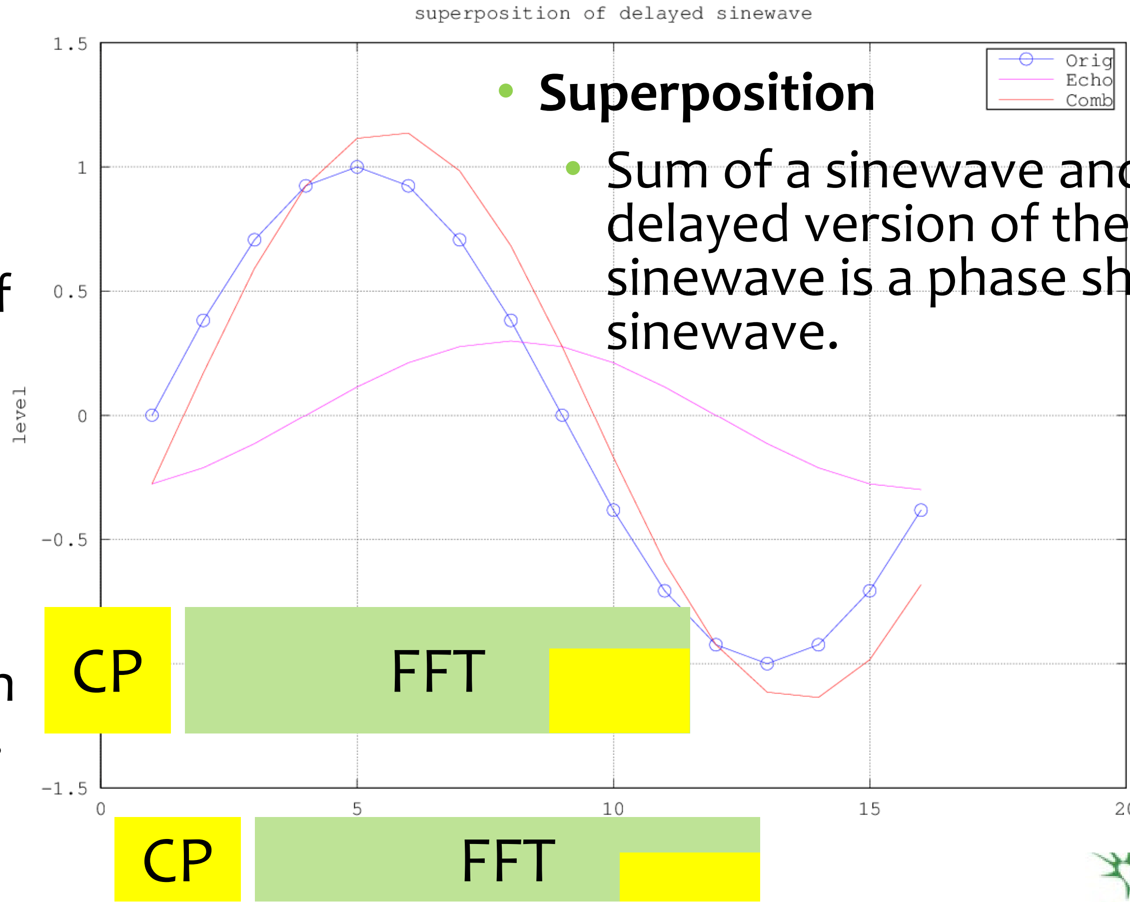
Properties of OFDM – Phase Shifts

- **Pilot tones**
  - have known amplitude and phase
- **Relative phase and amplitude of received pilots can be used to carry out equalisation in the frequency domain.**
  - Phase noise rotates all subcarriers by the same amount
  - Frequency dependent amplitude and phase can be corrected by interpolation of phase and amplitude change.
- **Pilots do not have to be transmitted every OFDM symbol**



Properties of OFDM - Echos

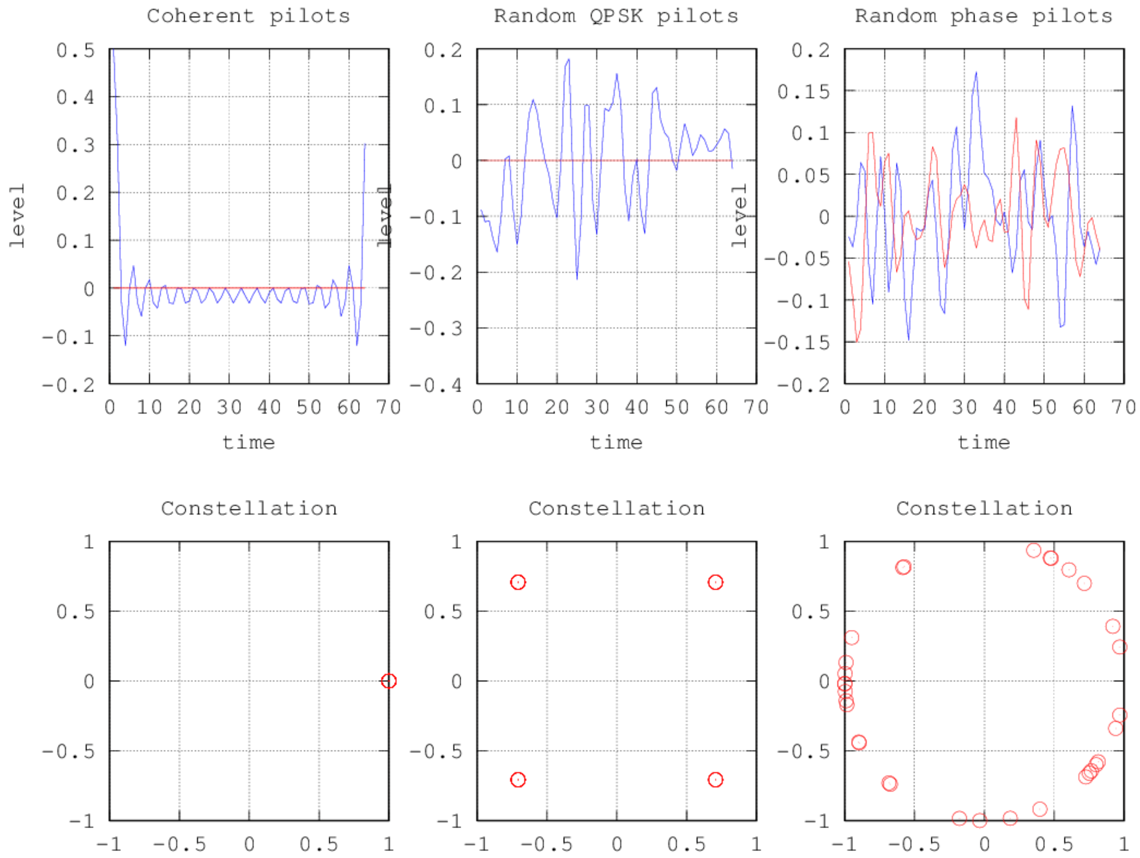
- **Cyclic Prefix**
  - Duplicates the end part of the FFT at the front of the signal. Adds history.
- **Echos**
  - Echo leads to phase shift of OFDM signal if echo is shorter than cyclic prefix.
- **Single Frequency Network**
  - Allows use of single frequency national network if transmitted with delay smaller than FFT size.



- **Superposition**
  - Sum of a sinewave and a delayed version of the same sinewave is a phase shifted sinewave.

Properties of OFDM - PAR minimisation

- **OFDM vulnerable to coherent symbols**
  - E.g. coherent pilots
  - Leads to very high peaks
  - Randomisation essential for low peak to average ratio.
  - Zadof-Chu type sequences similar to random QPSK.



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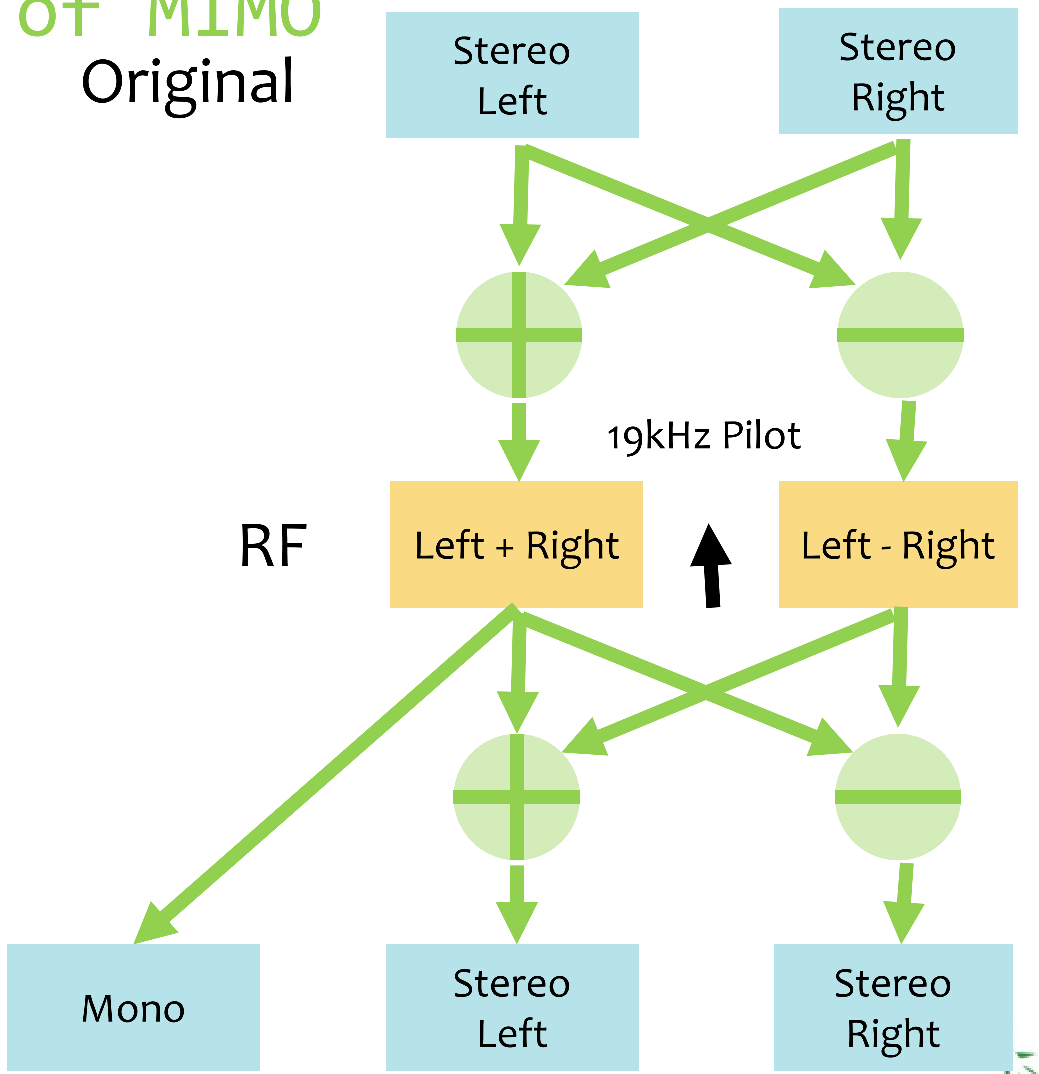
FM Stereo, a kind of MIMO

- **Uses Multiple Simultaneous Channels**
- **FM Stereo**
  - Channels combined
  - Two channels separated by frequency
    - Frequency <u>**diversity**</u>
- **Mono Reception**
  - Use left part of signal
- **Stereo Reception**
  - Analogue signal post processing needed to separate original Stereo channels.



MIMO Communications

- **Data capacity on a channel limited by Shannon Hartley Theorem**
  - Use more channels!
- **Antenna (Spatial) Diversity**
  - Multiple Antennas
  - Multiple Channels
- **Clever DSP/Modulation**
  - Multiple reference signals
  - Possible to use for Beam Steering part of the signal to particular users.