Advance Digital Radio
BT Mini Hackathon
Danny Webster




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1. Introduction

Modern Communication Standards

<1940s Morse AM FSK
1950s FM appeared

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
CDMA
QAM
APSK
Thuraya
TETRA
PSK
GNSS Bidou
GNSS GPS
GNSS Galileo
FM
DVB-T2
DVB-S2
AM
DAB

Lime microsystems

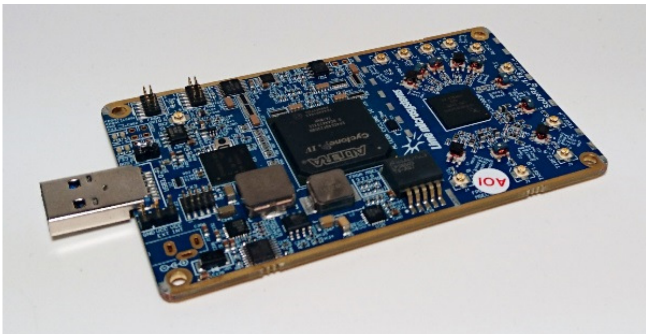
SDR – Partitioning for Low Cost

RF Parts
Antennas
SAW Filters
RF Switches
Power Amps

Optimal partitioning of the radio system leads to an easy to use low cost solution.

TRX RFIC
RF and DSP
Field Programmable

FPGA
Data link and
Extra DSP



PCIe Link

USB3 Link

Open Source Software/Apps

COMPUTER
Multicore
GHz Processor
And Memory

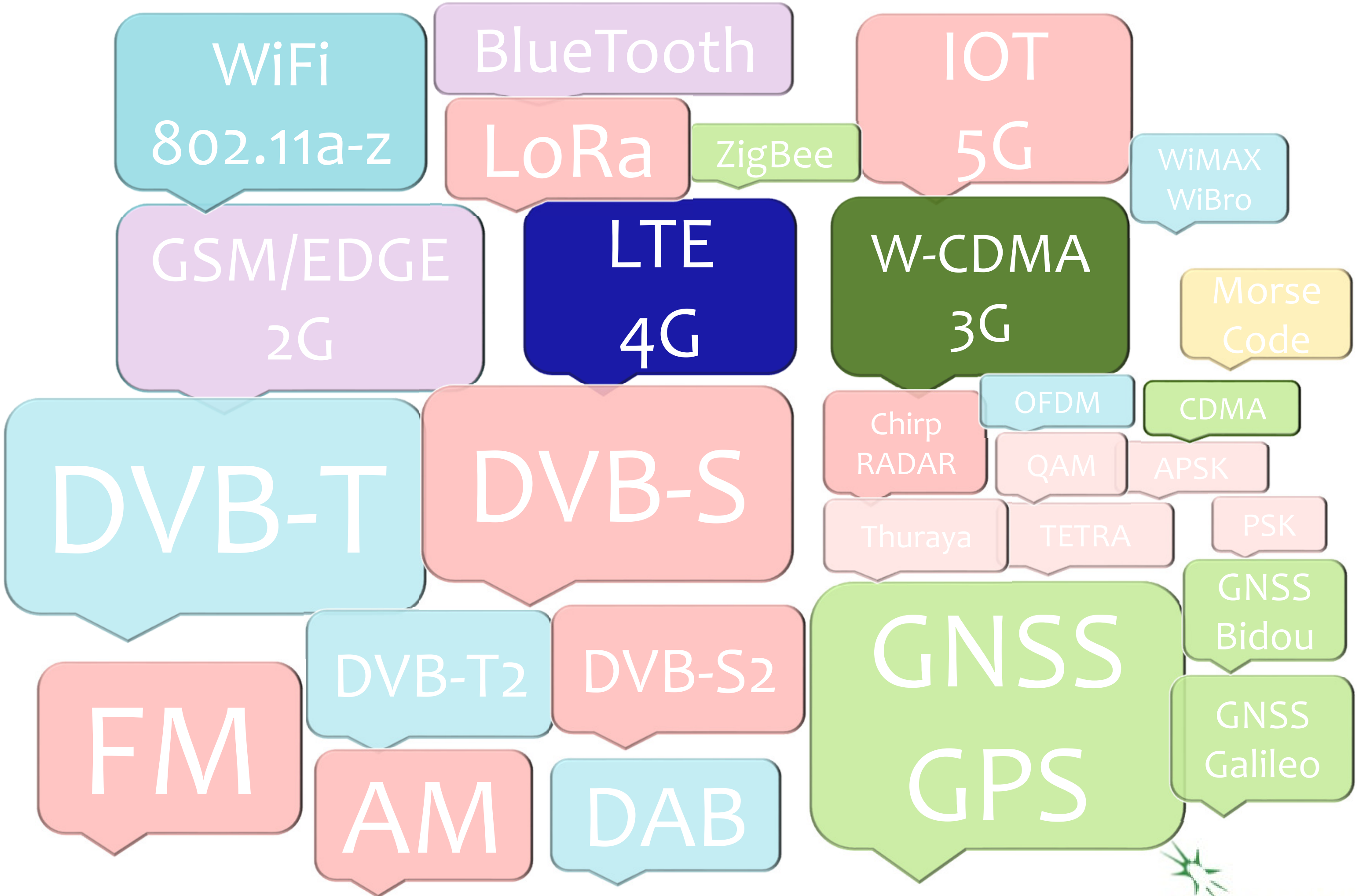
WiFi/Ethernet/ ADSL Network

Typical LimeSDR Budgets

LimeSDR	DAB	DVB-T2	GSM (2G)	W-CDMA UL (3G)	LTE (4G)	LTE (4G)	WiFi	BlueTooth	Zigbee	
	OFDM-PSK8	OFDM	GMSK	DSSS-BPSK	OFDM-QPSK	OFDM-QPSK	OFDM-QPSK	GMSK	DSSS-BPSK	
LO	215.00	480.00	870.00	870.00	870.00	870.00	2450.00	2450.00	2450.00	MHz
RF BW	1.50	7.77	0.18	3.84	20.00	1.40	20.00	1.00	0.25	MHz
Tx Level	**0.00**	**-6.00**	**4.00**	**3.00**	**-2.00**	**-2.00**	**-5.00**	**-5.00**	**-5.00**	**dBm**
Tx Filter loss	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	dB
TxAe	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	dBi
RxAe	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	dBi
Dist	**0.30**	**0.04**	**0.40**	**1.50**	**0.02**	**0.07**	**0.01**	**0.02**	**0.25**	**km**
Loss	68.63	58.11	83.27	94.75	57.25	68.13	54.20	66.25	88.18	dB
Other Loss	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	dB
Rx Level	**-66.63**	**-62.11**	**-77.27**	**-89.75**	**-57.25**	**-68.13**	**-57.20**	**-69.25**	**-91.18**	**dBm**
Thermal	-112.07	-104.93	-121.28	-107.99	-100.82	-112.37	-100.82	-113.83	-119.85	dBm
Eb/No*	10.00	8.00	9.00	7.00	8.00	8.00	8.00	9.00	8.00	dB
Spread Factor	1	1	1	256	1	1	1	1	32	
CodeGain	0.00	0.00	0.00	24.08	0.00	0.00	0.00	0.00	15.05	dB
RF Switch	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	dB
RX Filter Loss	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	dB
Rx NF	3.00	2.50	2.50	2.50	2.50	2.50	3.00	3.00	3.00	dB
Sensitivity	**-96.07**	**-91.43**	**-106.78**	**-119.57**	**-87.32**	**-98.87**	**-86.82**	**-98.83**	**-120.90**	**dBm**
Margin	**29.44**	**29.32**	**29.50**	**29.82**	**30.07**	**30.73**	**29.62**	**29.58**	**29.72**	**dB**

Lets make it a bit more manageable

Focus on
3G and 4G



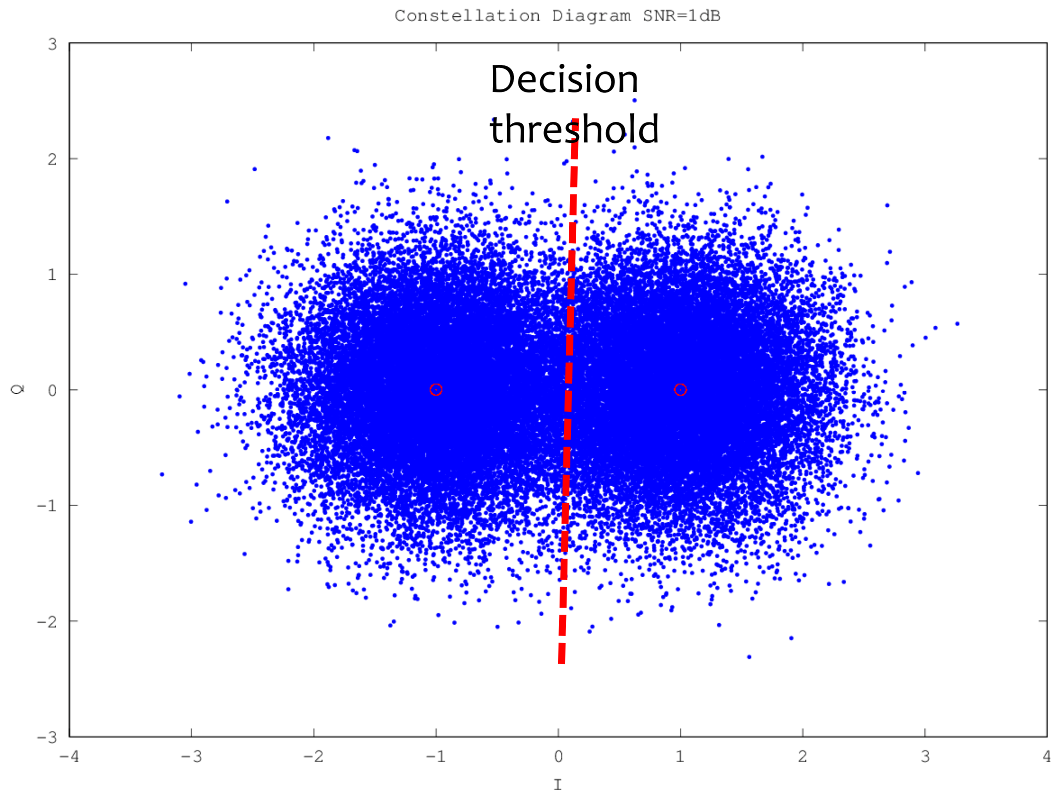
2. Reducing Data Loss

Introduction – Data Loss

- **Noise and Data Uncertainty**
- **Error Detection by Parity and CRC**
- **Error Multiplication by Encryption and Data Compression**
- **Error Reduction and Correction Techniques**

Noise and Symbol error

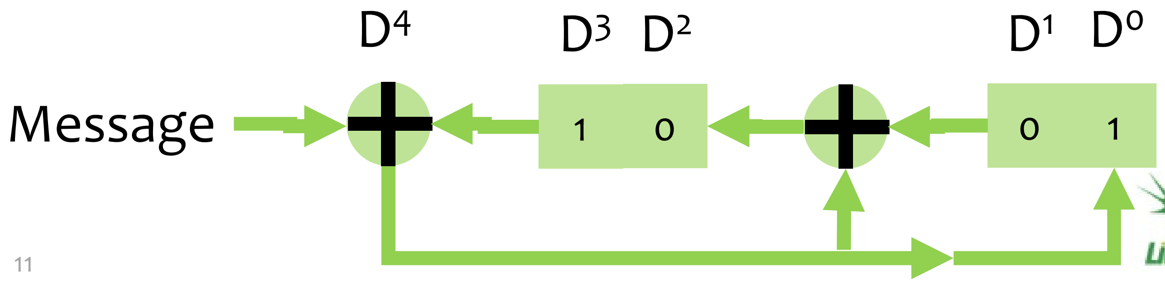
- **Ideal systems have**
  - Precisely defined locations
  - Either 1 or -1
    - how can you mess it up?
- **Real systems have added noise.**
  - Random positions defined by probability.
  - If noise too large, decision threshold crossed for some of the bits.
    - Data is partially damaged
    - Worse case half of bits are wrong!
    - What can we do?



Has Data been corrupted? CRC Checks

- **Simplest error detect code**
  - Parity bits
- **More sophisticated codes**
  - Cyclic Redundancy Codes (CRC)
- **Many systems use a handshaking procedure ACK/NACK**
  - 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
- **CRCs – closely related to PRS**
  - CRC=D^4+D^2+1
  - CRC is the result in the Shift Register



Bit Errors and Encryption

- **Example Block Encryption**
  - E.g. DES64
- **Alphabetical Substitution Encryption**
  - Magic Square type
  - No Q
- **Error Free Encoding**
- **Only one bit error in encrypted letter.**
  - 5 bit errors in decrypted letter.
- **Block 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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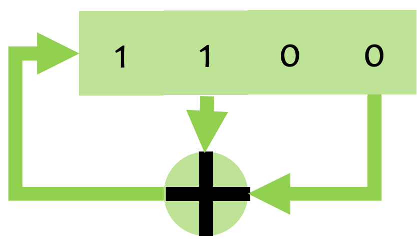
Bit Errors and Scramble Codes

- **Alternative to Block Encryption is a Running Cipher.**
  - XOR (mod2) with PRS/Gold
  - Gives data privacy if PRS is user, cell and time dependent.
  - PRS can cycle over several frames or subframes.
  - Adds randomness to repetitive data e.g. 0,0,0,0…
    - improves behaviour of radio links.
    - Real time Calibration
    - Reduced peak to average.

- **Pseudo Random Sequences**
  - Generated by shift registers with feedback
- **Gold Codes**
  - combine several PRSs of different length and phase via XOR
  - Used in 3G 4G and GPS



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 and complexity.**
- **Many FEC techniques.**
  - Viterbi codes are widely used in Radio links

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

Burst Errors and Interleaving

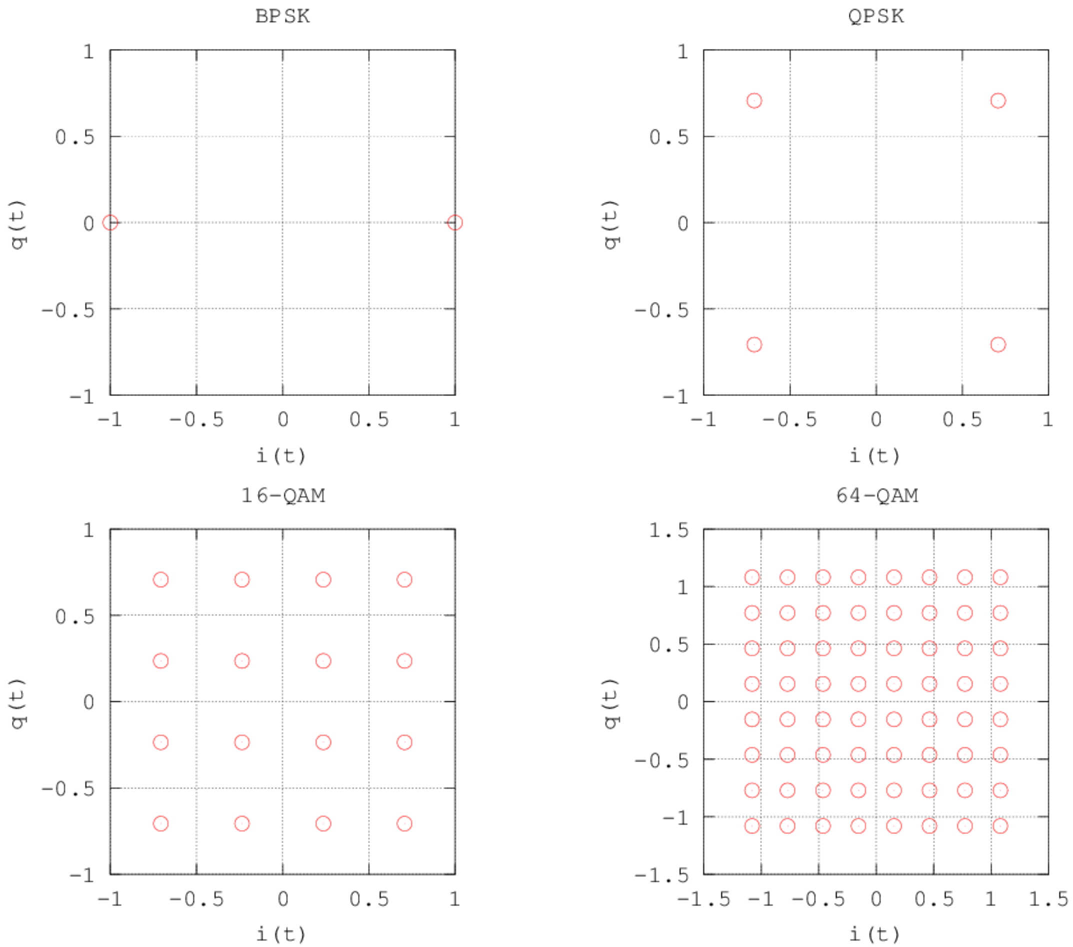
- **Forward Error Correction is good at correcting occasional errors.**
- **But can often fail if a burst of errors occurs.**
- **By interleaving data**
  - E.g. Matrix transpose
- **Burst of errors can be spread over several encoded words, or even entire frames.**
- **So looks like single bit errors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

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

3 Consecutive 3 bit words
With 1 bit error

Burst of errors affect
3 consecutive bits
An entire word corrupted

Bit Errors and QAM Density



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

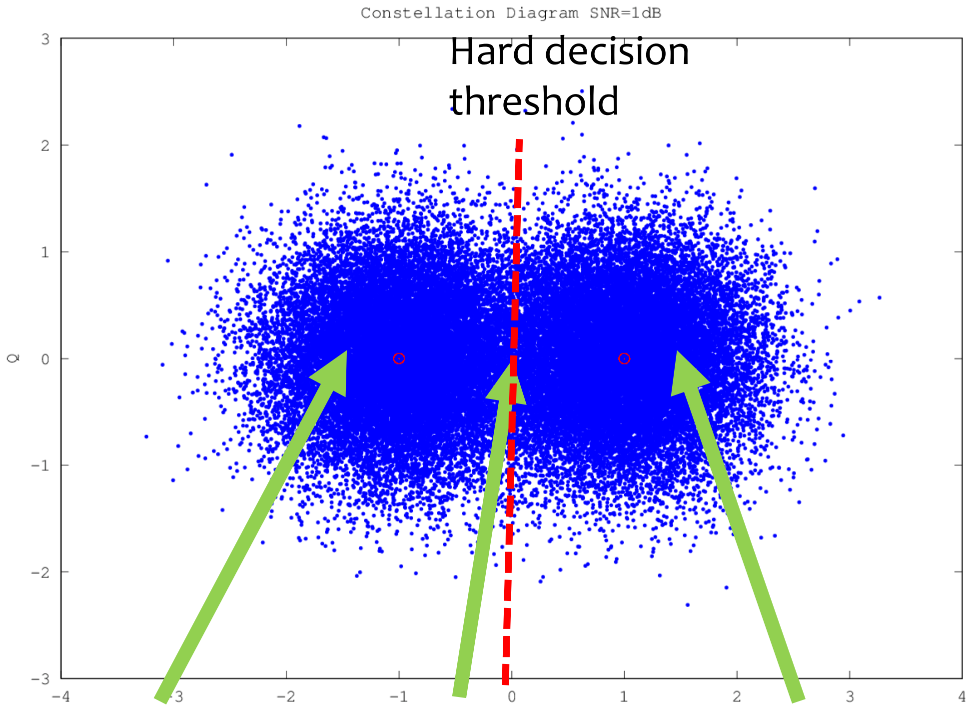
QAM and Bit Error Multiplication

- **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

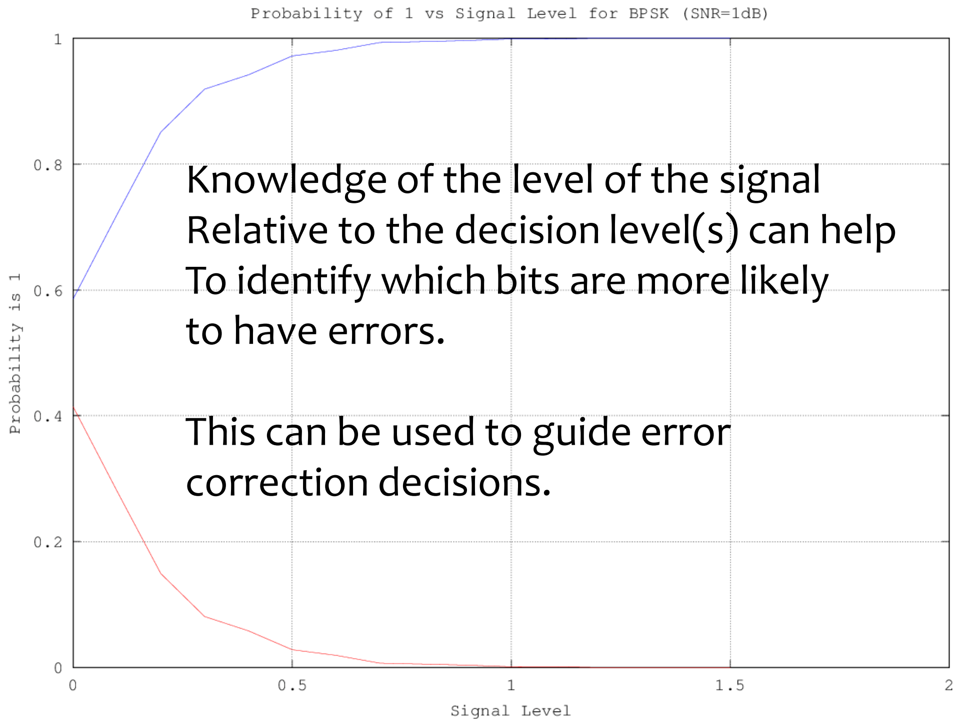
Soft Error Correction



Bit more likely error free here

Bit more likely Has error here

Bit more likely error free here

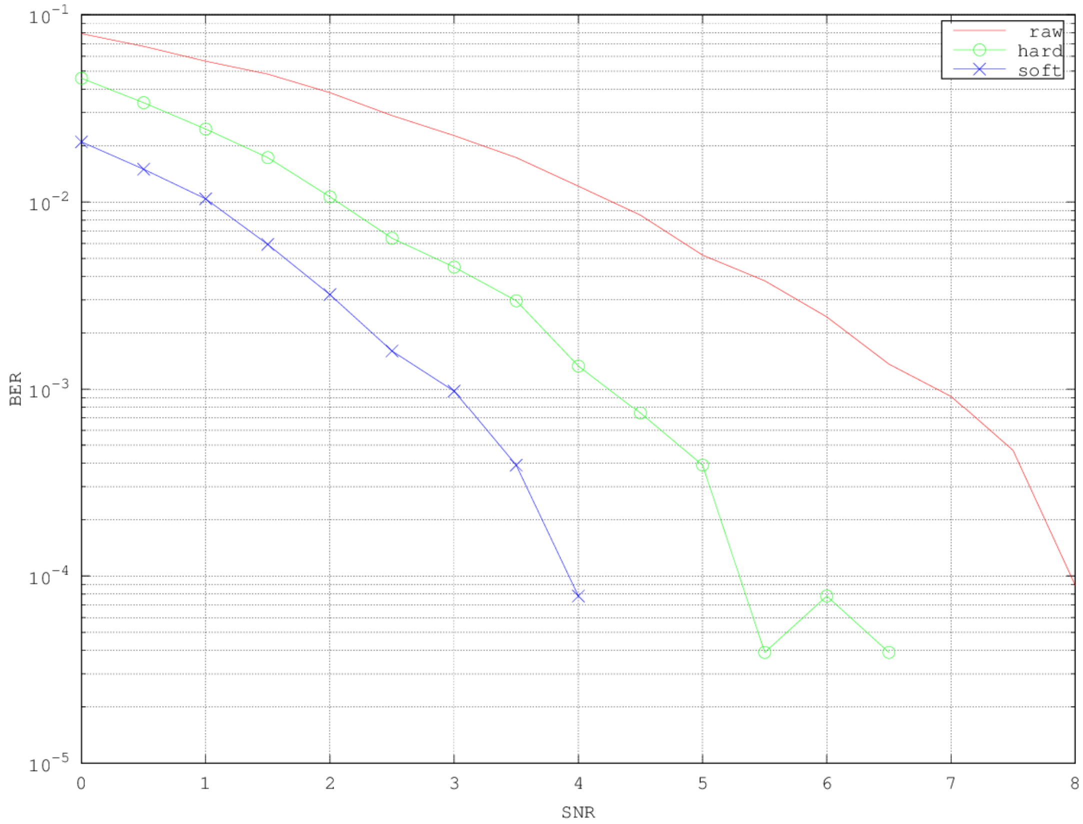


Knowledge of the level of the signal
Relative to the decision level(s) can help
To identify which bits are more likely
to have errors.

This can be used to guide error
correction decisions.

Soft Error Correction

- **Hard Error Correction**
  - Bit Value depends on decision threshold
- **Soft Error Correction**
  - Probabilistic decision about which bits are more likely to contain errors.
  - Evaluate multiple possibilities and select the most likely.
- **Soft Error Correction improves performance of FEC codes.**
  - E.g. Hamming 4/7 code – 1.3dB improvement



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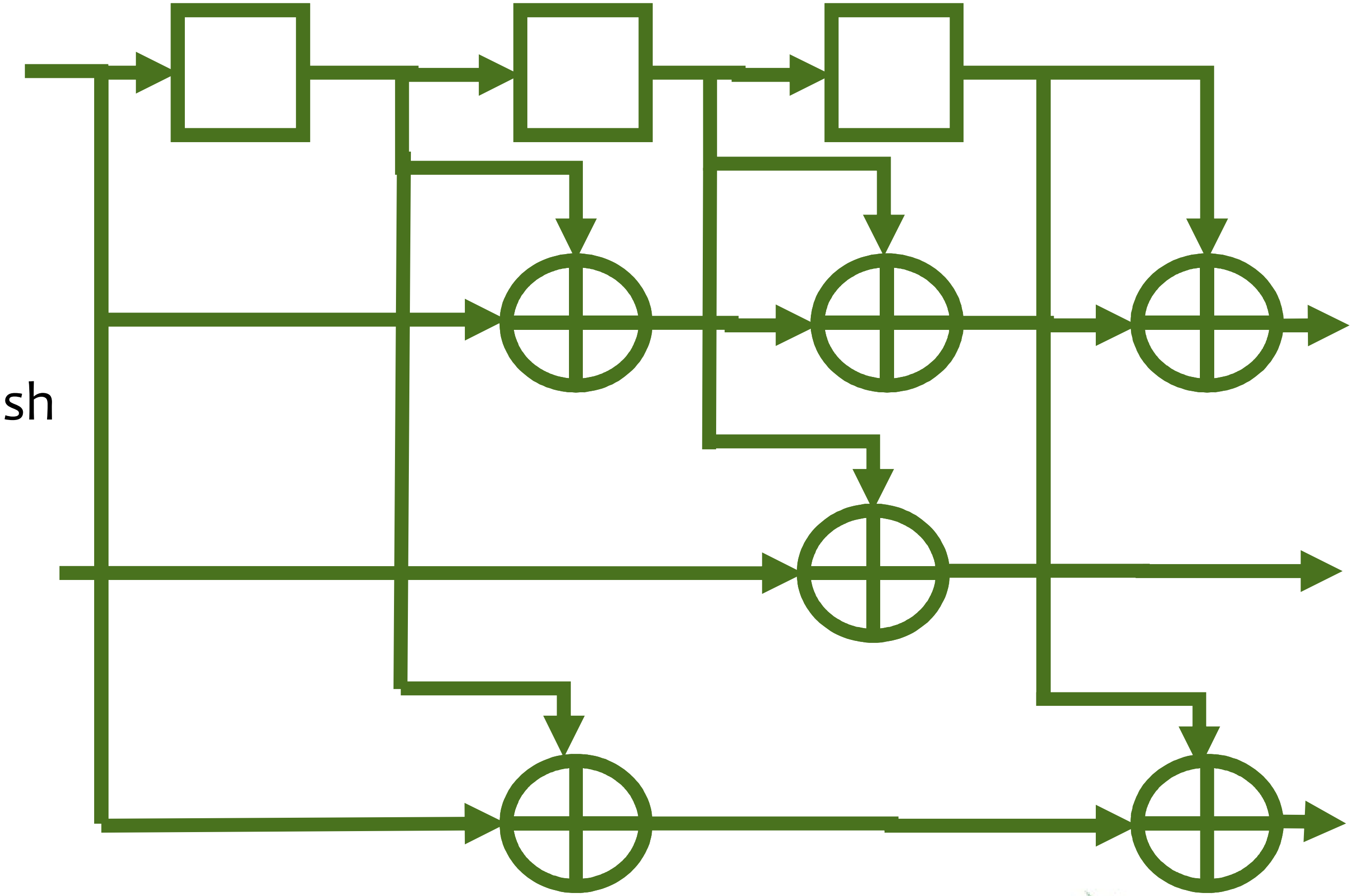
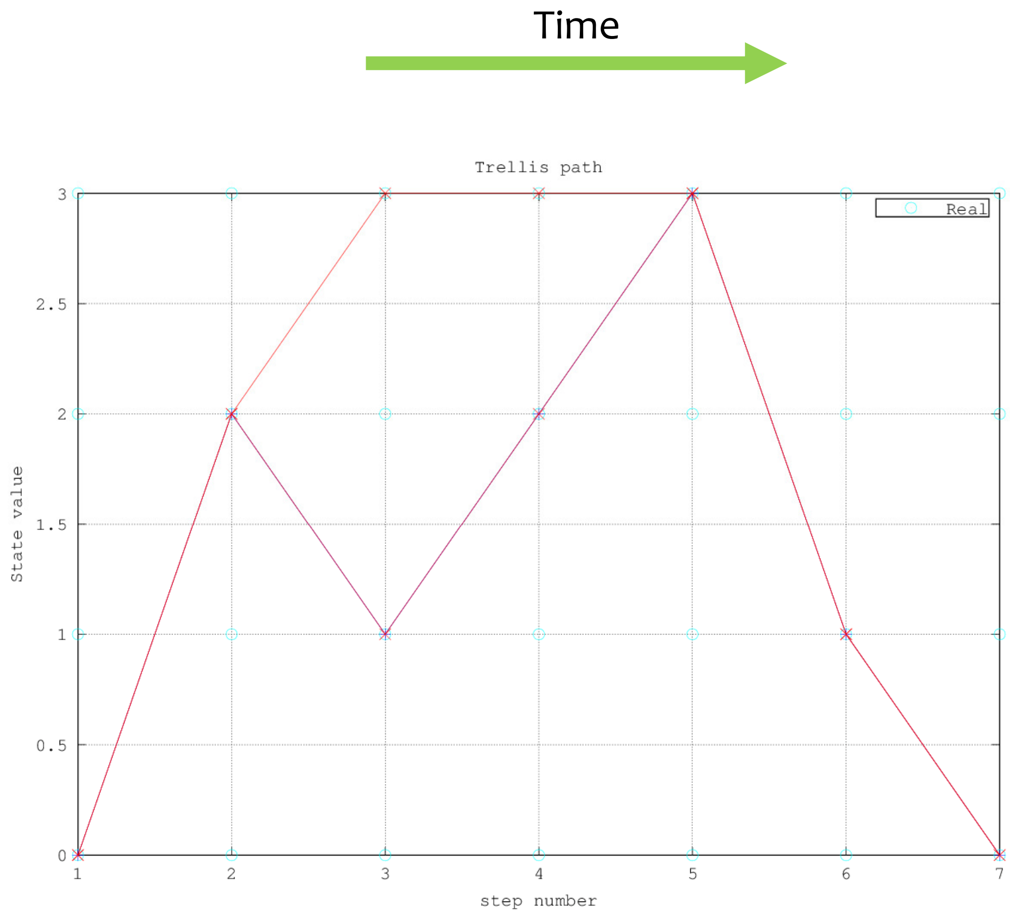
Convolutional Error Correction

- **Convolution Encoding**
  - Viterbi Encoder
  - Turbo Codes
  - State based encoders.
    - State depends on history
  - Usually have know start or finish states.
    - E.g. all Zero start
    - E.g. Tail biting
      - first and last state the same.



Convolutional Error Correction

- **Trellis Based Decoding (State – Time)**
  - Burst errors lead to multiple paths through trellis with different probabilities. Best path selected.
  - Paths re-converge after error burst ends and encoder settling time.
  - Traditional single pass decoding does not take advantage of knowledge of future convergence.
- **Itterative Decoding**
  - Decoding uses both past and present knowledge.
  - Data capacity can approach closely to Shannon limit.



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Error Correction and Data Efficiency

- **Shannon Hartley Theorem**
  - C=B log2(1+SNR)
  - Capacity falls with deteriorating signal to noise ratio for a given bandwidth.
  - This reduction in capacity can be interpreted as a need for an increase in FEC bits to correct errors.
  - Theoretical limit
  - =>Eb/No approx. -1.7dB
  - Modern Turbo codes and LDPC techniques get very close to this limit. Typically Eb/No 1dB
- **Mobile radio**
  - Reception quality varies with time and 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. WiFi/LTE etc.
  - E.g. 5/6 rate codes

3. Direct Sequence Spread Spectrum Signals CDMA

Introduction – Spread Spectrum

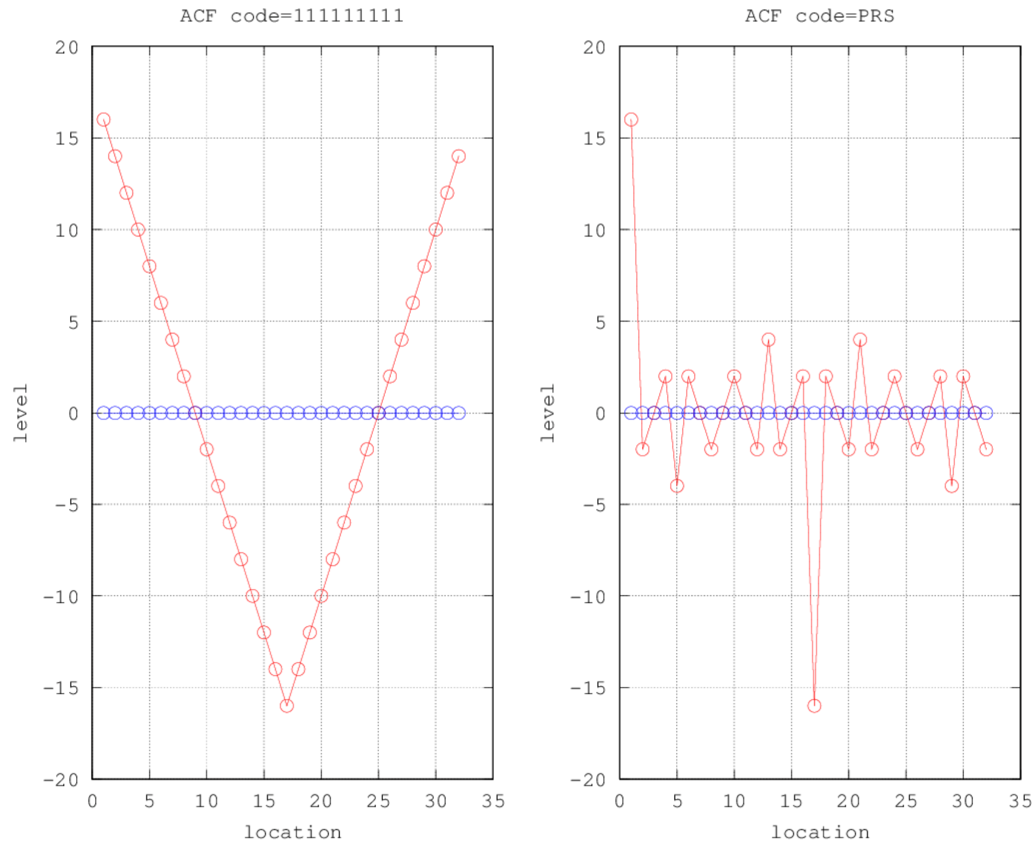
- **Spread Spectrum vs Error Correction Codes**
- **The Autocorrelation Function**
- **Multiple Access Channels**
- **Long range transmission systems**
- **Typical W-CDMA (3G) signals**

Spread Spectrum and Error Correction

- **Shannon Hartley**
  - Can increase bandwidth to maintain capacity for deteriorating SNR
- **Error correction increase number of transmitted bits.**
  - Imagine we can keep increasing the transmission rate, but keeping the information rate the same.
  - 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/No 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 and help construct echo cancel FIR filter
    - RAKE filters



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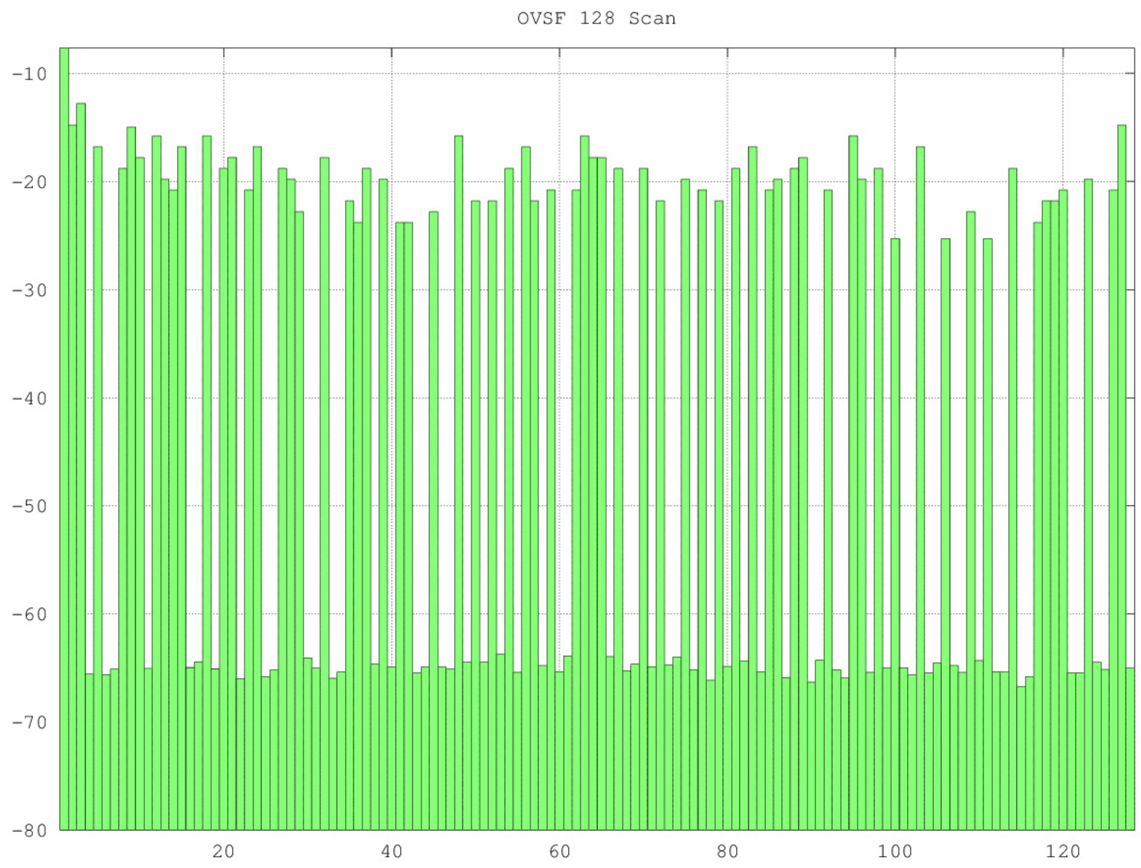
Code Domain Multiple Access (CDMA)

- **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.

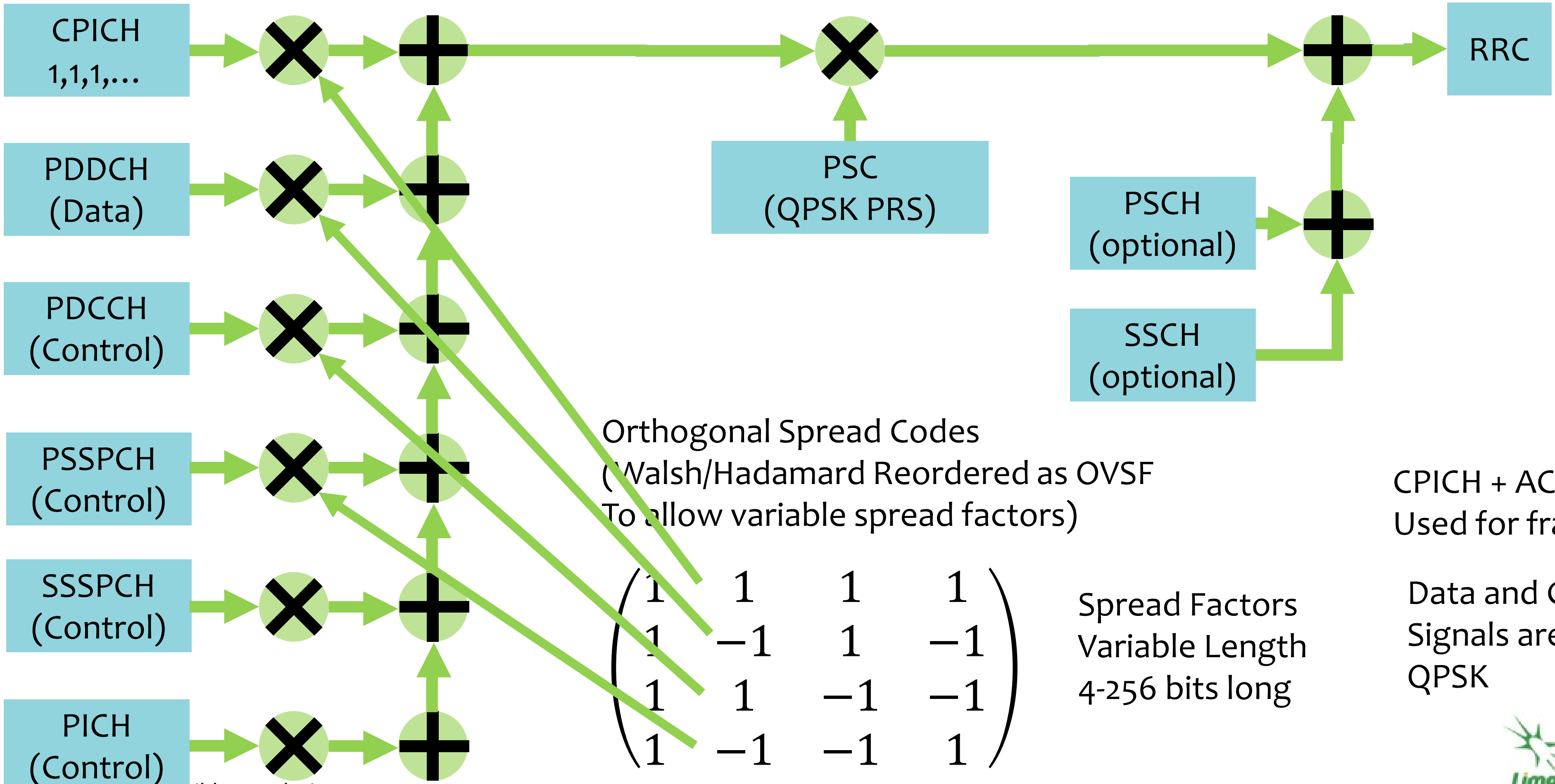


DSSS and Long Range Communications

- **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

W-CDMA DL Signals



Orthogonal Spread Codes
(Walsh/Hadamard Reordered as OVSF
To allow variable spread factors)

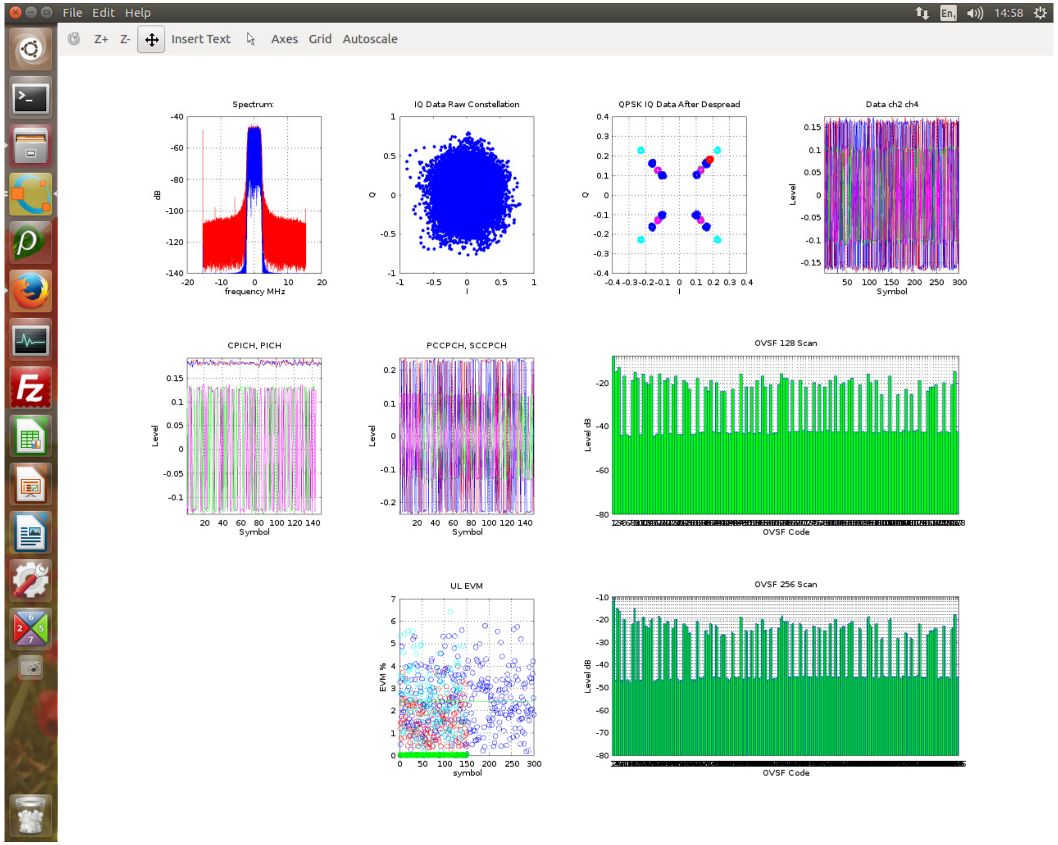
$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix}$$

Spread Factors
Variable Length
4-256 bits long

CPICH + ACF often
Used for frame sync

Data and Control
Signals are usually
QPSK

3G Signals Generated with LimeSDR



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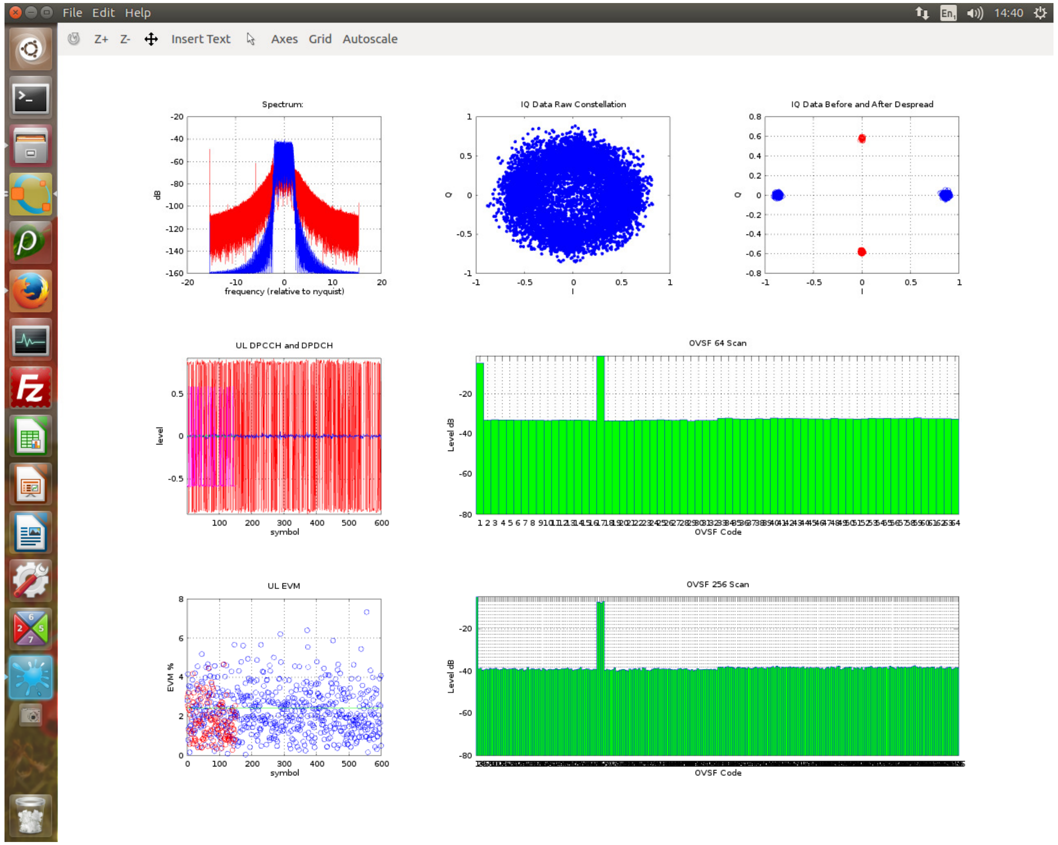
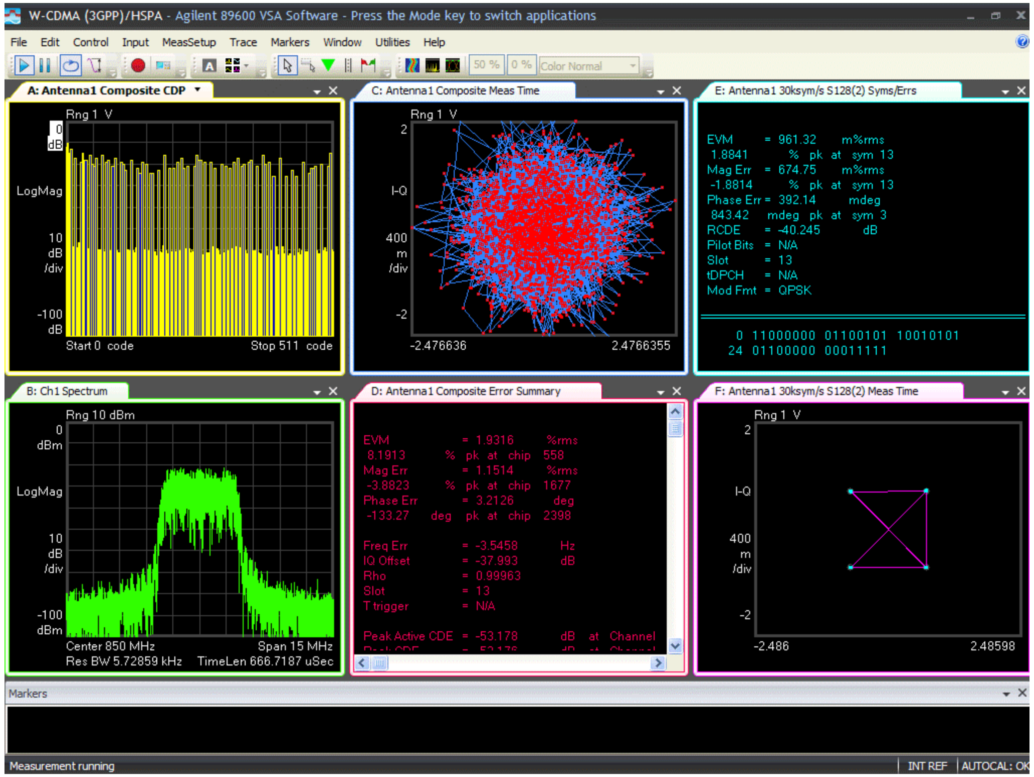


Uplink

4G Signals Generated with LimeSDR



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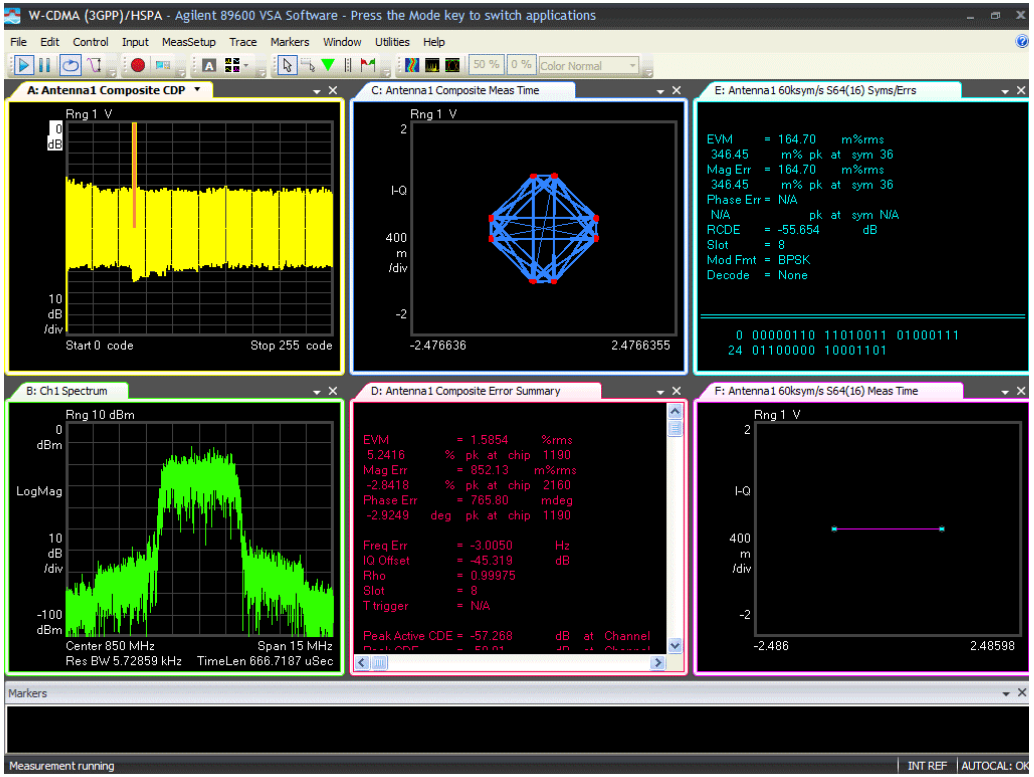


Uplink

Frequency Hopping – An Alternative CDMA

- **Technique to reduce effect of random interference and fading.**
  - Data interleaving spreads data over the hopping sequence.
  - Error correction will recover data.
- **A known random hop sequence can also improve privacy.**
- **Bandwidth increased, but "time shared" with other users.**
  - Used in Bluetooth and 4G
  - Easier to frequency hop in baseband than retune radio.

2. OFDM

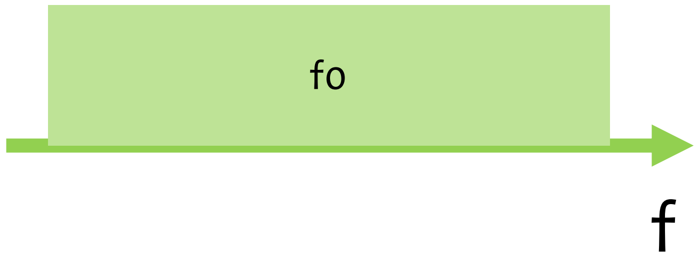
OFDM Introduction

- The OFDM Spectrum
- Equalisation of OFDM
- Cyclic Prefix and Echos
- Peak to Average Ratio Minimisation
- 4G Signals and Resource Block Map
- 4G Frequency Hopping
- Introduction to MIMO
- Lime 4G Physical Layer

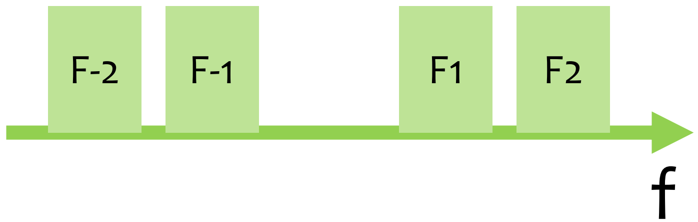
OFDM as a Signal Spectrum

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

Spread Spectrum

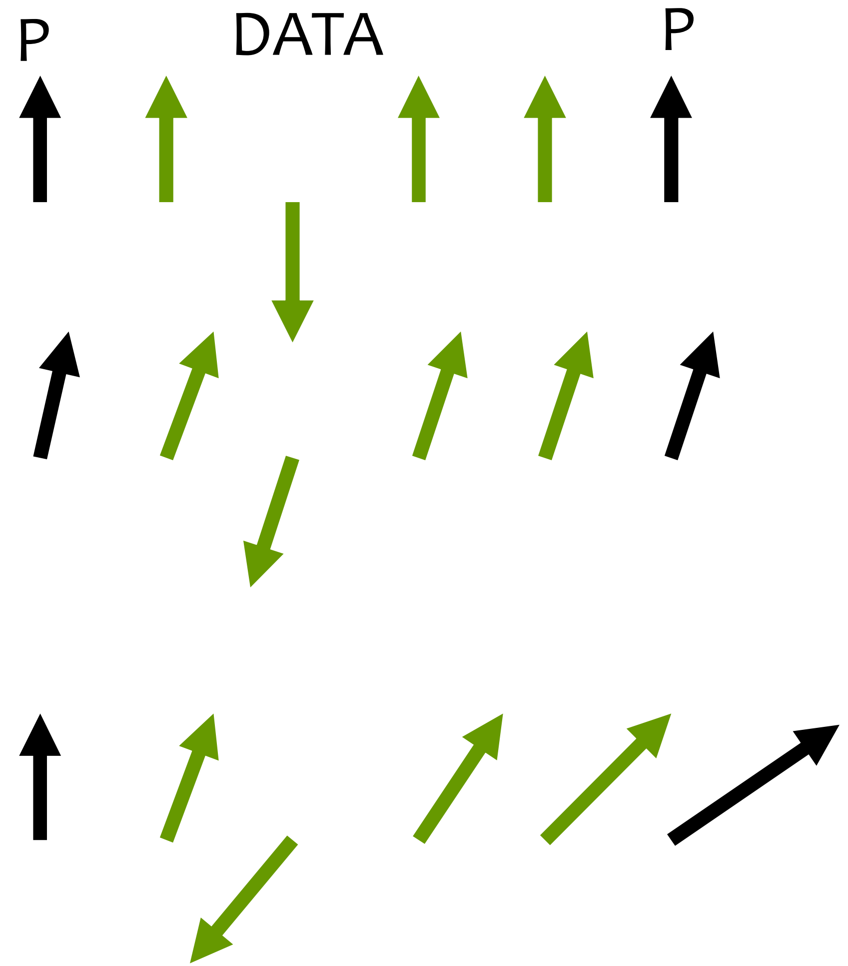


OFDM



Equalization 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**



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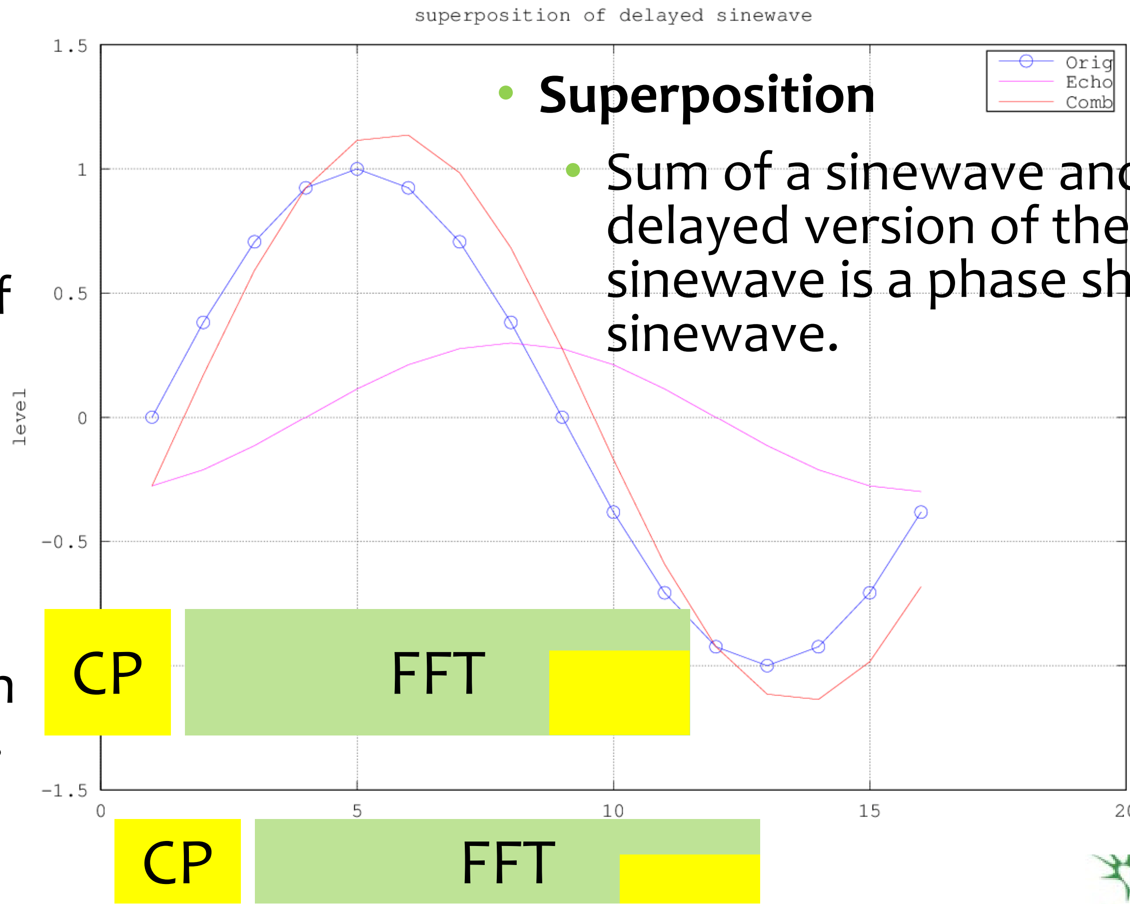
Properties of OFDM - Echos

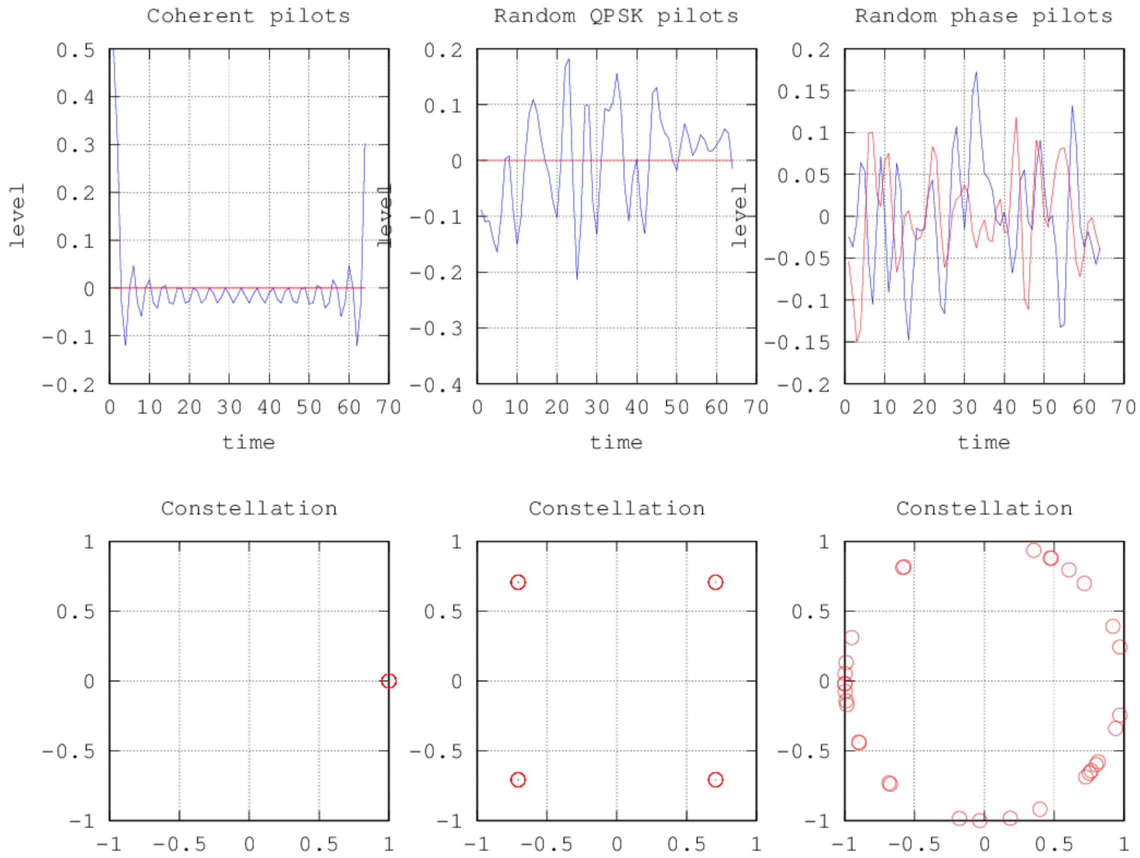
- **Cyclic Prefix**
  - Duplicates the end part of the FFT at the front of the signal. Adds history.
- **Echos**
  - Echo leads to phase shift of OFDM signal if echo is shorter than cyclic prefix.
- **Single Frequency Network**
  - Allows use of single frequency national network if transmitted with delay 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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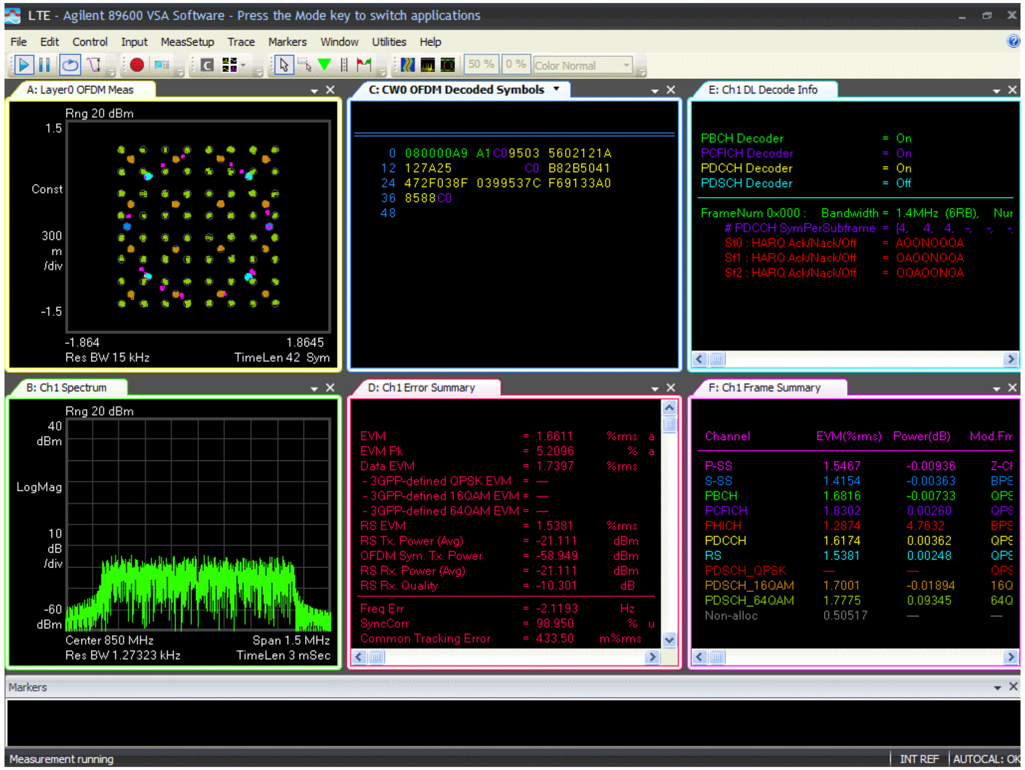
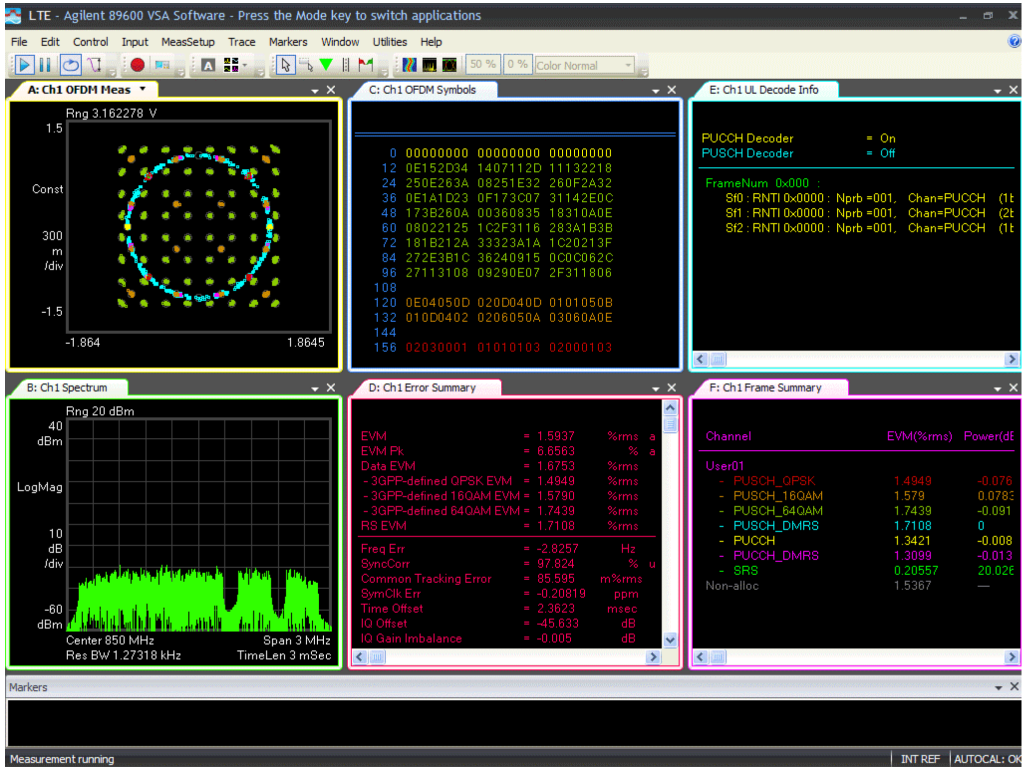
4G Signals Generated with LimeSDR





Downlink

OFDM BPSK/QPSK/QAM16/QAM64
Zadof Chu
QAM256 beginning to be used

Zadof Chu and
SC-FDMA

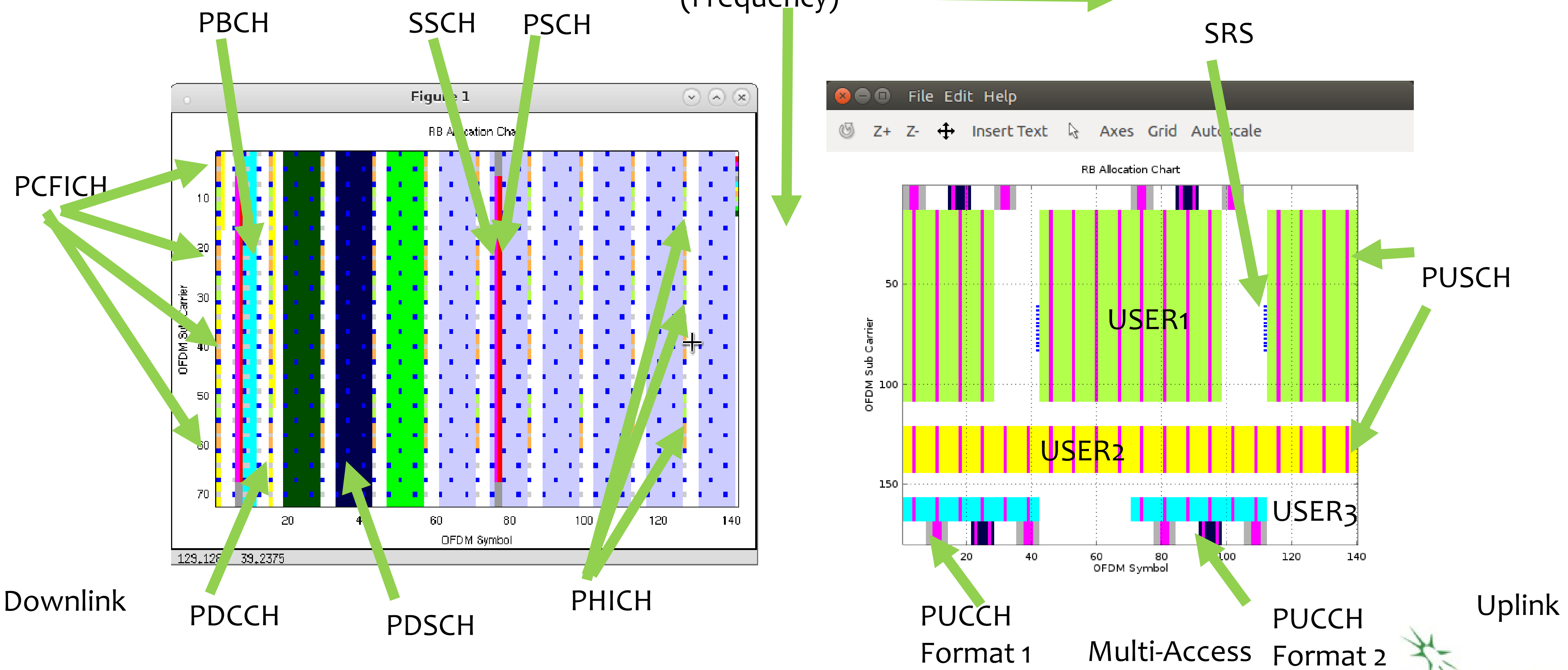
Uplink

4G Signals and the Resource Map

Frame Length 10ms, 140 OFMD Symbols

SubCarriers (Frequency)

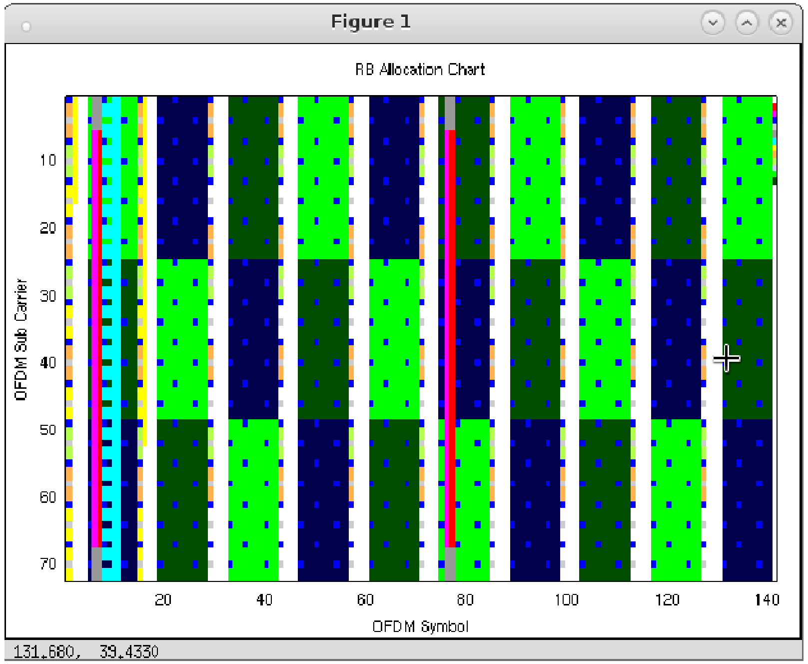
Symbols/Slots/Subframes (Time)



Lime microsystems

Frequency Hopping in 4G

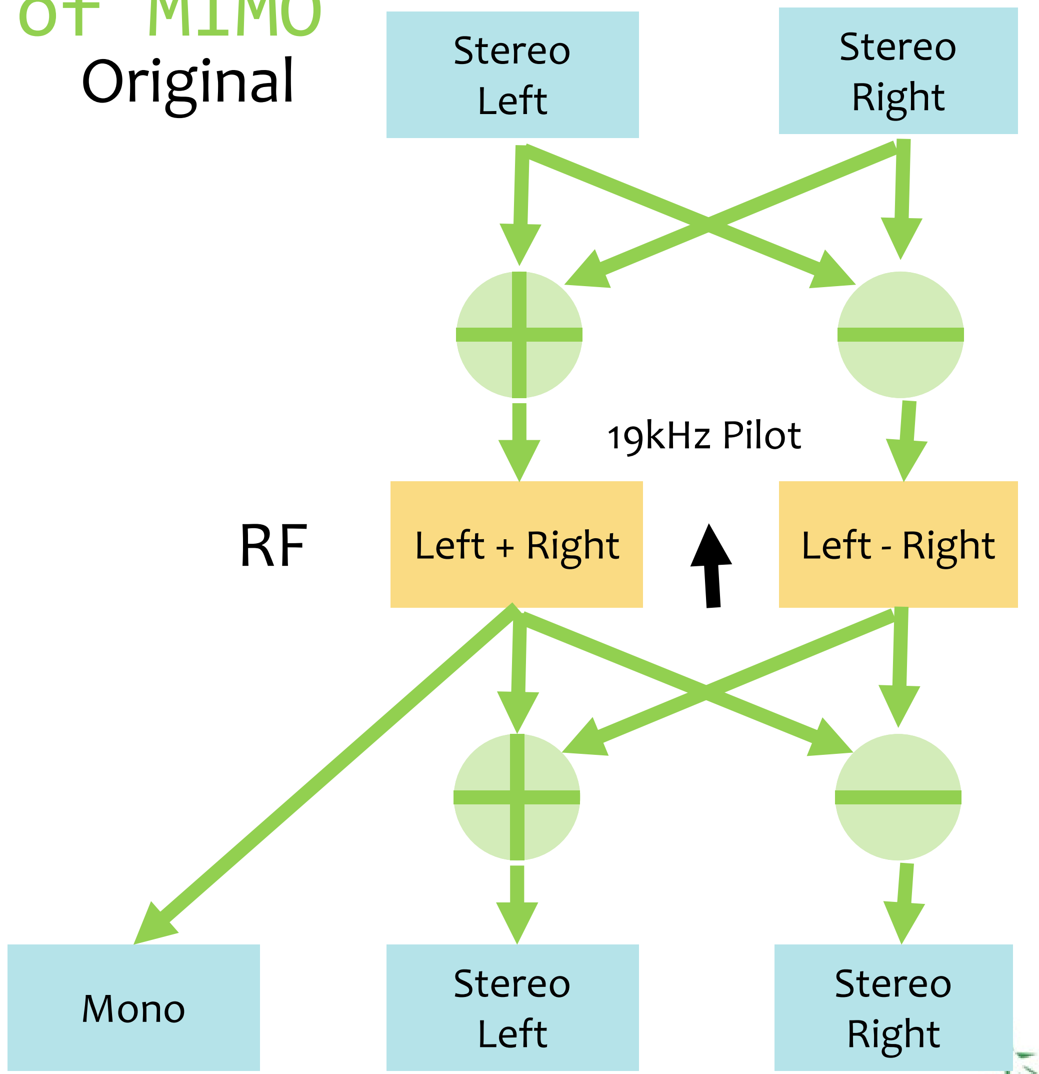
PDSCH can be made to frequency hop



PCFICH and PHICH are spread spectrum

FM Stereo, a kind of MIMO

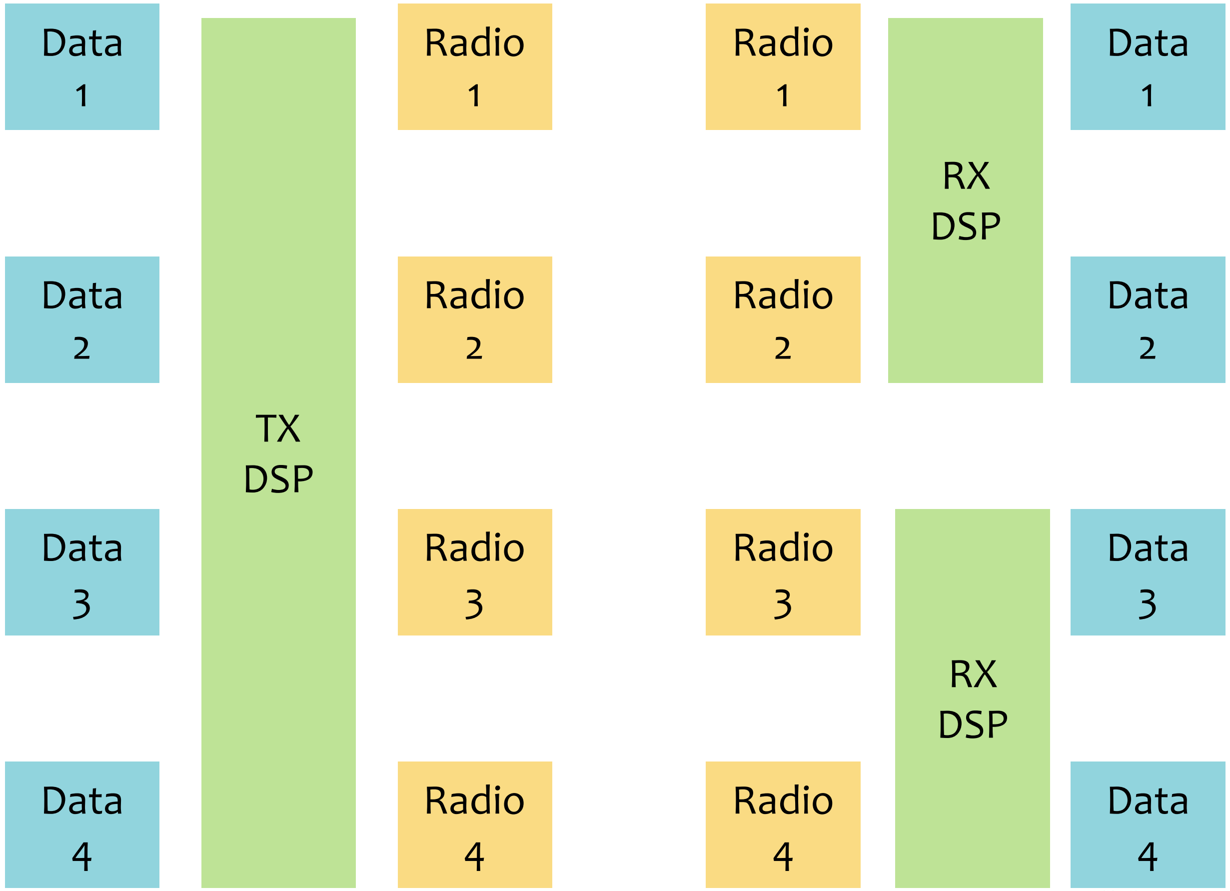
- **Uses Multiple Simultaneous Channels**
- **FM Stereo**
  - Channels combined
  - Two channels separated by frequency
    - Frequency **diversity**
- **Mono Reception**
  - Use left part of signal
- **Stereo Reception**
  - Analogue signal post processing needed to separate original Stereo channels.



Lime microsystems

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.



Lime 4G DL Physical Layer

CRC Enc

Turbo Enc

T Inter leaver

T Bit Collect

PDSCH Symbol Enc

TS 136.211 13.0.0

CRC Enc

Viterbi Enc

V Inter leaver

V Bit Collect

PRS Scramble

PBCH Symbol Enc

2x2 MIMO TRX

Via Octave And separate Lime Library

RB Frame Map

IFFT CP

MPCH Symbol Enc

MIMO Layer Map

USB 3.0

Lime SDR

TS 136.212 13.0.0
In Octave BCH(15,11) and matrix interleaving used for simplicity.

RB Frame Map

IFFT CP

EPDCCH Symbol Enc

EPDSCH Symbol Enc

NOT DONE

3rd Party

PHICH Symbol Enc

Ref Pilots

IN PROGRESS

PSCH

PCFICH Symbol Enc

OCTAVE WORKING

SSCH

C/C++ WORKING

Q Inter leaver

PDCCH Symbol Enc

Lime 4G UL Physical Layer

CRC Enc

Turbo Enc

Inter leaver

T Bit Collect

PRS Scramble

PUSCH Symbol Enc

SCDMA Precode

TS 136.211 13.0.0

PUCCH Symbol Enc

2x2 MIMO TRX

Via Octave
And separate
Lime Library

RB Frame Map

IFFT CP

PRACH Symbol Enc

MIMO Layer Map

USB 3.0

Lime SDR

TS 136.212 13.0.0

RB Frame Map

IFFT CP

DMref Symbol Enc

In Octave BCH(15,11) and
matrix interleaving used
for simplicity.

SRS Symbol Enc

Physical signals generated
Yet to add meaningful content