The Real Radio Link

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1. Introduction

Radio Link is an Hostile Environment

- **Radio Transceiver**
  - Phase Noise
  - DC offsets
  - I-Q Image Rejection
  - I-Q Cross Talk
  - Spurs
- **Other Radio Users**
  - Co-channel Interference
  - Adjacent Channel Interference
  - Out of band Interference
  - Deliberate Jamming
- **Propagation Effects**
  - Line of sight path loss
  - Urban Canyon and other obstacles
  - Multipath Echos and Fading
  - Absorption
  - Ionosphere & Solar flares
  - Weather related phenomena
  - Cosmic Noise
  - Antenna polarisation

2. The Noise Floor and Link Budgets

Thermal Noise

- **Background noise**
  - Depends on how hot a receiver is.
  - Depends on bandwidth of the receiver.
- **Excess noise**
  - Real electronics produce more noise than due to temperature.
  - Often expressed as Noise Figure.
  - Typical System NF=3dB.
  - I.e. 3dB higher than thermal noise.

$$P_{THdBm} = 10log_{10}(kT) + 10log_{10}(BW) + 30$$

k= $1.38E - 23$

T=300K

Sensitivity of a Receiver

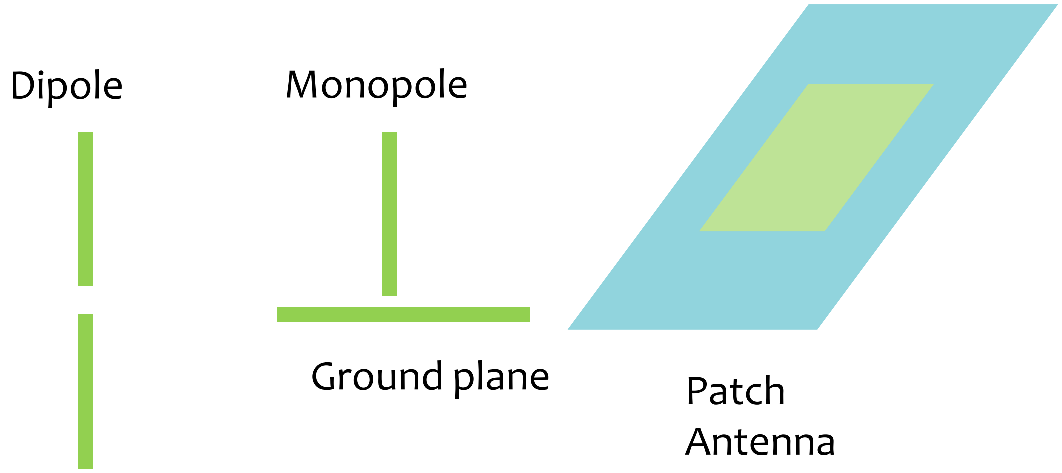
- **Depends on…**
  - Temperature
  - Bandwidth
  - System NF (Excess noise)
  - Signal Type
    - Modulation BPSK,QPSK,QAM16 etc
    - Forward Error Correction
    - Symbol encoding techniques.
    - Code Gain (DSSS only)
  - Losses
    - Cables, filters, switches

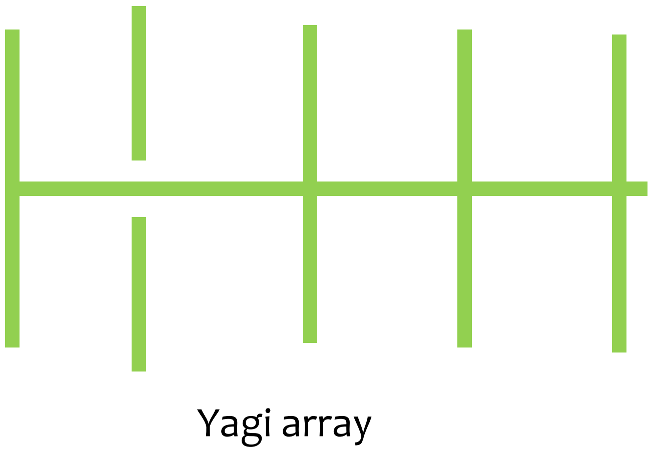
- The signal is usually described by
- E_b/N_o energy per bit to noise spectral density.
  - Typically 7-8dB for QPSK without FEC
- Usually defined for a bit error rate (BER)
  - Typically -0.5dB with Turbo Codes
  - Typically 1.5dB with Viterbi
  - Typically 3dB with Traditional Block Codes

$$P_{SENSdBm} = P_{THdBm}(BW,T) + NF + RX_{Loss} + E_b/N_0(BER)$$

Antenna Gain

- **Hertzian Dipole**
  - Fictional antenna
  - Uniform behaviour in every direction
  - Used as a Reference.
- **Omnidirection Antennas**
  - Dipoles and monopoles (Gain 2.2dBi)
  - Patch antenna
- **Directional Antennas**
  - Yagi array (Gain 6-18dBi)
  - Helical antenna
- **Polarization**
  - Horizontal, vertical, circular





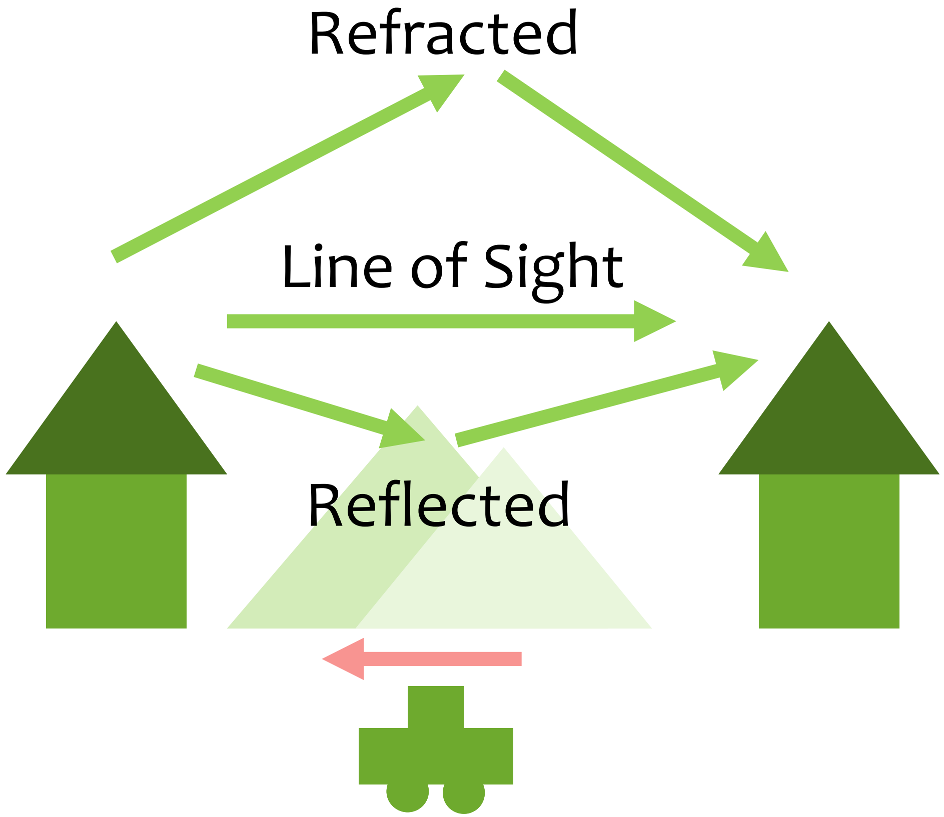
Propagation Loss

- **Friis Propagation equation**
- **Depends on …**
  - Distance D m
  - Wavelength λ m
  - Antenna Gains G dBi
  - Typically 45dB for indoor LoS
  - Typically 70dB for outdoor LoS
  - Typically 180dB for satellite
- **Antenna gain, height has a significant effect on useful range of a radio system.**
- **Path lengths are modified by refraction effects for long distance.**

$$P_{Rx} = P_{TxdBm} + G_{TxdBi} + G_{RxdBi} - 20log_{10}\left(\frac{4\pi D}{\lambda}\right)$$

Multipath Fading

- **Speed and time dependent.**
- **Common in the "urban canyon".**
- **Rician Fading**
  - One path dominates
  - Other paths time changing
- **Rayleigh Fading**
  - All paths have similar levels
  - Probability model
  - 30dB Margin for 99.9% reception
  - 20dB Margin for 90.0% reception
- **Paths**
  - Direct
  - Refraction (Weather)
  - Reflection (Landscape, Vehicles)
  - Diffraction (Obstruction)



Lime microsystems

Obstructions

- **Can Radio Waves Pass through Walls?**
  - Yes, but…
  - Attenuation is frequency and material dependent.
- **Can Radio Waves go round corners?**
  - Yes, Edge Diffraction
  - But…
  - Lossy. Dependent on wavelength, angle and shape/material of wall.

Typical LimeSDR LoS Link Budgets

	Range of LimeSDR without external amplification(Conservative)												
LimeSDR	DAB	DVB-T2	GSM (2G)	W-CDMA UL (3G)	LTE (4G)	LTE (4G)	LTE (4G)	LTE (4G)	LTE (4G)	WiFi	BlueTooth	Zigbee	
	OFDM-PSK8	OFDM	GMSK	DSSS-BPSK	OFDM-QPSK	OFDM-QPSK	OFDM-QPSK	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	2450.00	2450.00	2450.00	MHz
RF BW	1.50	7.77	0.18	3.84	5.00	20.00	1.40	5.00	20.00	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**	**-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	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	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	1.00	1.00	1.00	dBi
Dist	**0.500**	**0.037**	**0.840**	**2.600**	**0.107**	**0.053**	**0.051**	**0.027**	**0.013**	**0.009**	**0.027**	**0.250**	**km**
Loss	73.07	57.43	89.72	99.53	71.82	65.72	74.38	68.85	62.50	59.31	68.85	88.18	dB
Other Loss	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	dB
Rx Level	**-71.07**	**-61.43**	**-83.72**	**-94.53**	**-71.82**	**-65.72**	**-77.38**	**-71.85**	**-65.50**	**-62.31**	**-71.85**	**-91.18**	**dBm**
Thermal	-112.07	-104.93	-121.28	-107.99	-106.84	-100.82	-112.37	-106.84	-100.82	-100.82	-113.83	-119.85	dBm
Eb/No*	5.00	8.00	2.00	2.00	-0.50	-0.50	-0.50	-0.50	-0.50	2.00	5.00	8.00	dB
Spread Factor	1	1	1	256	1	1	1	1	1	1	1	32	
CodeGain	0.00	0.00	0.00	24.08	0.00	0.00	0.00	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	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	2.50	2.50	2.50	dB
Rx NF	3.00	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	3.00	3.00	3.00	dB
Sensitivity	**-101.07**	**-91.43**	**-113.78**	**-124.57**	**-101.84**	**-95.82**	**-107.37**	**-101.84**	**-95.82**	**-92.82**	**-102.83**	**-120.90**	**dBm**
Margin	**30.00**	**30.00**	**30.06**	**30.04**	**30.02**	**30.10**	**29.99**	**29.99**	**30.32**	**30.51**	**30.98**	**29.72**	**dB**

LimeSDR DAB Radio Link Budget Example

Range of a Radio is usually a probability not a certainty!

3km
-88.6dB

Tx 0dBm ERP

0.5km
-73.1dB

TX

Strong Reception
Indoor Omnidirectional Antenna possible

RX1

Rx -73dBm
Sens -101dBm
Margin 28dB

Borderline Reception
Outdoor Directional Antenna Recommended

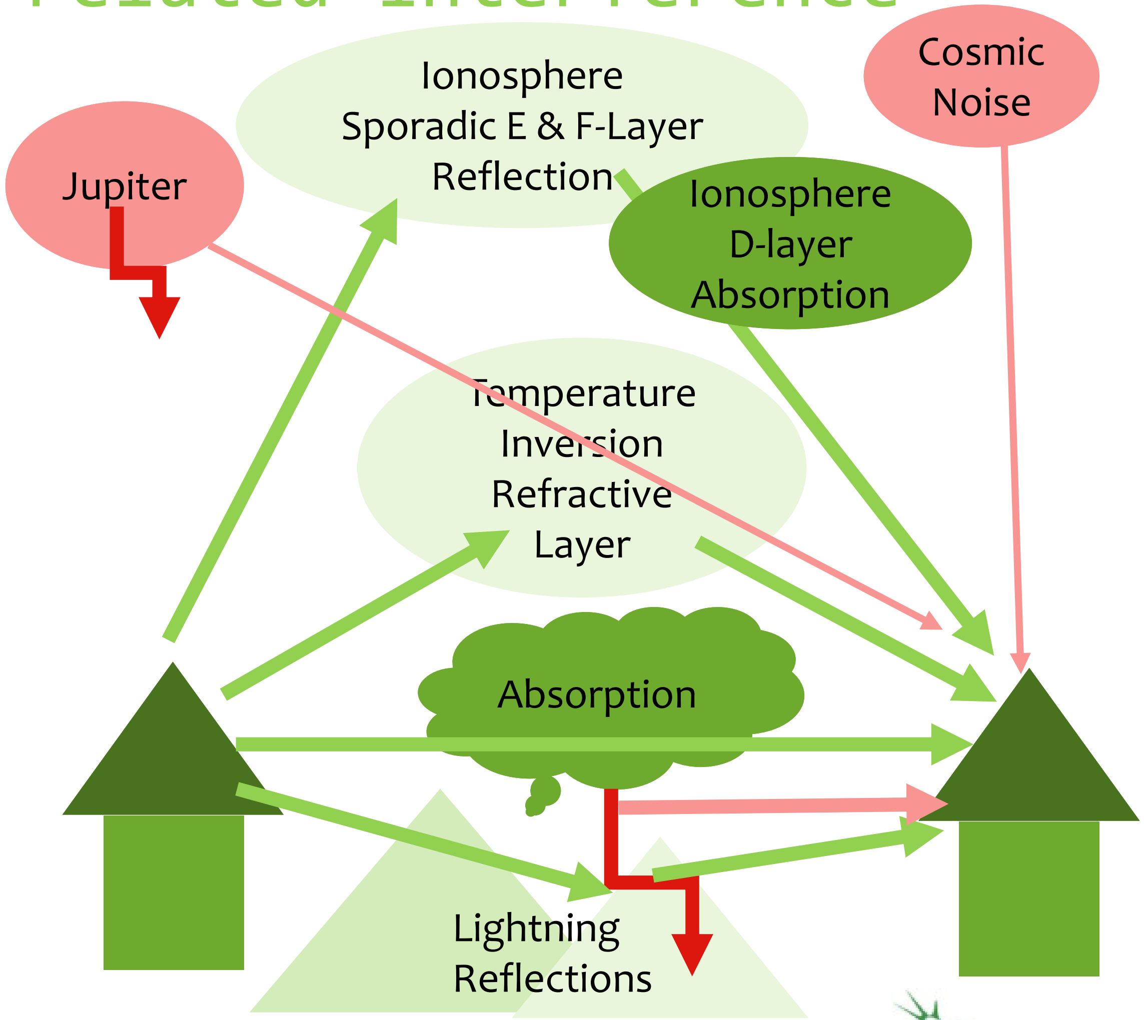
RX2

Rx -89dBm
Sens -101dBm
Margin 11dB

Lime microsystems

Weather and Space related interference

- **Enhanced propagation**
  - Solar flares and ionosphere (HF/VHF)
  - Temperature inversion (VHF/UHF)
    - Inverted Mirage effect
  - Ducting along Weather fronts
    - Waveguide effect
  - Unexpected distant strong signals
    - Extends horizon to over 260miles.
- **Lighting & Meteors**
  - Burst noise (MF/HF)
  - Reflections from ionized path
- **Attenuation from Absorption (Rain)**
  - Mostly affects high microwaves
  - However 915 and 2450MHz Water.
  - Also Ionosphere (D-layer) (HF)



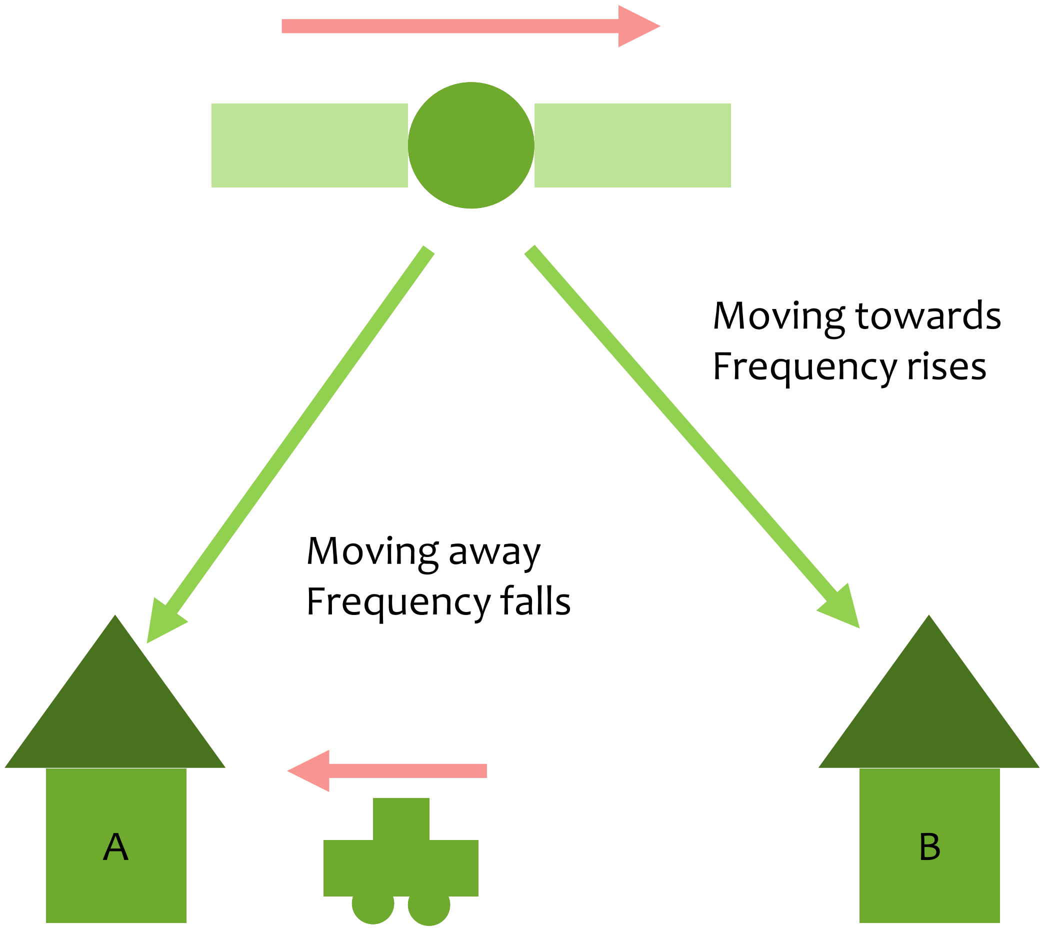
LimeSDR and Space Communications

- **GNSS Satellites**
  - Yes
  - external antenna module
    - away from buildings.
- **Moon bounce**
  - No and Yes
  - external power amplifier
    - >100W
  - high gain antenna arrays
  - Spread spectrum signals or Morse Code

	GPS	MoonBounce	
	DSSS-BPSK	DSSS-BPSK	
LO	1575.45	432.00	MHz
RF BW	2.05	0.05	MHz
Tx Level	**43.52**	**50.00**	**dBm**
Tx Filter loss	0.00	0.00	dB
TxAe	13.40	22.00	dBi
RxAe	2.00	22.00	dBi
Dist	**25,236**	**740,000**	**km**
Loss	184.43	250.00	dB
Other Loss	0.50	0.50	dB
Rx Level	**-126.01**	**-156.50**	**dBm**
Thermal*	-110.72	-126.84	dBm
Eb/No*	8.00	8.00	dB
Spread Factor	20460	20460	
CodeGain	43.11	43.11	dB
RF Switch	0.50	0.00	dB
RX Filter Loss	2.50	0.00	dB
Rx NF	2.50	2.50	dB
Sensitivity	**-140.33**	**-159.45**	**dBm**
Margin	**14.32**	**2.95**	**dB**

The Doppler Shift

- **Radio waves described by wavelength and velocity.**
- **Frequency is the observed number of waves passing you in a given time period.**
  - Depends on relative velocity and speed of light.
- **What happens if something moves?**
  - Observer A sees –ve frequency shift
  - Observer B sees +ve frequency shift
  - Mobile observer sees a different frequency shift
  - GPS approx +/-4kHz
  - Doppler shift varies with time and place.
  - Red shift



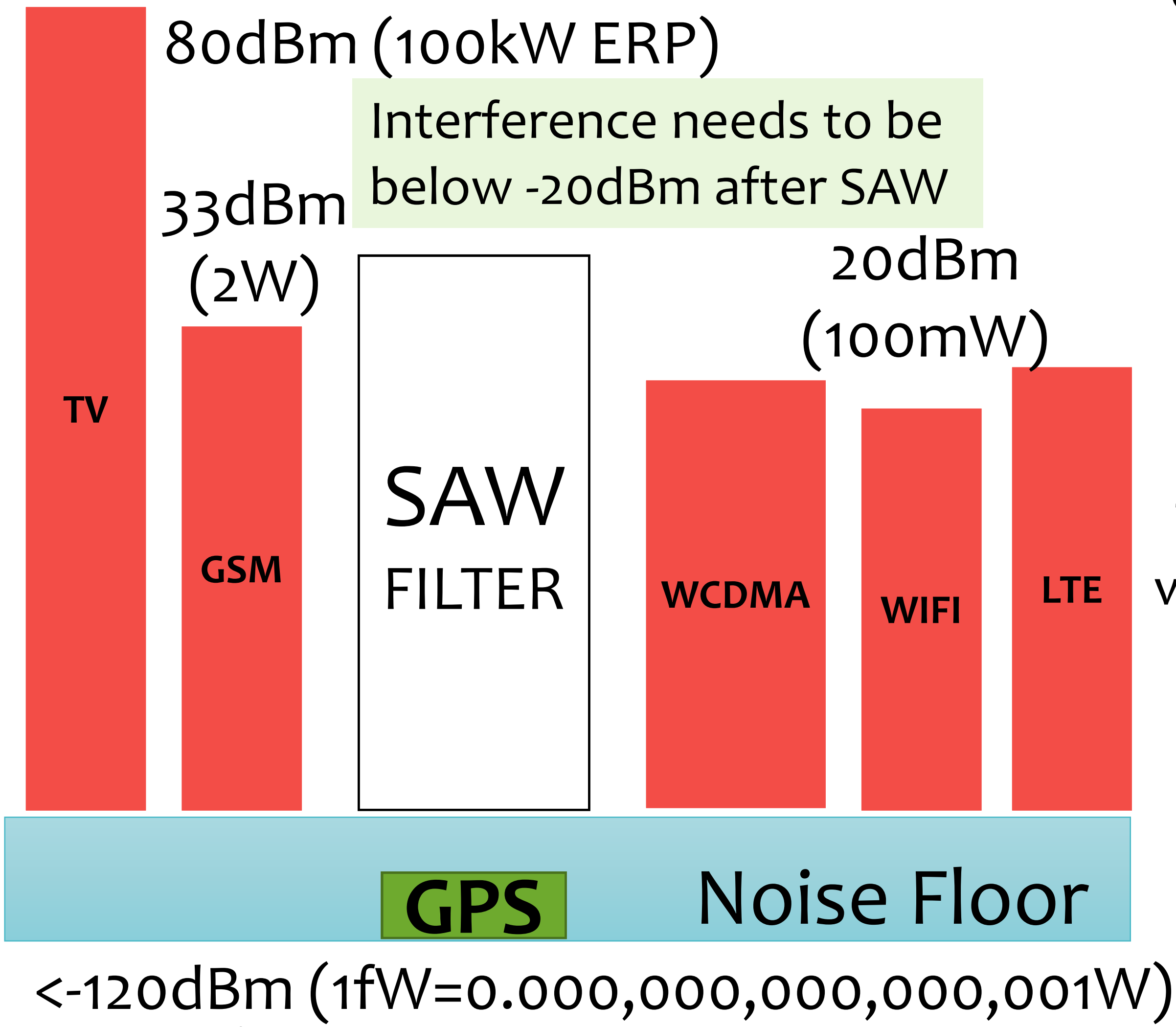
3. Bad Neighbours

Bad Neighbours

- **“No man is an island”**
  - John Donne 1624.
- **Especially true for Urban radio links.**
- **We are surrounded by radio links.**
  - UHF TV Transmission
  - VHF Radio Transmission
  - 2G/3G/4G Mobile Radio
  - Point to Point and Satellite links
  - WiFi and Bluetooth Devices
  - 5G Internet of Things
  - And many more…

- **How do we live with bad neighbours?**
  - SAW RF Band Select Filter
  - Directional antennas

SDR GPS Receiver: Dynamic Range



Collocation of Broadcast, Mobile and WiFi With GNSS leads to challenges (Bad Neighbours!)

Receiver must be able to work with very low signals in the presence of strong interfering signals.

This simultaneously requires low NF, very low far out phase noise (-160dBc), high P1dB and good IIP2 and IIP3 and a good ADC.

Often your own TX is your worst interferer in collocated radios Need SAW filters in active antenna.

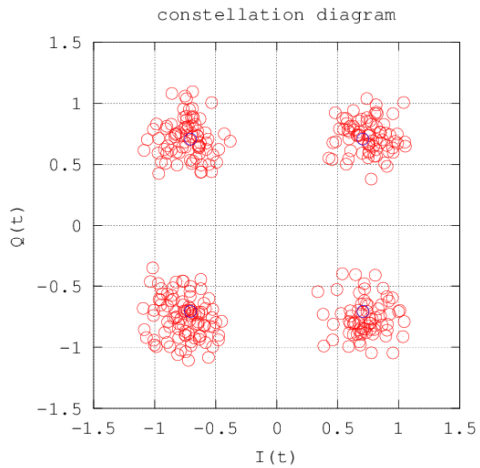
How NOT to be a Bad Neighbour!

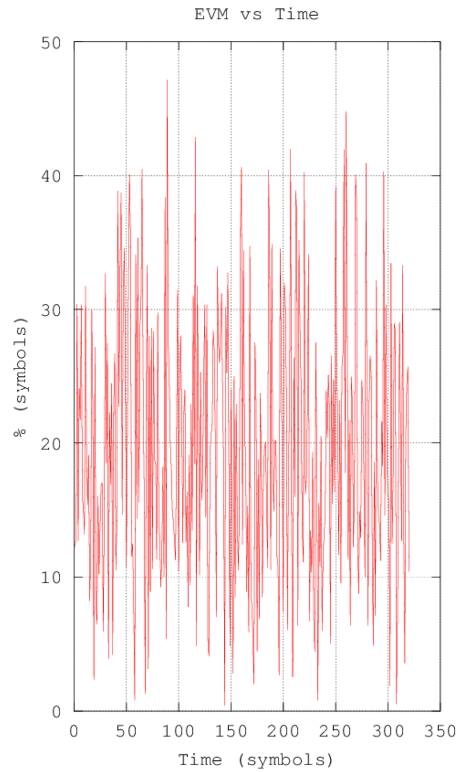
- **Think about other radio users**
  - Spread spectrum signals?
- **Use RF Band Select Filter**
  - E.g. SAW
  - Removes harmonic responses and EMC spurs
- **Use Pulse Shaping Filter**
  - E.g. RRC FIR
  - Minimise Adjacent Channel interference
- **Consider Directional Antennas**
  - Direct Power to where you need it.
- Only **transmit with the power you need.**
  - OFCOM License regulations
- **Transmit within the band you are licensed.**
- **Some UK License Exempt Bands**
  - UK Frequency Allocation Table 2013
    - Annex B Table 1 Non-specific short range devices
  - VHF 138.32MHz (0.15MHz BW) 10dBm ERP
  - VHF 173.27MHz (0.14MHz BW) 0dBm ERP
  - UHF 433.9MHz (1.7MHz BW) 10dBm ERP
  - UHF 866MHz (6MHz BW) 13dBm ERP
  - WiFi 2442MHz (83MHz BW) 10dBm ERP
  - ERP=Tx Power+Tx Antenna Gain (dipole)

4. Effects on Receivers

Thermal Noise

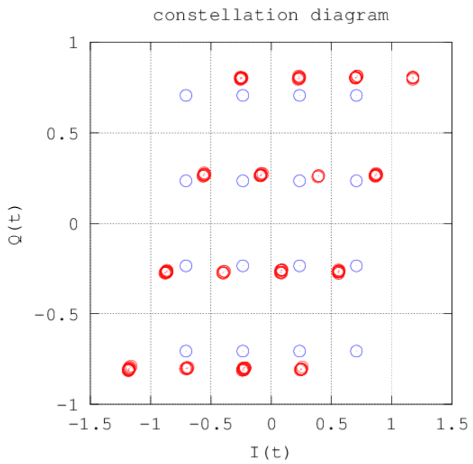
- **Leads to uncertainty in Constellation diagram.**
- **Receiver noise can be minimised through RF matching.**
- **Optimum "Noise Match" is usually near but not the same as a "reflection match" s11.**

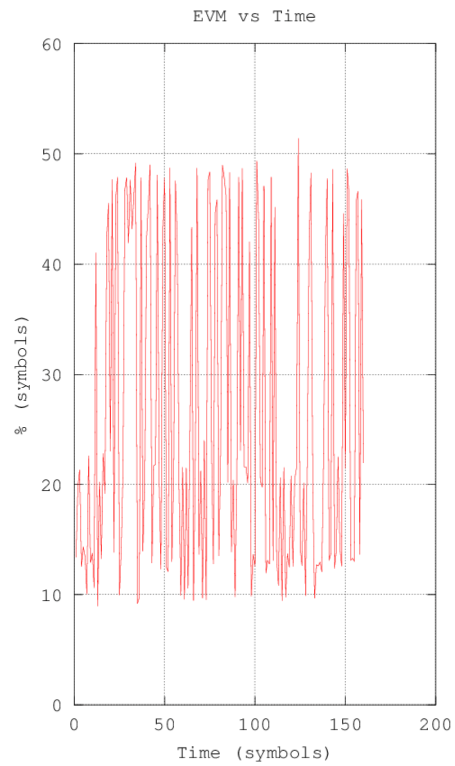




IQ Gain Mismatch

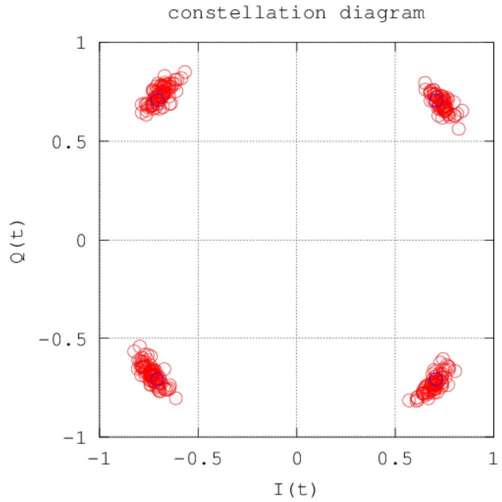
- **LimeSDR**
  - Two quadrature radio receivers operating simultaneously with slight gain and phase mismatch.
  - Leads to rotation and shifts of IQ constellation.
  - Can be removed by calibration.

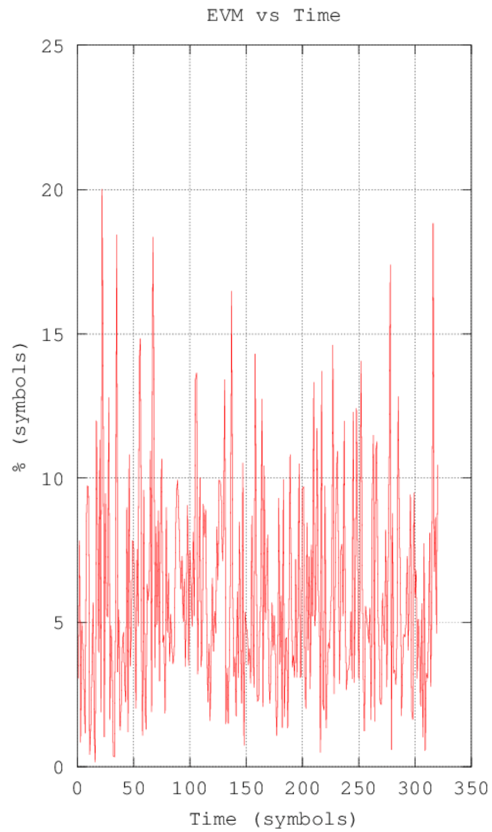




Phase Noise

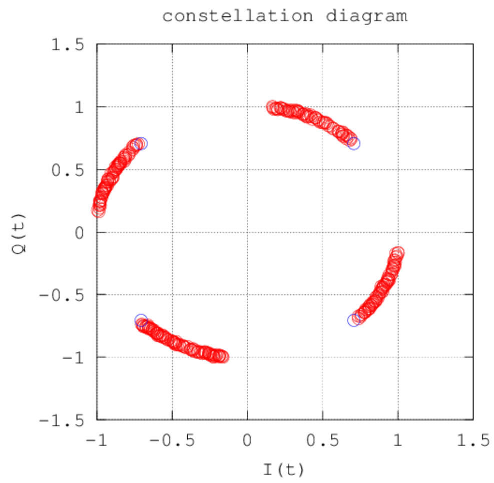
- **LimeSDR**
  - Originates in PLL
  - Phase noise causes both slow and fast rotation of the IQ constellation.
  - Slow phase drift corrected by synchronisation.
  - Fast rotation looks like noise, but only in phase.
  - Phase noise can be minimised through synthesiser settings.

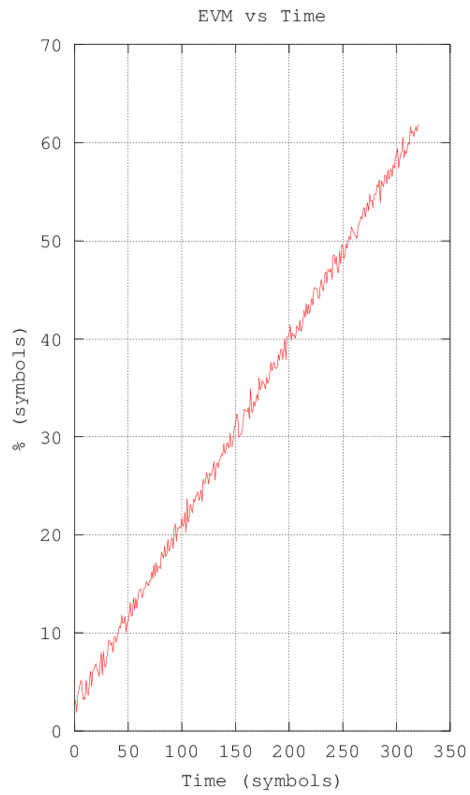




Frequency Error and Doppler Shift

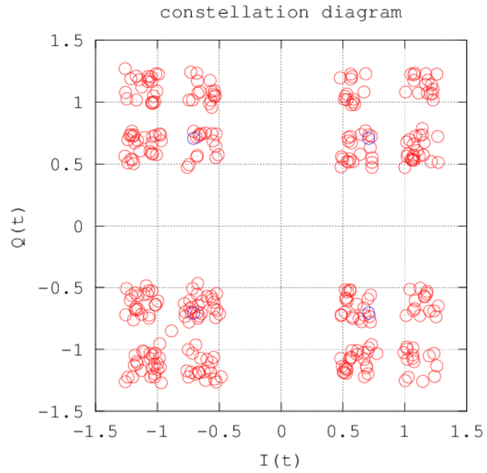
- **LimeSDR Crystal Oscillator.**
  - Although very accurate it changes very slightly with temperature and age.
  - Synthesiser frequency amplifies this. Typically 1kHz error at 2GHz.
- **Doppler shift adds extra error to frequency.**
  - Introduces a time varying rotation to the received signal.
  - ACF measures phase rotation on synchronisation signals.
  - Can measure the phase shift and then correct.

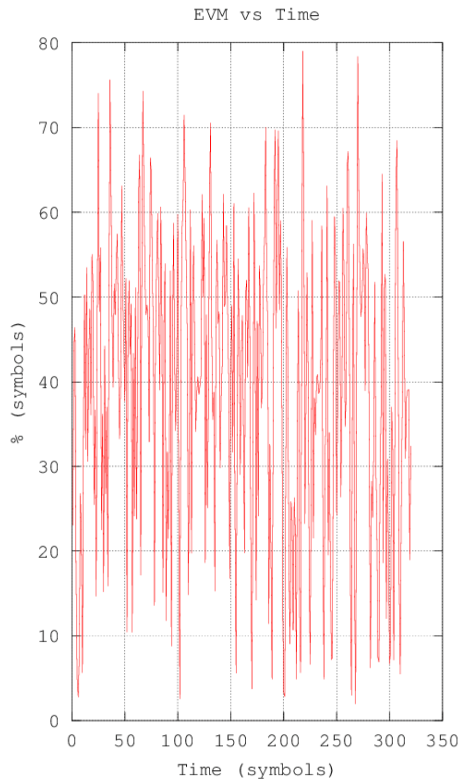




Multipath Echos

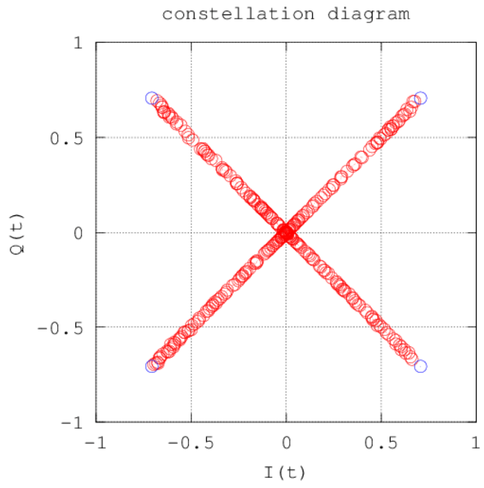
- **Multipath**
  - Usually echo is weaker than main signal.
  - Echo is usually time varying
  - Echo uncorrelated with wanted signal.
  - Leads to intersymbol interference not corrected by RRC filter.
  - ACF good at detecting echos.
  - Need RAKE filter to correct echo.

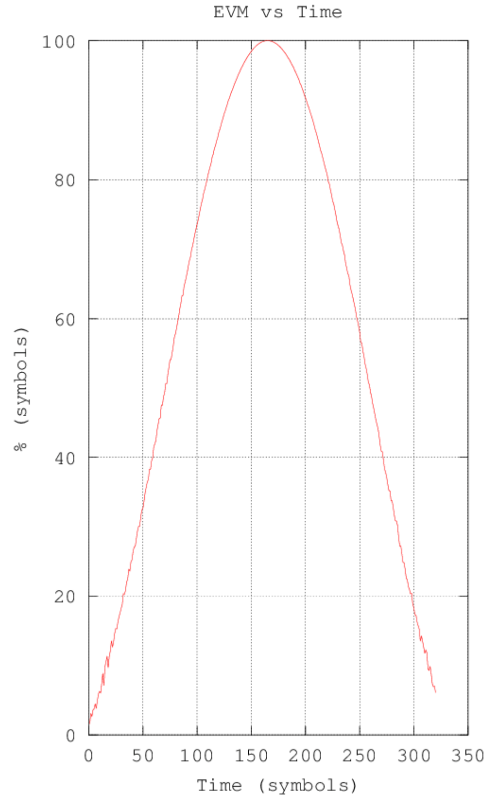




Multipath Fading

- **Fading is usually time and speed dependent.**
- **Fading is corrected by AGC on synchronisation or pilot signals.**
    - Signal loss can occur in deep fades.





Summary

- **The radio link is a very hostile environment.**
  - Behaviour changes with time, location, antenna, weather and even space events.
  - Possible to calculate a link budget for normal operating conditions.
  - Maximum range of a radio is a probability depending on many factors.
- **The receiver itself also can degrade performance.**
  - Calibration, set up and matching are important.
- **Bad Neighbours can interfere with detection of weak signals.**