EEEN3006J

Wireless Systems

Dr Declan Delaney

(declan.delaney@ucd.ie)

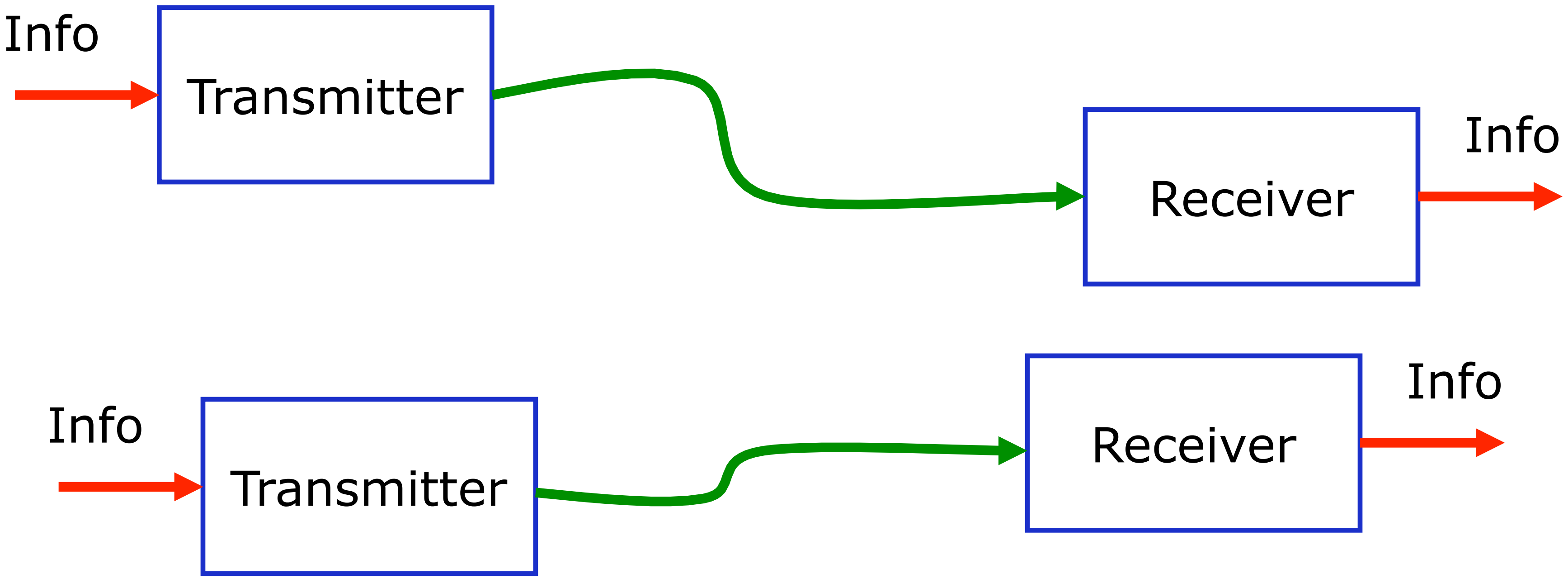
Brian Mulkeen

Beijing Dublin International College

Purpose of this lecture

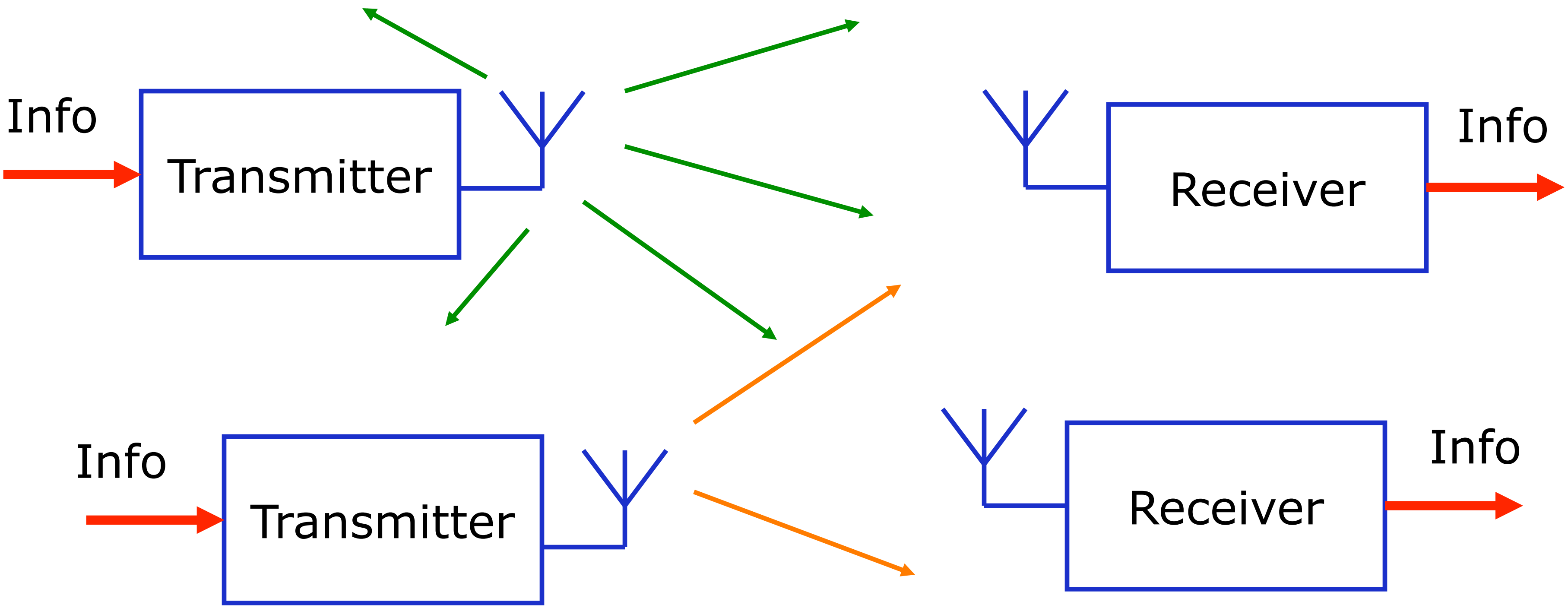
- Requirements for transmitters.
  - Technical
  - Regulatory
- Transmitter architecture.
- Nonlinear systems, e.g. amplifiers.
  - How this affects transmitter design.

Wired Communication System



- Signal travels along cable, fibre, etc.
  - guided to destination
  - some loss in cable
  - other signals kept out

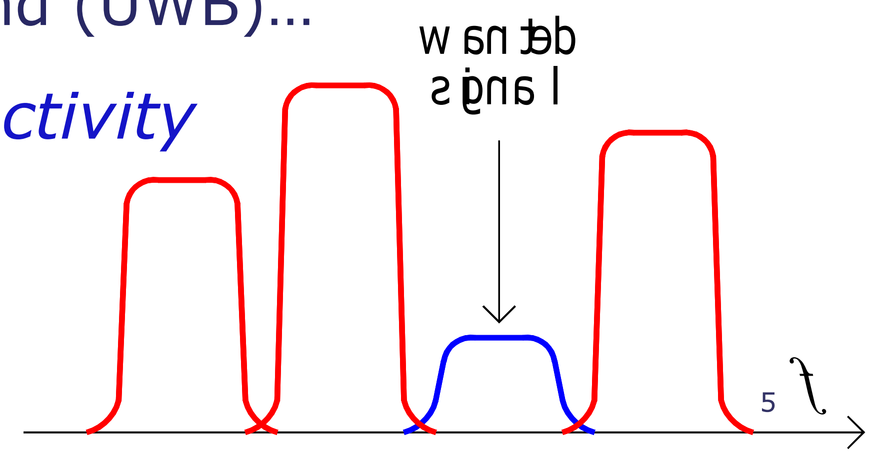
Practical Problems of Wireless Systems



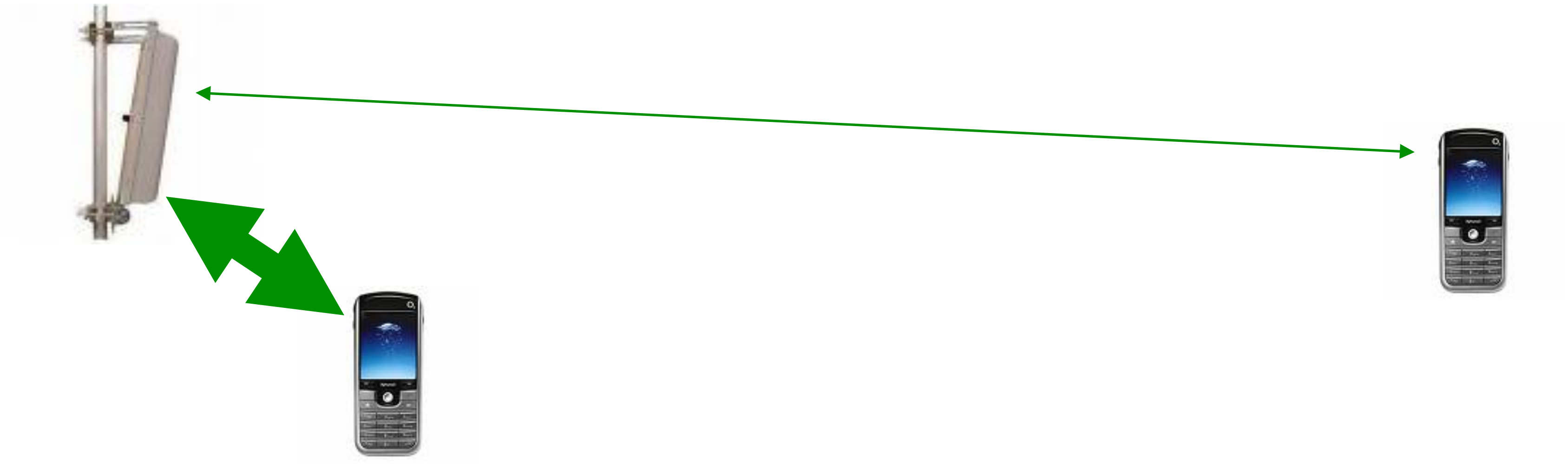
- Signal travels in free space
  - not guided, so the signal spreads out in space
  - Hence, a very small fraction of the signal power reaches the receiver
  - interference to and from other systems

How do we deal with high power loss?

- High transmit power? *sensitive* receiver
  - design calculations - *link budget*
  - transmit power often limited
    - technical, regulation, safety
- Directional antennas ?
- High frequency, usually relatively narrow BW
  - most of spectrum controlled and regulated
  - use frequency planning to separate users ?
  - but note ultra-wide-band (UWB)…
- Need good receiver *selectivity*
  - select wanted signal
  - ignore adjacent signals



Mobility issues



- Mobile transmitter and/or receiver
  - time-varying channel
  - receiver must cope with huge power range
- Receiver *dynamic range* important
  - ability to cope with large range of power
  - both wanted signal and interferers

Circuit Design Issues

- Radio Frequency (RF) - relatively high
  - most new systems 100s MHz to 10s GHz
- shorter wavelength
  - comparable to circuit dimensions
  - voltage and current not same along wire
  - transmission line effects important
- small parasitic L, C, more significant
  - 10 mm length of thin wire has $L \sim 13$ nH
  - at 1 GHz, $X \sim 80\ \Omega$ >> resistance of wire
  - 2 pF stray capacitance at 1 GHz: $X \sim 80\ \Omega$
  - if both, can get resonance at 1 GHz

TRANSMITTERS

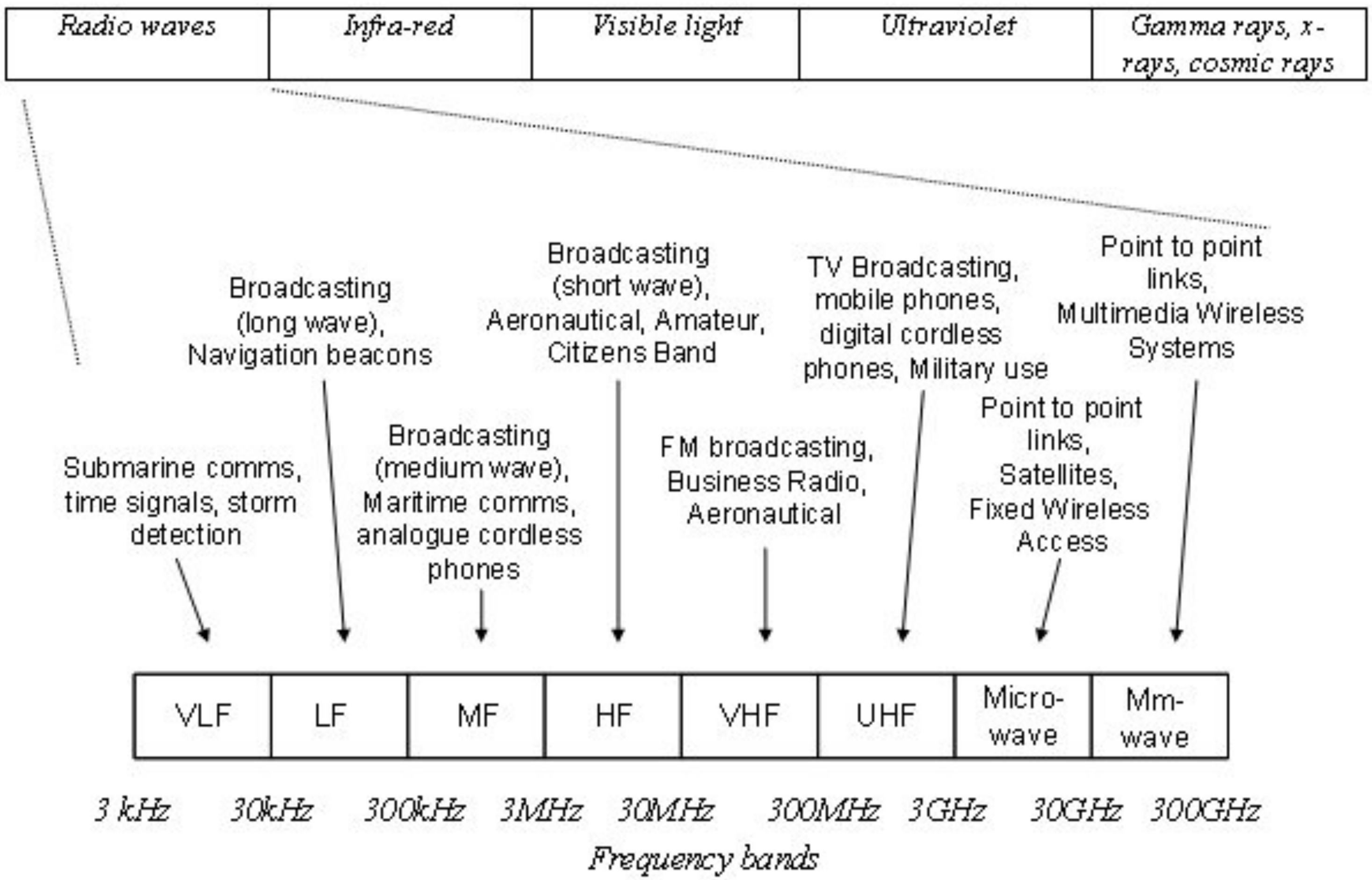
Requirements & Specifications: Power

- The transmitter must produce the required output power
  - This could be 100 kW or more for broadcasting
  - It could be hundreds of mW for a mobile phone communicating with a base station
  - It could be 1 mW for short-range device such as a Bluetooth connection.
- Mobile systems often need adjustable transmit power
  - We set it to minimum necessary for the communication.
    - This minimises interference.
    - It also saves battery life.

Requirements

- Frequency
  - We require the output to be at the correct frequency within some tolerance
    - The tolerance may depend on the architecture.
    - It may also be specified by the regulatory body.
  - often need adjustable
    - operate on any channel in some band of frequencies
- Minimise unwanted emissions
  - avoid interference to other users/systems
  - Extend battery life

Frequency Spectrum



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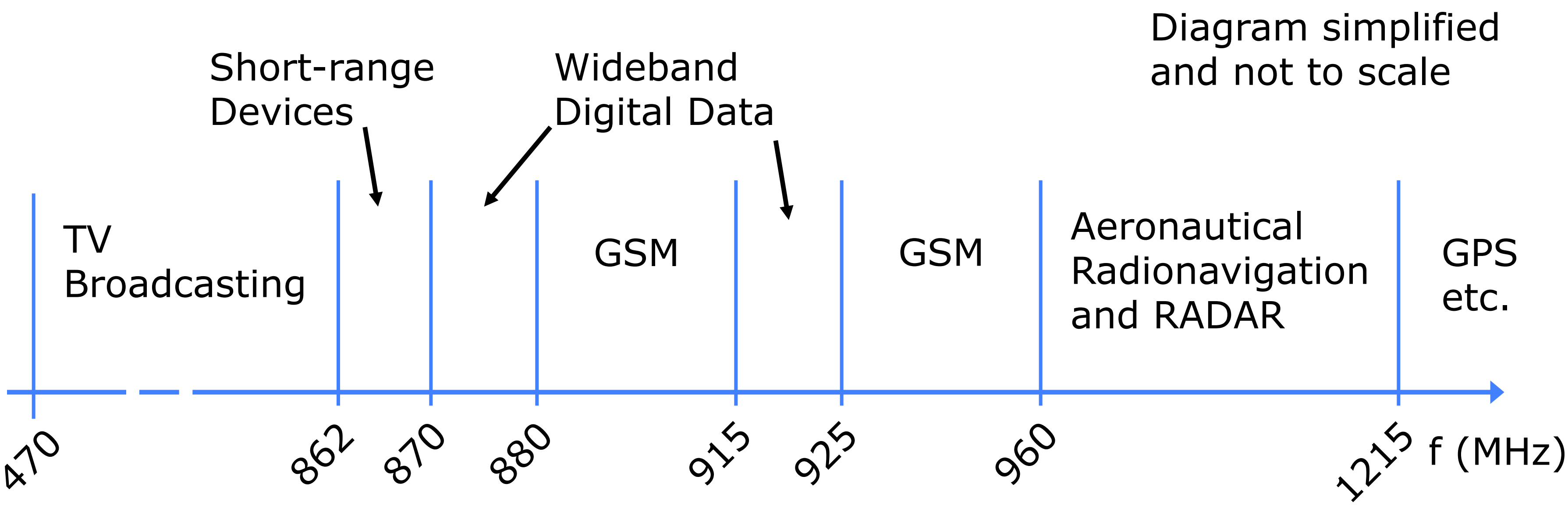
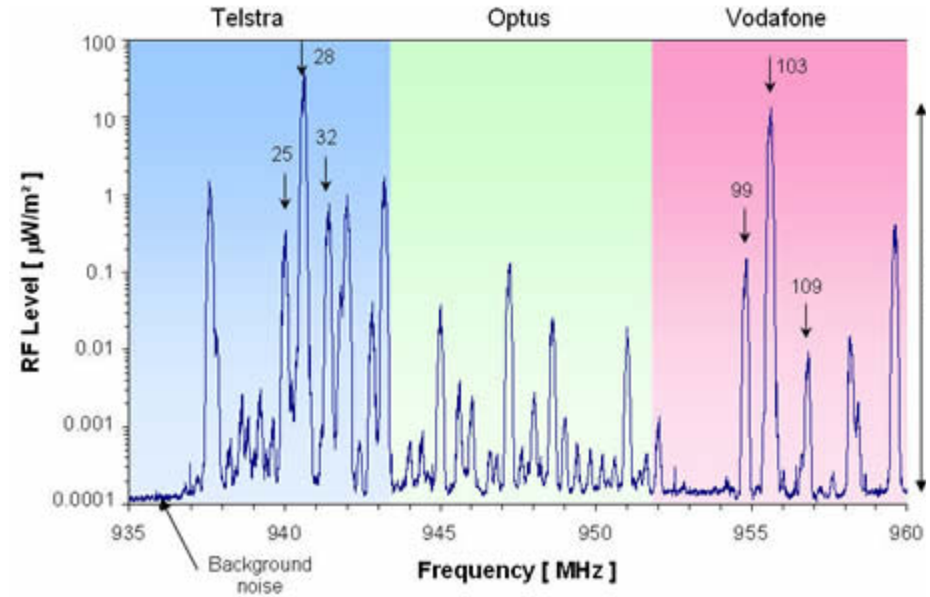
Frequency Band (MHz)	ITU Allocation and Footnotes applicable to Ireland	European Common Allocation	National Usage	National and European Legislation	Relevant CEPT Decisions and Recommendations	Notes
			(MCA) (1920 – 1980 MHz / 2110 – 2170 MHz)	European Legislation: Decision 2013/654/EU		
	FIXED	Fixed				
	5.388	5.388 EU29				
1980 - 2010	FIXED	Fixed				
	MOBILE	MOBILE	IMT-2000/UMTS Satellite component	National Legislation: S.I. 214 of 1998 S.I. 158 of 2003 European Legislation: Decision 128/1999/EC		See ComReg document 08/08R (as revised)
	MOBILE-SATELLITE (E/S) 5.351A	MOBILE-SATELLITE (E/S) 5.351A		European Legislation: Decision 2007/98/EC Decision 626/2008/EC Decision 2009/449/EC	ECC/DEC/(06)09	
	5.388 5.389A	5.388 5.389A				
2010 - 2025	FIXED	Fixed				
	MOBILE 5.388A	MOBILE 5.388A	IMT-2000/UMTS Terrestrial (1900 - 1980 MHz / 2010 - 2025 MHz / 2110 - 2170MHz)	National Legislation: S.I. 158 of 2003 S.I. 340 of 2003 S.I. 34 of 2014 European Legislation: Decision 128/1999/EC	ECC/DEC(06)01 ERC/REC/(01)01	See ComReg document 02/02R and 08/08R (as revised)
	5.388	5.388 EU29				
2025 - 2110	FIXED	FIXED	Fixed: Point – Point Radio Links (Infrastructure) (2025 - 2110 MHz and	National Legislation: S.I. 370 of 2009	Recommendation T/R 13-01: Annex C	See ComReg documents 09/89R (as revised) and 09/89A

Frequency Allocations



- Frequency spectrum mostly regulated
  - *band* of frequencies allocated to some purpose
  - band often subdivided into *channels*
  - different channels for different users
  - channel BW 25 kHz to many MHz
  - limit on tx power or power spectral density

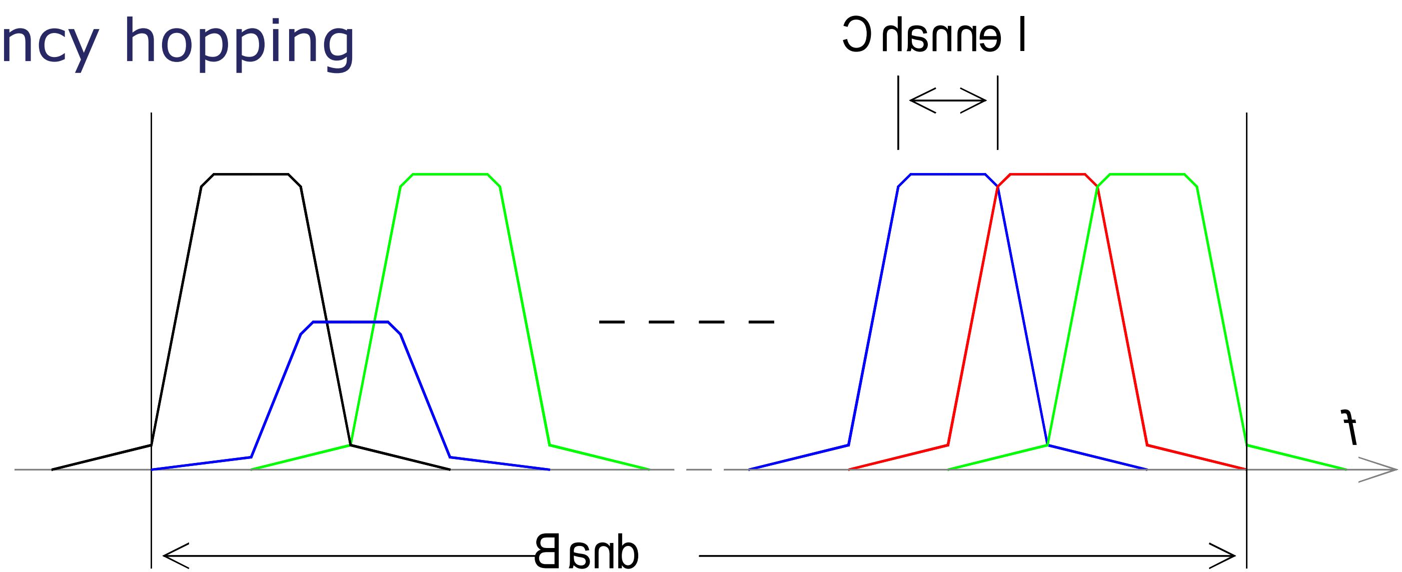
Example - GSM 900



www.arpansa.gov.au

Original specification

- uplink band 890 - 915 MHz
- downlink 935 - 960 MHz
- channel spacing 200 kHz
- 124 channels each way
- base-station uses several channels, separated in frequency
- frequency hopping



GSM Emissions

- Intended emission
  - graph shows max.
  - limits interference to other channels
- Spurious emissions
  - while transmitting
    - < 250 nW   < 1 GHz
    - < 1 μW   > 1 GHz
  - while not tx
    - < 2 nW   < 1 GHz
    - < 25 pW some bands
- Frequency tolerance
  - base   0.05 ppm
  - mobile   0.1 ppm

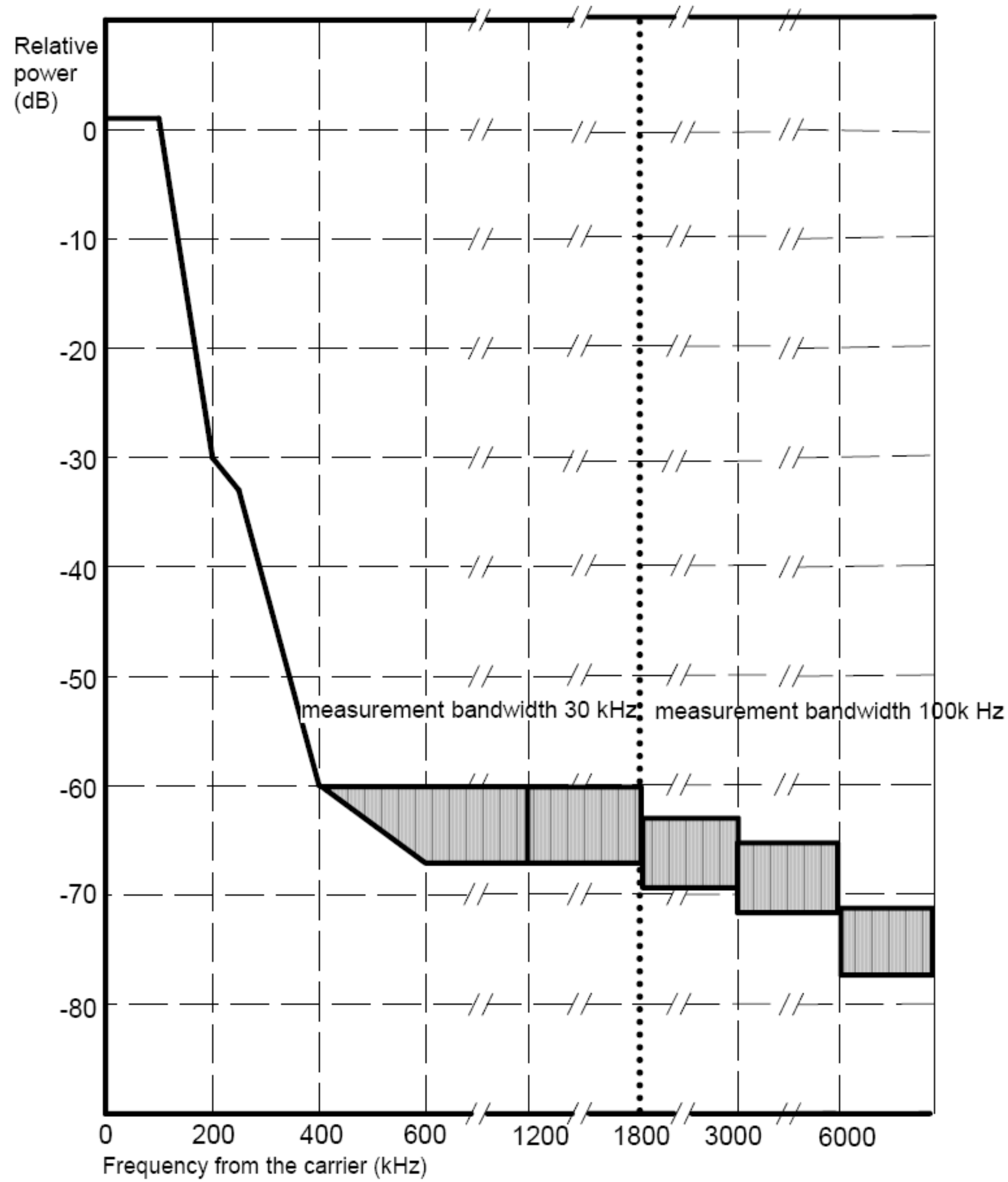
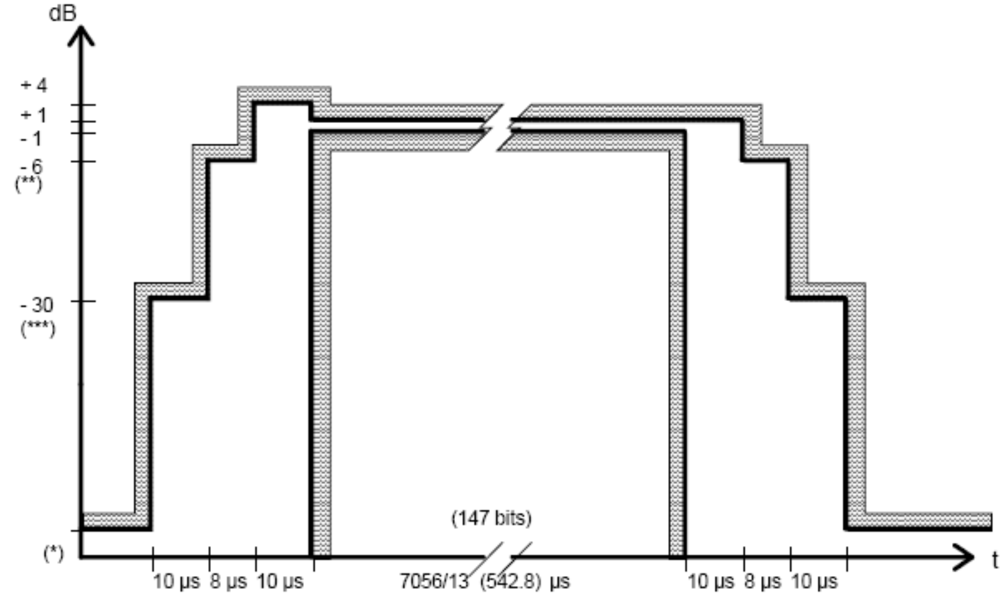


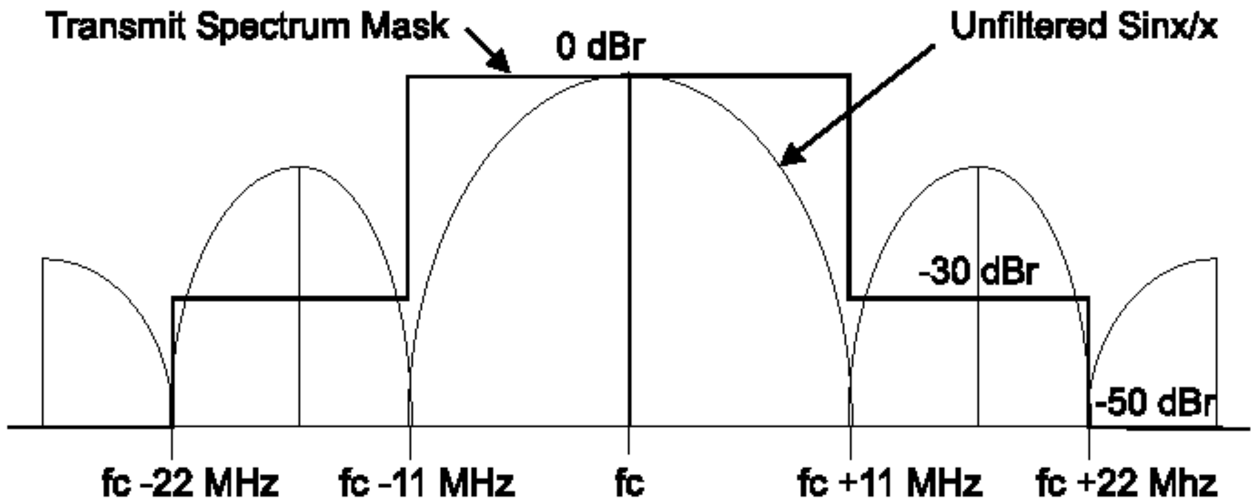
Figure A.1a: GSM 400, GSM 900, GSM 850 and GSM 700 MS spectrum due to GMSK modulation

GSM Transmit Power



- Burst transmission
  - on-off in <20 µs
- Maximum transmit power (mobile device)
  - class 2 device 8 W 39 dBm
  - class 5 device 0.8 W 29 dBm
  - average power less by factor ~8
  - tolerance ±2 dB
- Adjustment (transmit power control)
  - reduce in steps of 2 dB
  - minimum 3 mW 5 dBm

Example: Wireless LAN



- IEEE standard 802.11b
  - Industrial Scientific & Medical (ISM) band
    - largely unregulated - limit on power & p.s.d.
  - band is 2.4 to 2.4835 GHz in most of Europe
  - 13 channels at 5 MHz spacing
    - but signal bandwidth ~22 MHz
    - only 3-4 non-overlapping channels available
  - frequency tolerance ±25 ppm (~60 kHz)
  - transmit power max 100 mW EIRP
    - adjust in steps to < 1 mW

Example: RF24 transceiver for Arduino

nRF24L01 Product Specification

NORDIC SEMICONDUCTOR

5.2 General RF conditions

Symbol	Parameter (condition)	Notes	Min.	Typ.	Max.	Units
f_{OP}	Operating frequency	a	2400		2525	MHz
PLL_{res}	PLL Programming resolution			1		MHz
f_{XTAL}	Crystal frequency			16		MHz
Δf_{1M}	Frequency deviation @ 1Mbps			±160		kHz
Δf_{2M}	Frequency deviation @ 2Mbps			±320		kHz
R_{GFSK}	Air Data rate	b	1000		2000	kbps
$F_{CHANNEL\ 1M}$	Non-overlapping channel spacing @ 1Mbps	c		1		MHz
$F_{CHANNEL\ 2M}$	Non-overlapping channel spacing @ 2Mbps	c		2		MHz

a. Usable band is determined by local regulations
b. Data rate in each burst on-air
c. The minimum channel spacing is 1Mhz

Table 5. General RF conditions

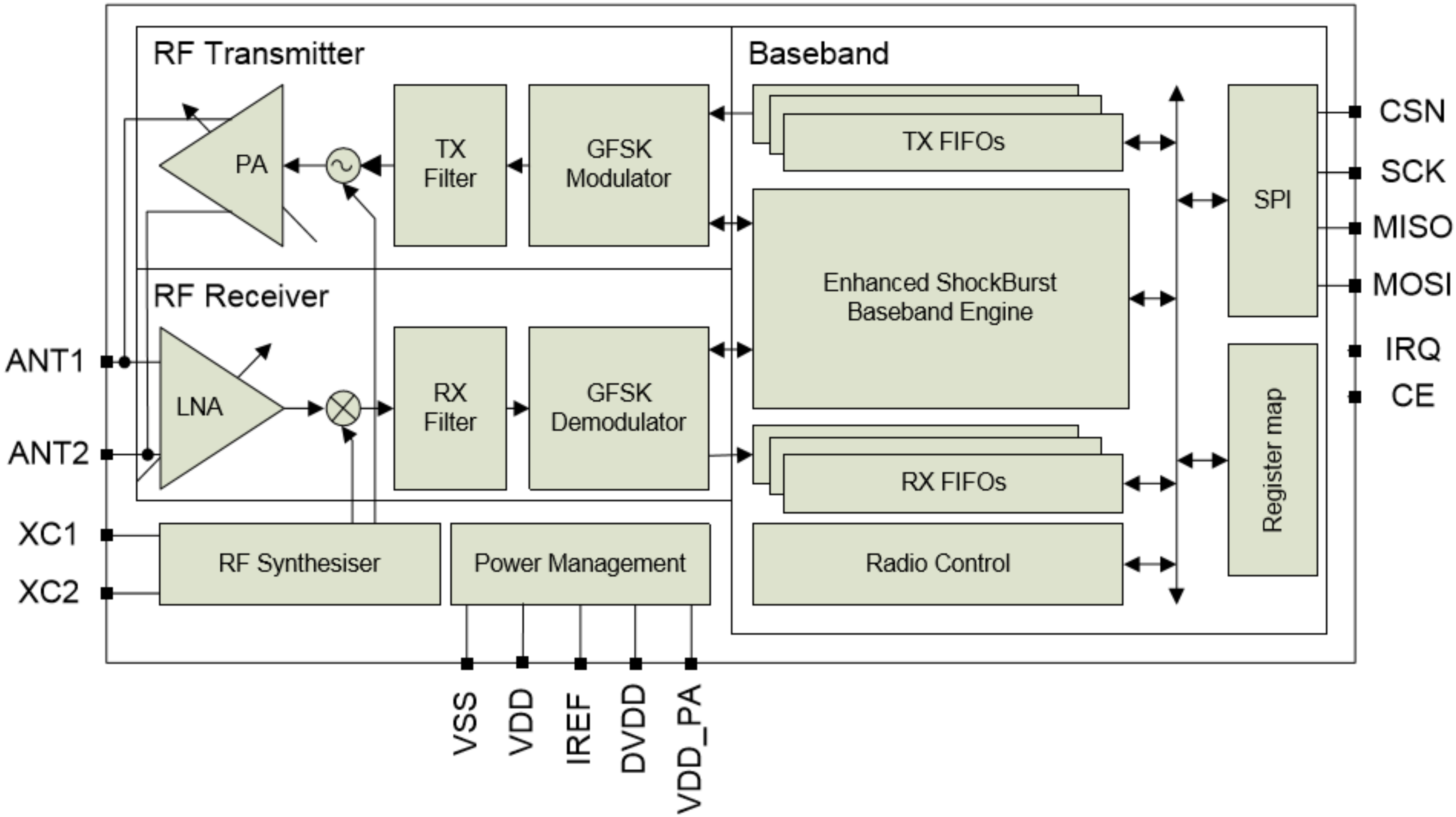


Figure 1. nRF24L01 block diagram

5.3 Transmitter operation

Symbol	Parameter (condition)	Notes	Min.	Typ.	Max.	Units
P_{RF}	Maximum Output Power	a		0	+4	dBm
P_{RFC}	RF Power Control Range		16	18	20	dB
P_{RFCR}	RF Power Accuracy				±4	dB
P_{BW2}	20dB Bandwidth for Modulated Carrier (2Mbps)			1800	2000	kHz
P_{BW1}	20dB Bandwidth for Modulated Carrier (1Mbps)			900	1000	kHz
P_{RF1}	1st Adjacent Channel Transmit Power 2MHz				-20	dBm
P_{RF2}	2nd Adjacent Channel Transmit Power 4MHz				-50	dBm

a. Antenna load impedance = 15Ω+j88Ω

Table 6.Transmitter operation

6.4 PA control

The PA control is used to set the output power from the nRF24L01 power amplifier (PA). In TX mode PA control has four programmable steps, see Table 14.

The PA control is set by the `RF_PWR` bits in the `RF_SETUP` register.

SPI RF-SETUP (RF_PWR)	RF output power	DC current consumption
11	0dBm	11.3mA
10	-6dBm	9.0mA
01	-12dBm	7.5mA
00	-18dBm	7.0mA

Conditions: **VDD** = 3.0V, **VSS** = 0V, T_A = 27ºC, Load impedance = 15Ω+j88Ω.

Table 14. RF output power setting for the nRF24L01

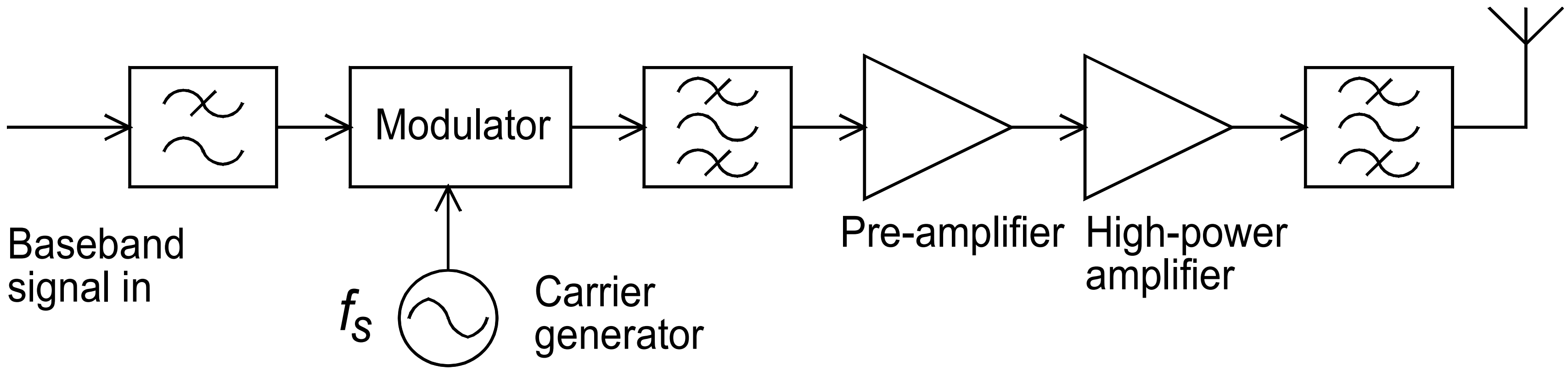
6.5 LNA gain

The gain in the Low Noise Amplifier (LNA) in the nRF24L01 receiver is controlled by the LNA gain setting. The LNA gain makes it possible to reduce the current consumption in RX mode with 0.8mA at the cost of 1.5dB reduction in receiver sensitivity.

The LNA gain has two steps and is set by the `LNA_HCURR` bit in the `RF_SETUP` register.

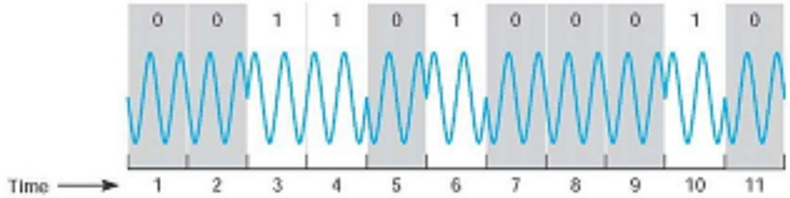
- An ideal wireless system transmits the message with only a time delay.
  - Can be recovered exactly.
- We often use compression to raise the overall modulation level of the signal
- Compression distorts the overall dynamic range of the original signal, but results in an improved signal-to-noise ratio.
- Other types of distortion such as intermodulation and harmonic distortion must also be kept at a minimum.

Simple Transmitter



- Modulation directly at signal frequency
  - carrier source determines freq. accuracy
  - first filter(s) define shape of spectrum
  - last filter blocks unwanted outputs from HPA
- Add adjustable transmit power
  - perhaps with feedback control (ALC)

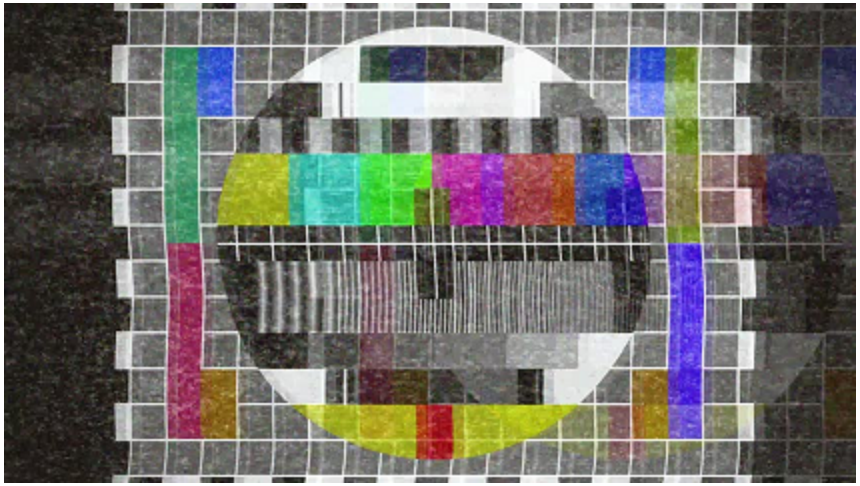
What is modulation?



- Modulation: embedding a message into another signal (i.e. the carrier) suitable for its transmission over the (wireless) channel.
- The information is embedded by modifying one of 3 main parameters of the carrier signal: amplitude, frequency or phase.
- The carrier signal is always an analogue signal. The information signal can be analogue (analogue modulation) or digital (digital modulation).

Analogue Modulation Schemes

- Because of noise, it is not possible to exactly recover the transmitted information.
- However, in many systems, reception can be "good enough" for the purpose at hand.
  - E.g., analogue television was often "watchable" even in poor signal conditions.



Noisy TV test signal

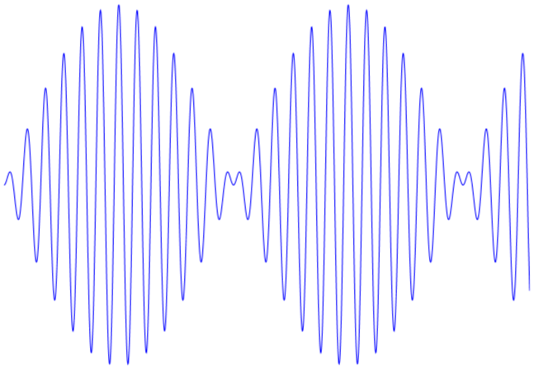
- The input signal directly modifies the amplitude, phase, or frequency of the carrier.
- Digital modulation is simply a special case of analogue.
  - A clear understanding of analogue modulation is important to understanding digital modulation.
- (You have already met modulation in Communication Theory, so the next few slides are simply to refresh your memory.)

Amplitude Modulation (AM)

- Perhaps one of the simplest forms of modulation is Amplitude Modulation, or AM, where the input signal varies the amplitude of the carrier signal.
- The modulation is carried out multiplying the information signal, m(t), and the carrier signal, sin(2πfCt), as

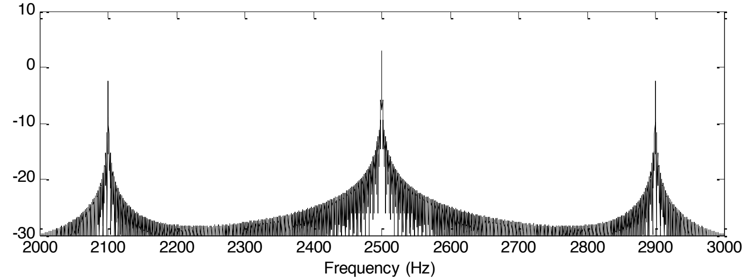
$$s(t) = m(t)\sin(2\pi f_C t)$$

- AM can be done in a number of ways, some of which suppress the carrier.
- The bandwidth of the AM signal varies depending on the AM method.
- AM is commonly used in broadcast as well as aircraft communications for its simplicity.



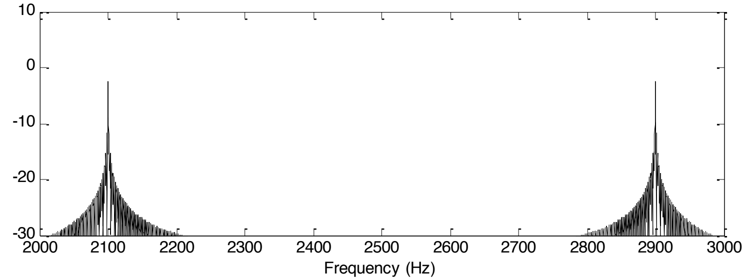
Amplitude Modulation (AM) spectrum

1)



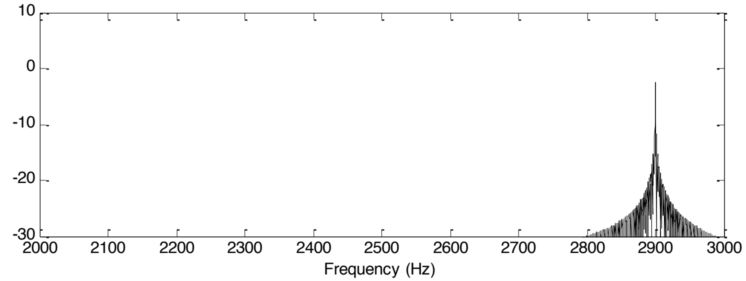
Double side band large carrier (DSB-LC)

2)



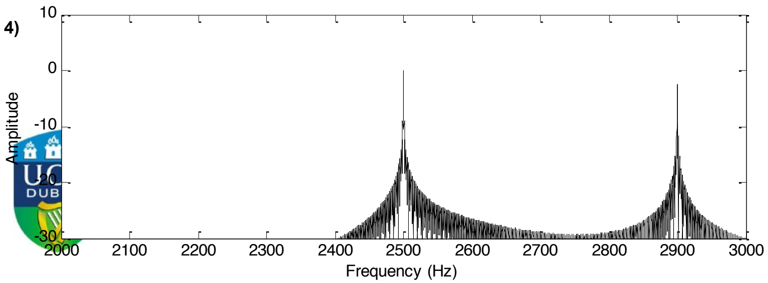
Double side band suppressed carrier (DSB-SC)

3)



Single side band suppressed carrier (SSB-SC)

4)



Single side band large carrier (SSB-LC)

Quadrature Amplitude Modulation

- Amplitude Modulation uses a single carrier signal. What if we superimposed two AM signals at the same frequency, but with the carrier 90 degrees out of phase?
- The result is QAM, and it allows us to share the same spectrum among two signals of equal bandwidth because the carriers are orthogonal.

$$s(t) = m_1(t) \cdot \cos(2\pi f_c t) + m_2(t) \cdot \sin(2\pi f_c t)$$

- To demodulate a QAM signal, it is necessary to generate synchronized reference carriers, or the demodulated signals will have crosstalk.
- Because the message is encoded in the amplitude of the signal, systems which distort the amplitude will distort the message itself.
  - Leads to linearity requirements in RF circuitry that decrease efficiency and add to cost.

- However, in amplitude-only systems it is possible to use switching modulators to achieve efficiency > 90 %.
- Coherent reception must be used for systems other than DSB+C because of the phase content. This requires a way to synchronize to the carrier and adds complexity to the receiver system.

An Alternative: Frequency Modulation

- Instead of varying the amplitude (magnitude) of a carrier wave, what if we modulated the frequency (or phase) of a carrier signal?
- Phase Modulation: $s(t) = A\cos(2\pi f_c t + k \cdot m(t))$
- Frequency Modulation: $s(t) = A\cos\left(2\pi f_c t + k\int_{-\infty}^{t} m(\tau)d\tau\right)$
- Analogue FM systems generally use a combination of FM and PM in the form of FM with pre-emphasis (this results in PM at high frequencies).

Bandwidth of FM Signals

- If we expand the phase- or frequency-modulated signal by way of a power series expansion, we see that the signal consists of an infinite number of terms where the message is successively raised to increasing powers:

$$s(t) = A\left[\cos(2\pi f_c t) - ka(t)\sin(2\pi f_c t) - \frac{k^2}{2!}a(t)^2\cos(2\pi f_c t) + \ldots\right]$$

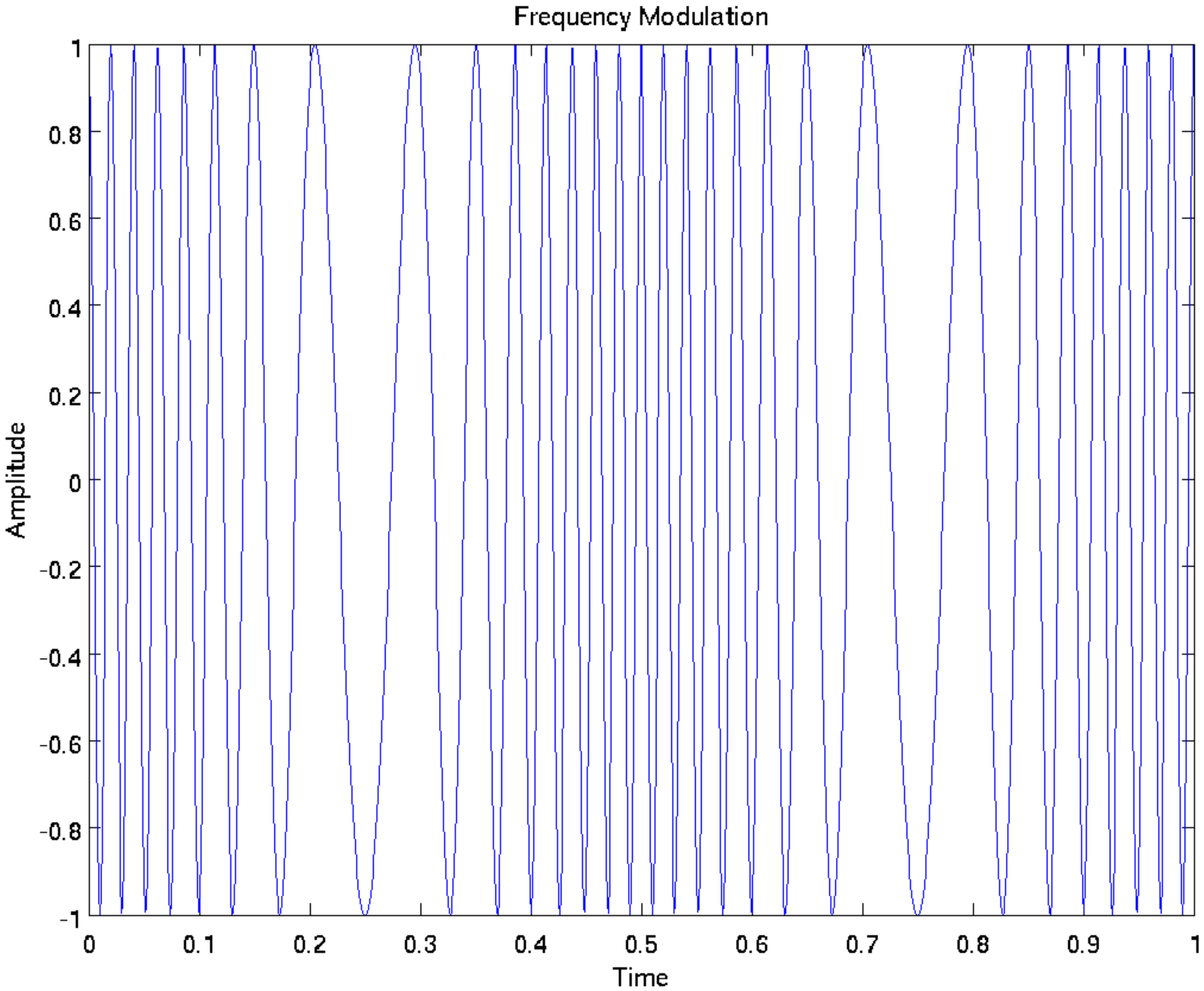
$$a(t) = \int_{-\infty}^{t} m(\tau)\,d\tau$$

- The resulting signal has infinite bandwidth. We apply a band-pass filter to the signal.

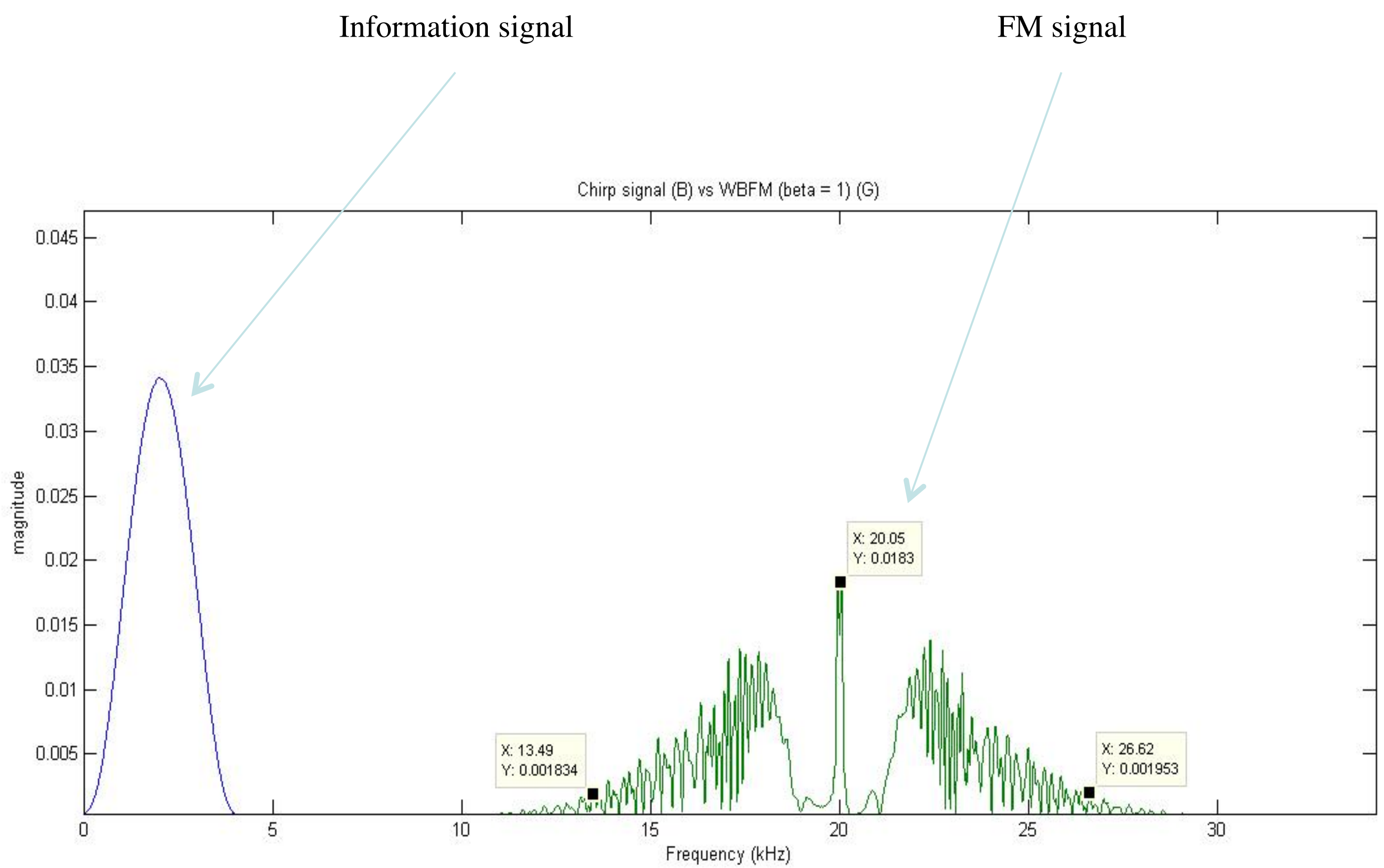
- A good rule of thumb is that the approximate bandwidth of an FM signal is given by Carson's Rule, where β is the modulation index:

$$W_{\text{FM}} = 2W_{\text{INFO}}(1+\beta)$$

Frequency Modulation



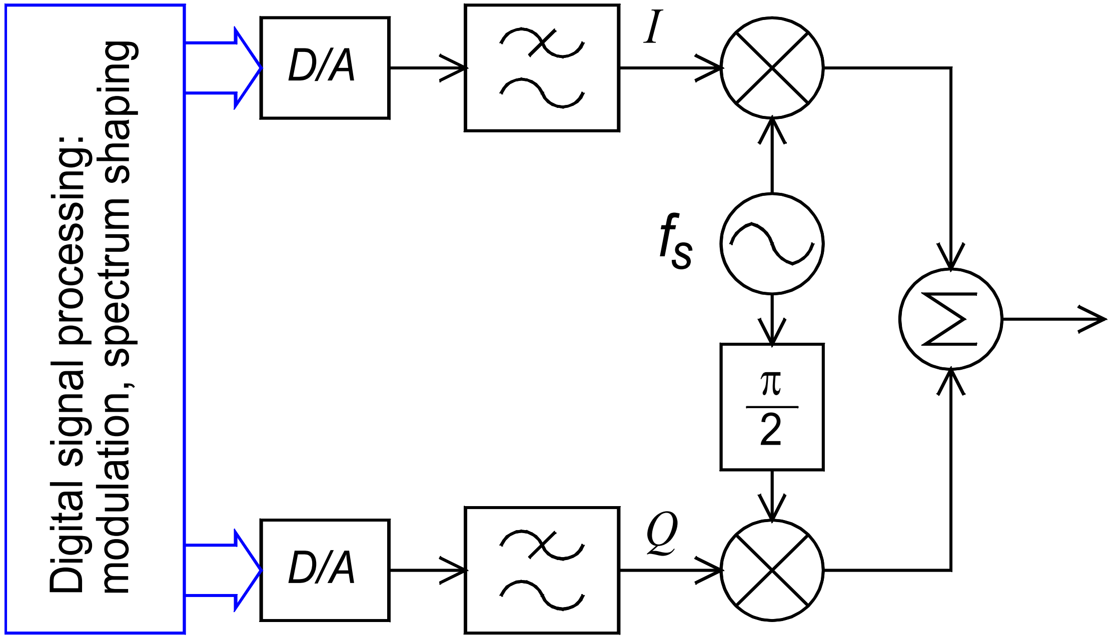
Frequency Modulation Spectrum

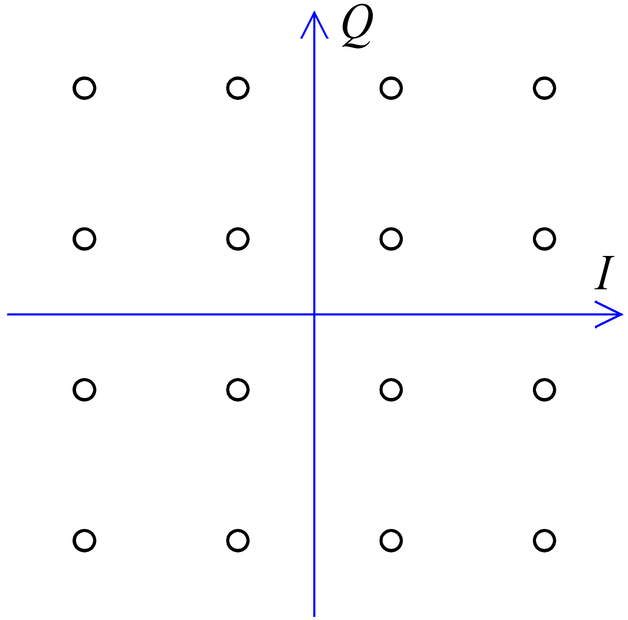


Frequency Modulation and Linearity

- Phase-modulated systems are much more resilient to nonlinearities in the RF circuitry.
- Advantage: Can use highly nonlinear amplifiers (Class C, typically) to improve efficiency.
  - Typical tube-type FM transmitters are nearly 80% efficient, and solid state amplifiers can be up to 65% efficient.
  - **Class-C amplifiers** conduct less than 50% of the input signal and the distortion at the output is high, but high efficiencies (~90%) are possible.

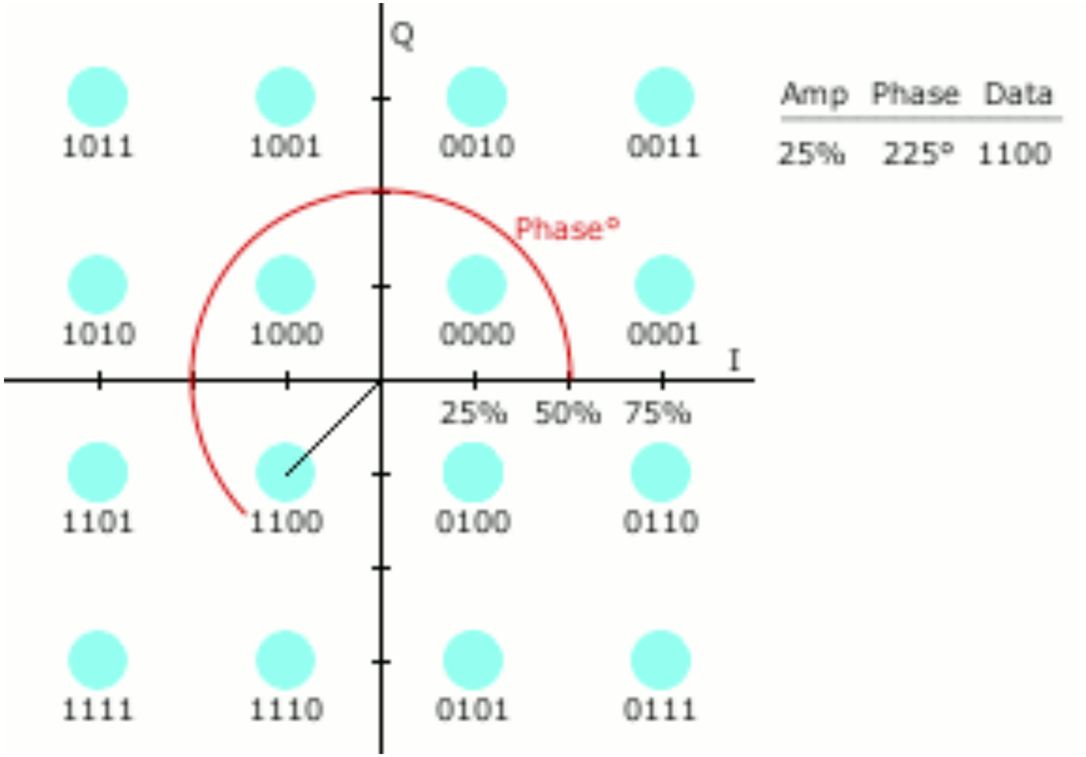
Quadrature Modulation





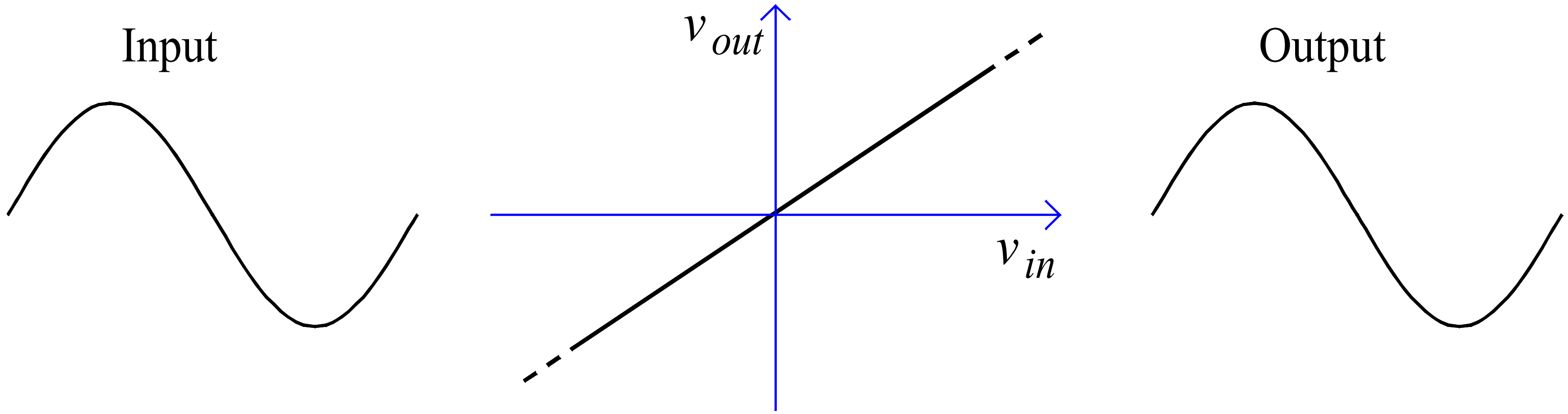
$$I(t)\cos(2\pi f_S t) - Q(t)\sin(2\pi f_S t)$$

- QAM
  - needed by many digital modulation schemes
  - two baseband signals, *I*, *Q*, from D/A conv.
  - can generate any type of modulation…
  - most of modulation done digitally…


Q
1011
1001
0010
0011
Phase°
1010
1000
0000
0001
I
25%
50%
75%
1101
1100
0100
0110
1111
1110
0101
0111
Amp Phase Data
25% 225° 1100

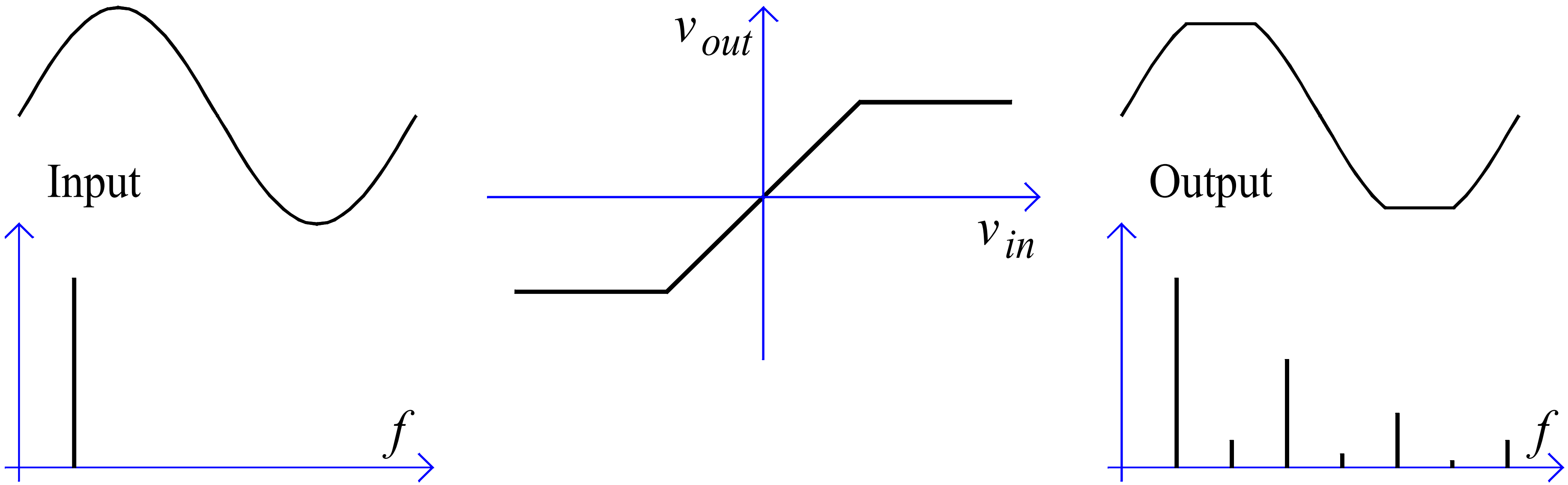
NON-LINEAR SYSTEMS

Linear System



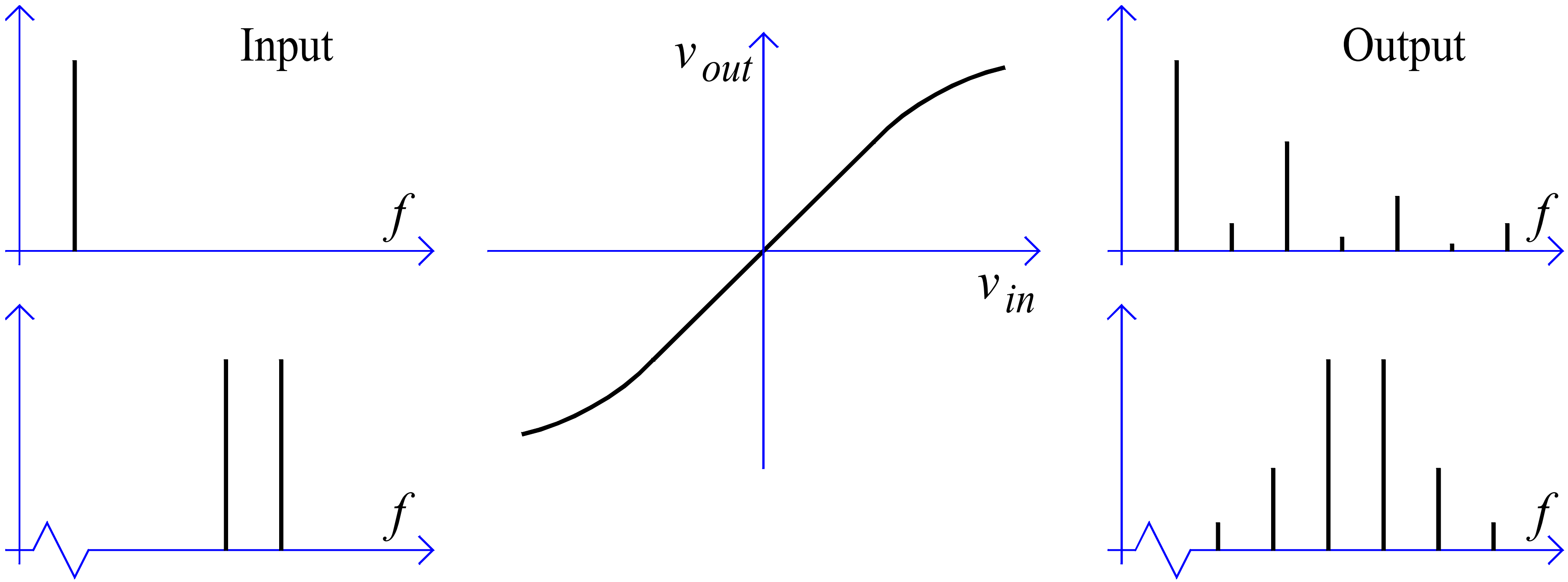
- Output voltage proportional to input voltage
  - output power proportional to input power
- Superposition
  - input components processed independently
- No new frequencies generated
  - output only has components at frequencies present in input signal
  - so no increase in signal bandwidth

Non-Linear System



- Output voltage not proportional to input
  - example is severe non-linearity - clipping
  - even simple sinusoidal input is distorted
- New frequency components possible
  - here, harmonics, at multiples of input freq.
  - symmetry $\Rightarrow$ odd harmonics

Non -Linear System

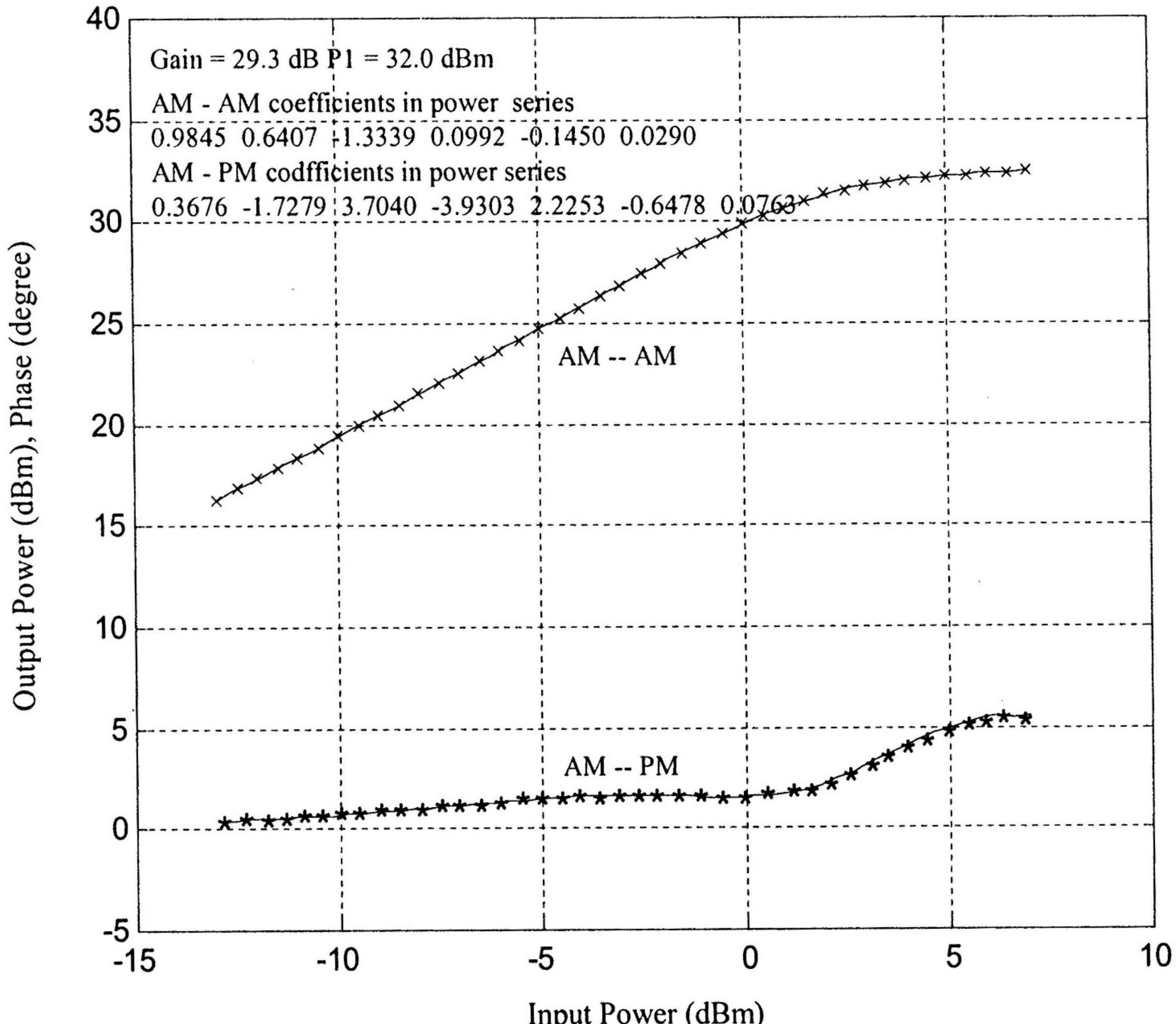


- Superposition does not apply
  - input components interact (*intermodulation*)
  - produce new output components
    - called Intermodulation Products (IMP)
  - example is more typical amplifier characteristic

Significance ?

- All amplifiers are non-linear
  - often analyse using linear model
  - *small-signal model* - valid for small signals
  - if large signal applied, use non-linear model
- Issue for power amplifier at tx output
  - signals are required to be large
  - design is compromise: distortion vs. efficiency
- Issue for first amplifier in receiver
  - input signal power varies over huge range
  - no control over input signals
  - need high gain to amplify weak signals…
- Many mixers deliberately non-linear

Amplifier Behaviour

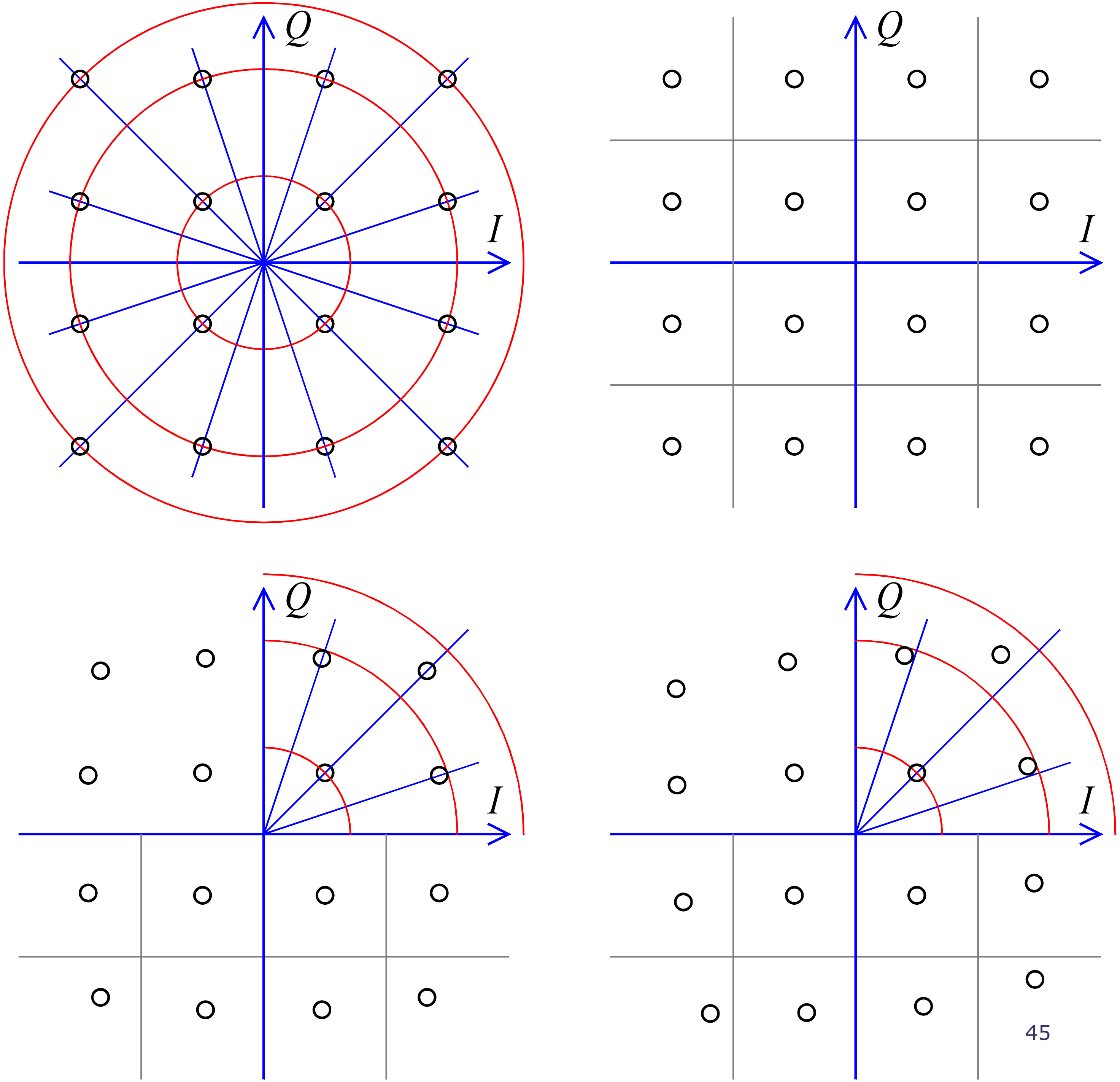


Graph from Qizheng Gu, *RF System Design of Transceivers for Wireless Communications*

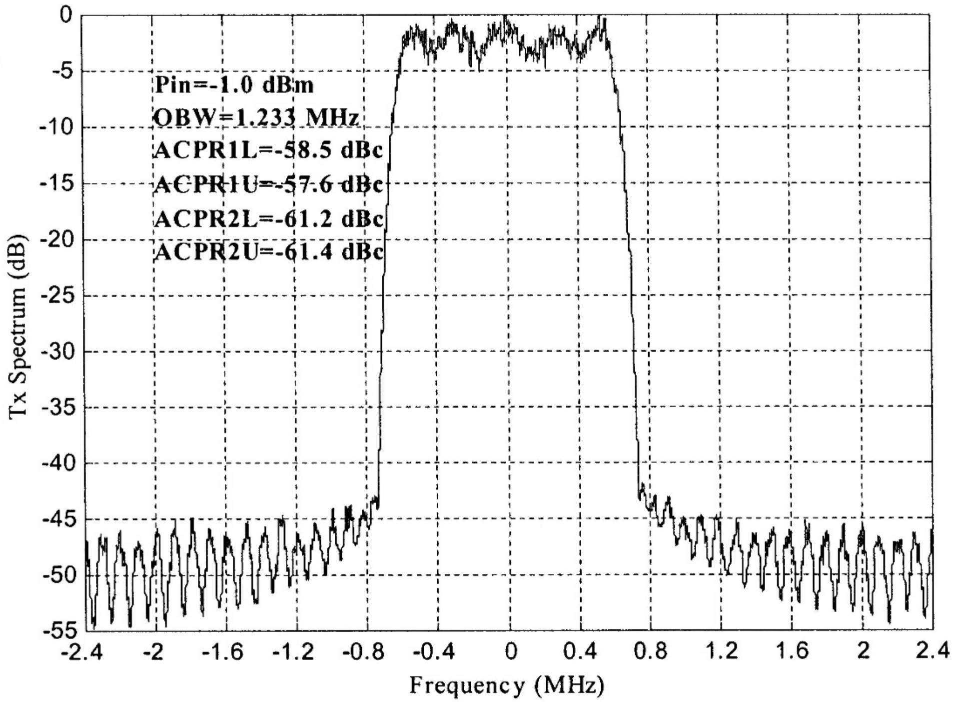
- From user view-point
  - gain varies with input power (AM-AM)
  - phase shift varies with input power (AM-PM)

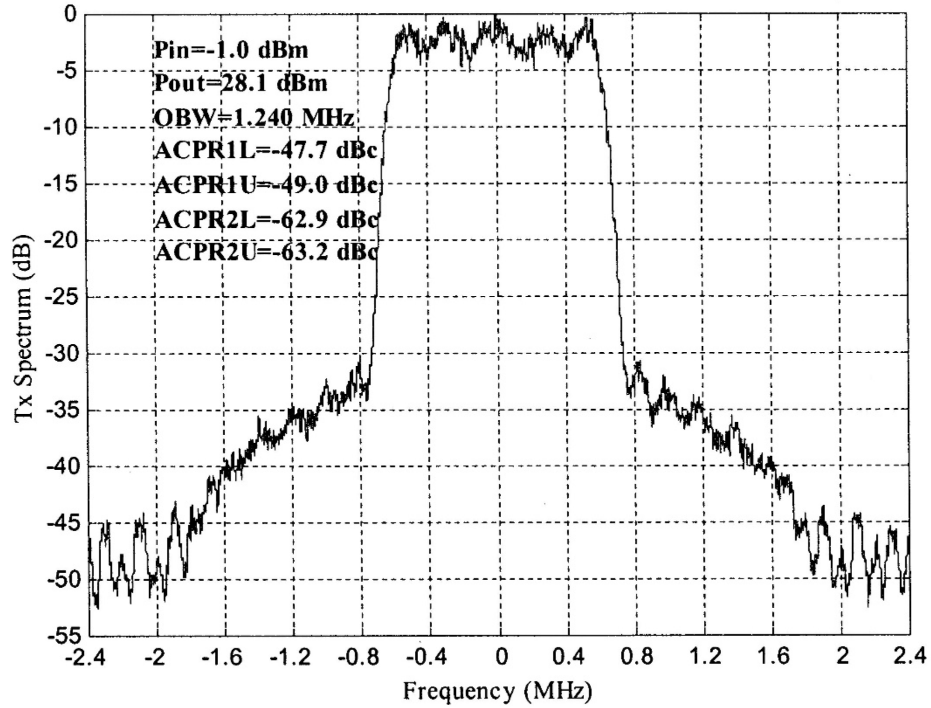
Result: signal distortion

Example: 16-QAM



Result: frequency spectrum

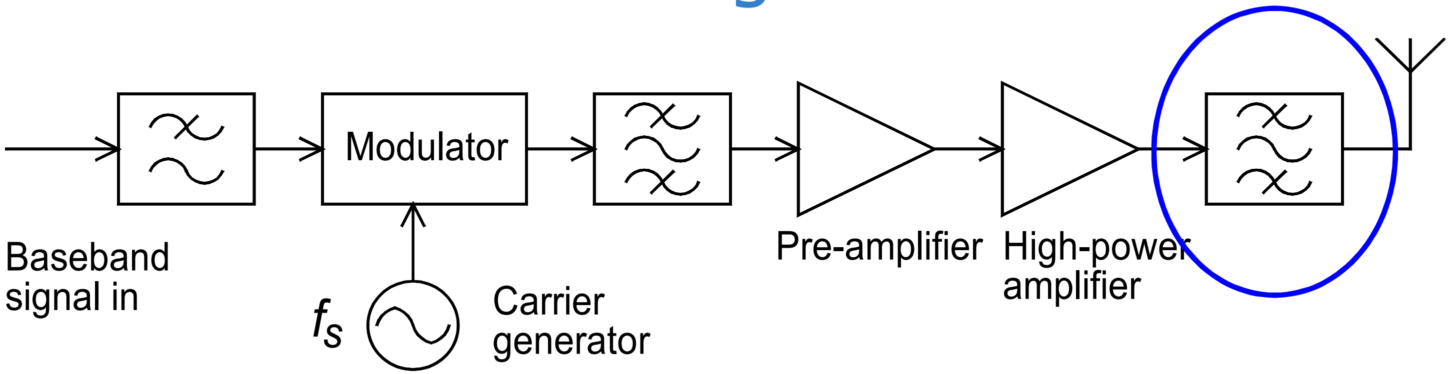




From Qizheng Gu

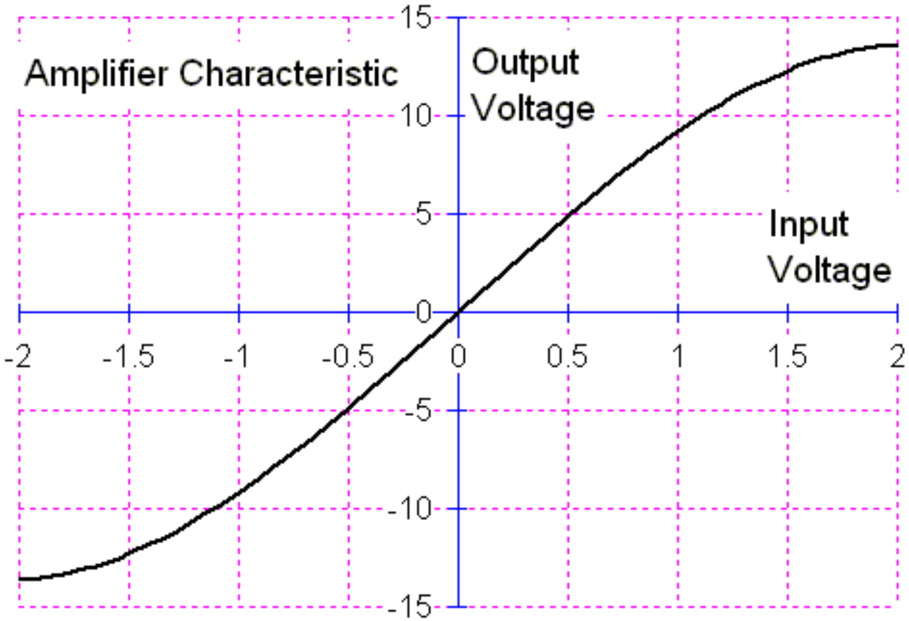
- Harmonics generated
  - easily removed by simple low-pass filter
- “Spectral re-growth”
  - carefully designed and filtered signal gives new output components, wider bandwidth

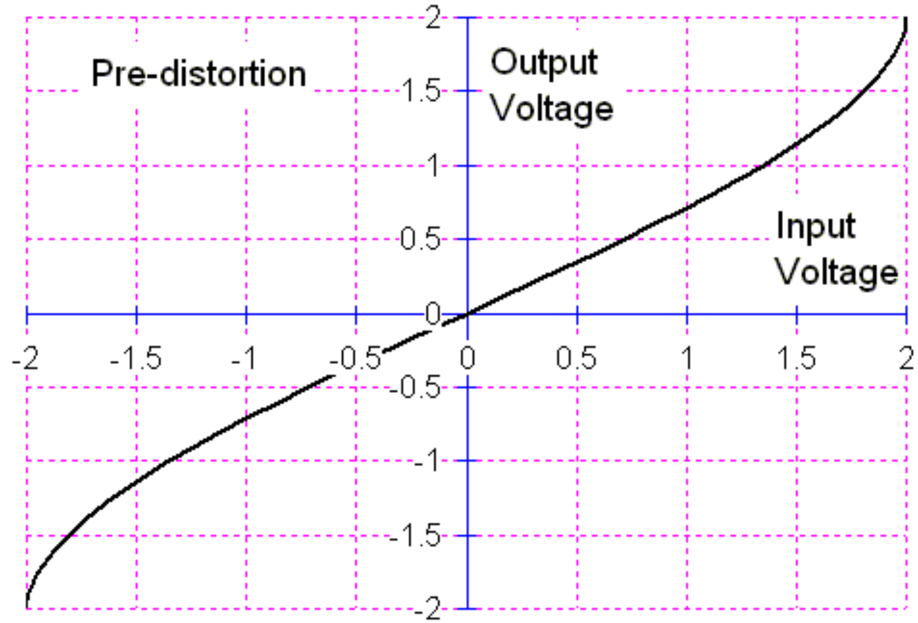
Transmitter Design



- Filter after high-power amplifier
  - remove harmonics, out-of-band components
  - must be passive filter - linear
  - must have low loss in passband
  - so must be simple (low-order) filter
  - so cannot help with spectrum shaping
- Design signal so constant amplitude (e.g. FM)
  - but modern digital modulation schemes have large peak-to-average power ratio (PAPR)

Transmitter Design





- Operate amplifier well below saturation
  - stay in more linear region
  - but amplifier efficiency lower
- Pre-distortion
  - distort signal in opposite way beforehand
  - becomes feasible with digital processing

Software-defined radio

- In theory, most of the parts of a transmitter (and receiver) can be done on a computer.
  - E.g. Filtering
- This would be desirable because it would be very flexible.
  - Can just change settings file.
- In practice, much of the transmitter (and receiver) remain analogue because the required sampling rates are too high otherwise.