ECE 4880
Fall 2016

Chapter 11

Present Wireless Network Designs

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Goals

- From the present standards of wireless network to apply the RF design principles:
  - Short-range WLAN: Wi-Fi, Bluetooth, etc.
  - Long-range, reliable-service cellular networks: 3G, 4G, 5G.
  - Broadcasting based network: AM/FM/HAM radio, TV, etc.
  - Radar systems: Ground, air and multi-static radars, RFID, etc.

- How system requirements set the component requirements

Wi-Fi: Brief History

- **1985**: FCC deregulated 2.4-2.5 GHz for unlicensed ISM (industrial, scientific and medical) communities.

- **1997:** Original standard and implementation by CSIRO (Australia)
  - Original name: IEEE 802.11b Direct Sequence. Then becomes: “Wireless Fidelity” or Wi-Fi.
  - Maximum data rate : 2 Mbps (original) to 54 Mbps
  - Interference Mitigation: Direct sequence and frequency hopping
  - Collision sense media access with collision avoidance(CSMA/CA)
  - Forward Error Correction
  - Compatibility with current Ethernet networks (PHY and MAC)

- **1999:** 802.11b (2.4GHz), 802.11a (5.0 GHz)

- **2003**: 802.11g

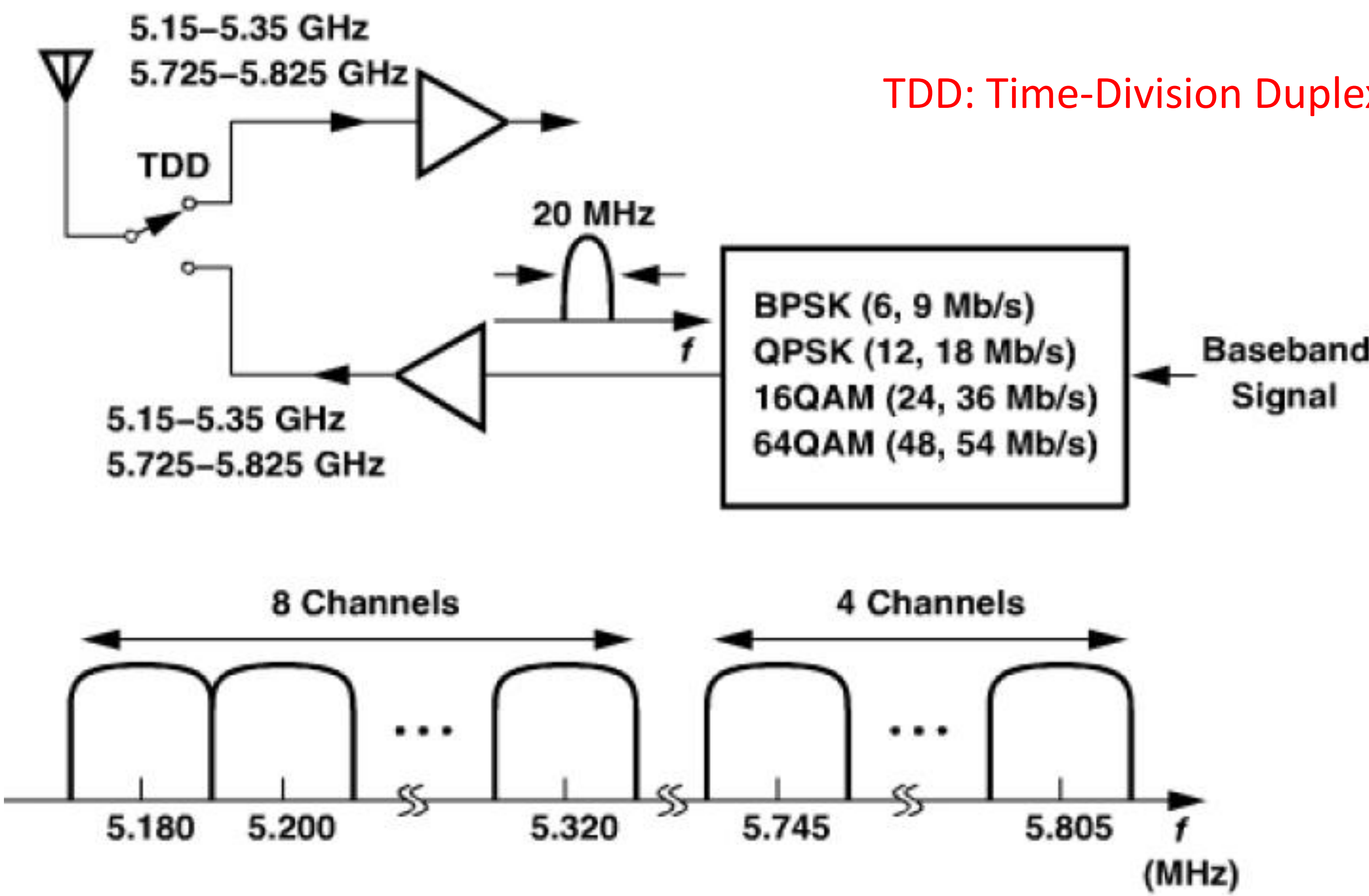
Justin Berg, “The IEEE 802.11 Standardization – Its History, Specifications, Implementations, and Future” Technical Report GMU-TCOM-TR-8

Wi-Fi System Level Specifications

IEEE Specification	**802.11 g**		**802.11 b**		**802.11 a**	
FCC Frequency Band	2.4 GHz (2.412-2.484 GHz)		2.4 GHz (2.412-2.484 GHz)		5 GHz (5.15-5.35, 5.725-5.825 GHz)	
Interference Mitigation	OFDM		DSSS		OFDM	
Data Rate (Mbps)	BPSK	6, 9	CCK	**11**, 5.5	BPSK	6, 9
	QPSK	12, 18	QPSK	2	QPSK	12, 18
	16 QAM	24, 36	BPSK	1	16 QAM	24, 36
	64 QAM	48, **54**			64 QAM	48, **54**

Wi-Fi Air Interface Example (5G)

TDD: Time-Division Duplex



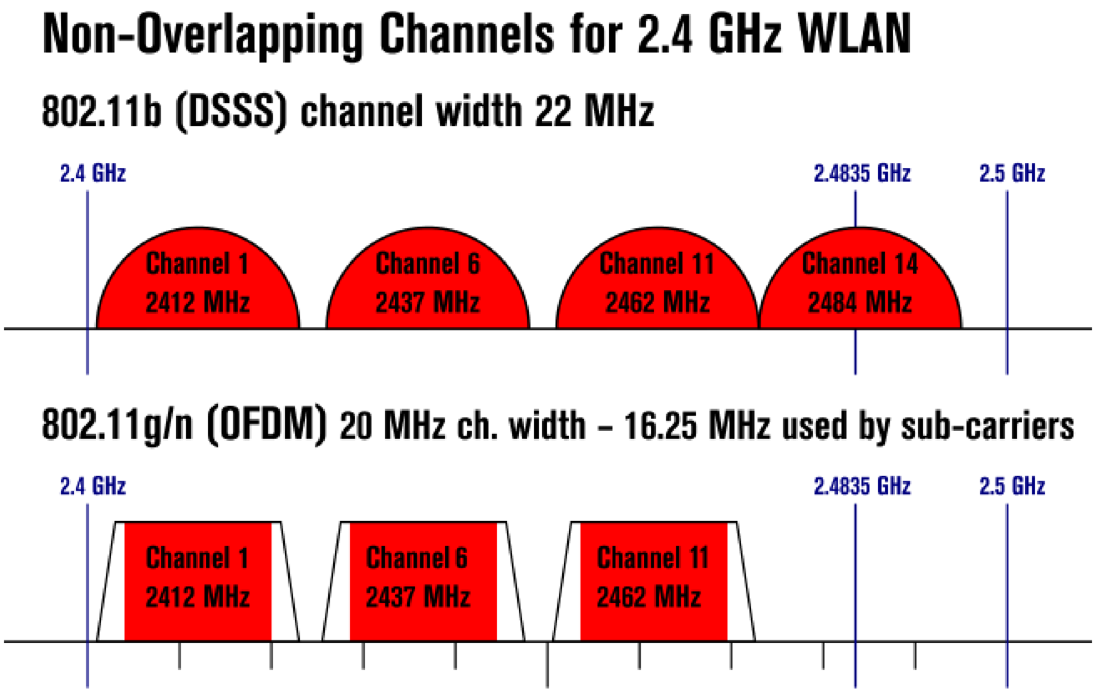
IEEE 802.11a Air Interface

“RF Electronics”, Behzad Razavi

Wi-Fi Channel Division

❑ **802.11b:**
- Channel spacing: 22 MHz

❑ **802.11g/a:**
- Channel Spacing: 20 MHz
- Occupied BW: 16.25 MHz
- OFDM Subcarriers: 52
- OFDM carrier spacing: 0.3125 MHz



Channel 1 - 11 are used in US

Wikipedia 2015, List of WLAN Channels, USA. Can be accessed at website: https://en.wikipedia.org/wiki/List_of_WLAN_channels#USA

US FCC EiRP Regulation

Band		Maximum Power from Intentional Radiator (dBm)	Maximum Antenna Gain (dBi)	EiRP (dBm)
2.4 GHz		30	6	36
5 GHz	5.15-5.25	16	6	22
	5.25-5.35	23	6	29
	5.725-5.825	29	6	35

ETSI ERP Regulation

<table>
<tr><th colspan="2">Band</th><th>ERP (dBm)</th><th>IEEE Standard</th></tr>
<tr><td colspan="2">2.4 GHz</td><td>20</td><td>802.11g</td></tr>
<tr><td colspan="2">2.4 GHz</td><td>18</td><td>802.11b</td></tr>
<tr><td rowspan="2">5 GHz</td><td>5.15-5.35</td><td>23</td><td rowspan="2">802.11a</td></tr>
<tr><td>5.725-5.825</td><td>36</td></tr>
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FCC TX Spectrum Mask

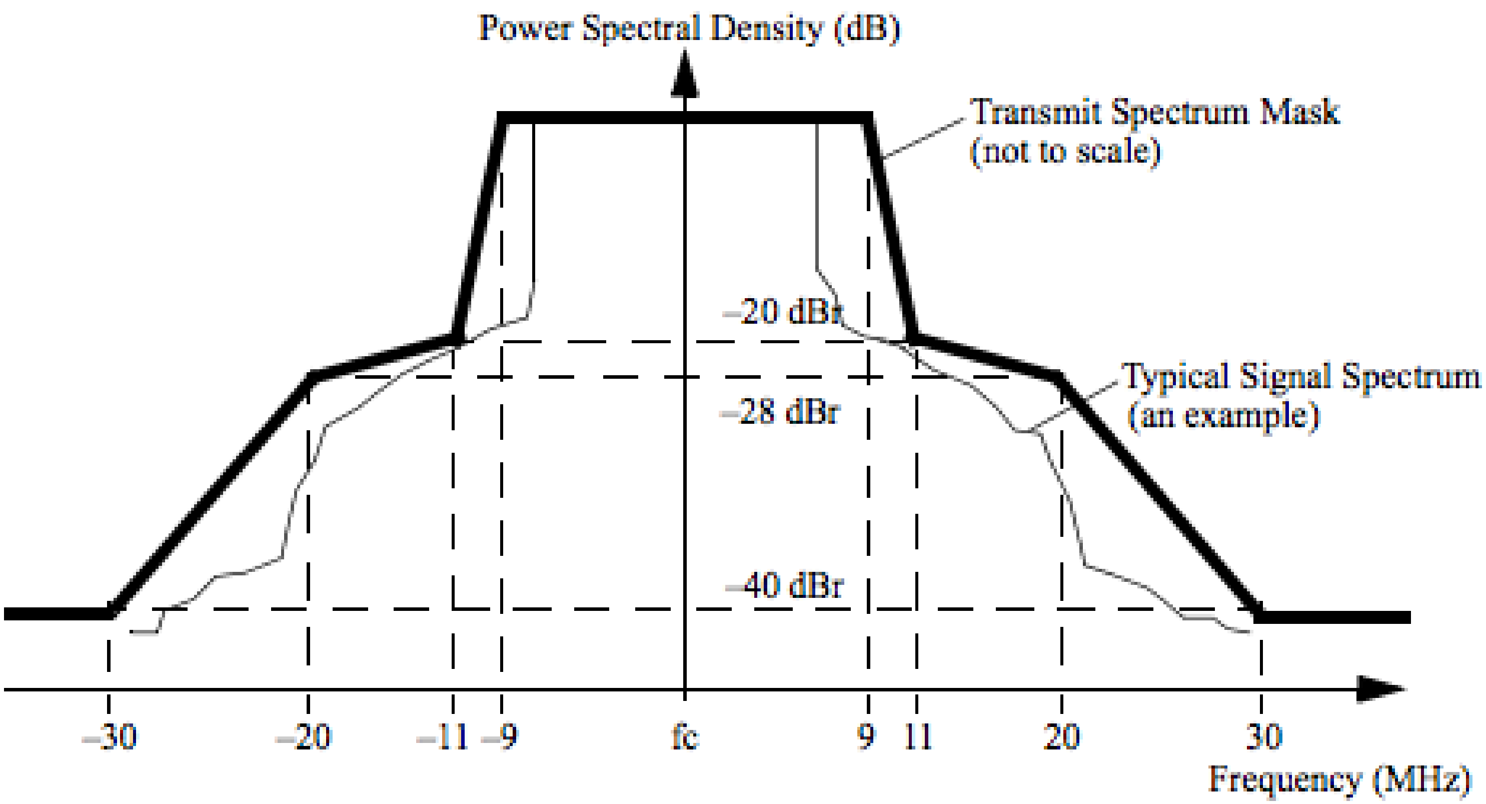


Figure 18-13—Transmit spectrum mask for 20 MHz transmission

IEEE Standard for Information technology—
Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements - Part 11

Interference Mitigation: DSSS

Direct Sequence Spread Spectrum (DSSS)

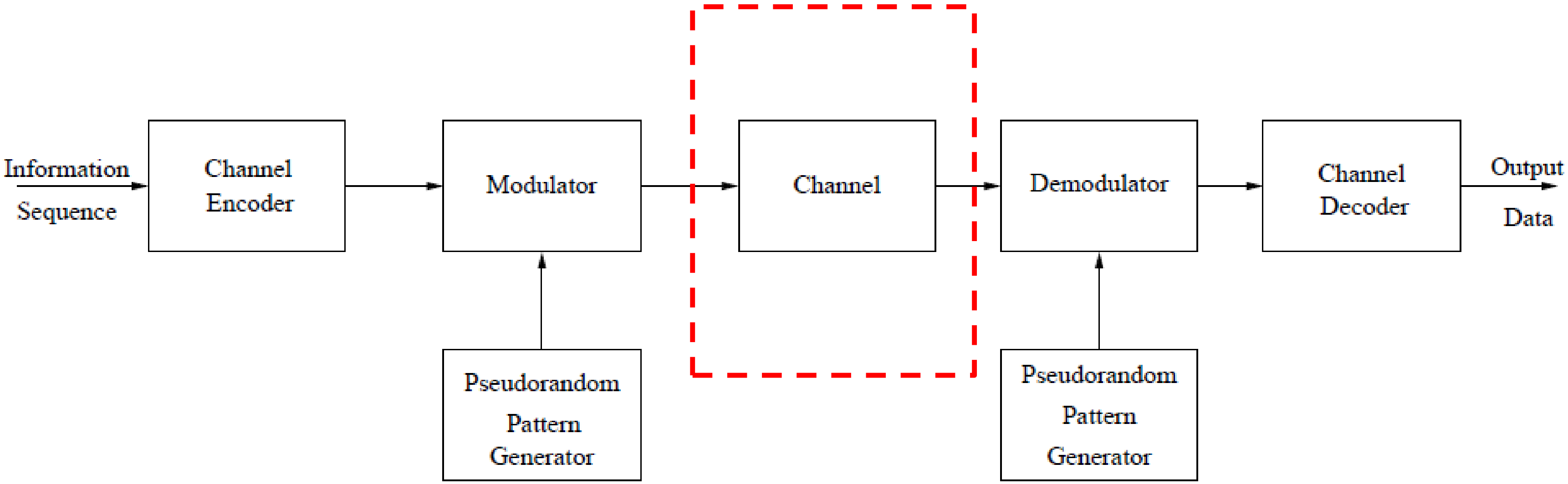
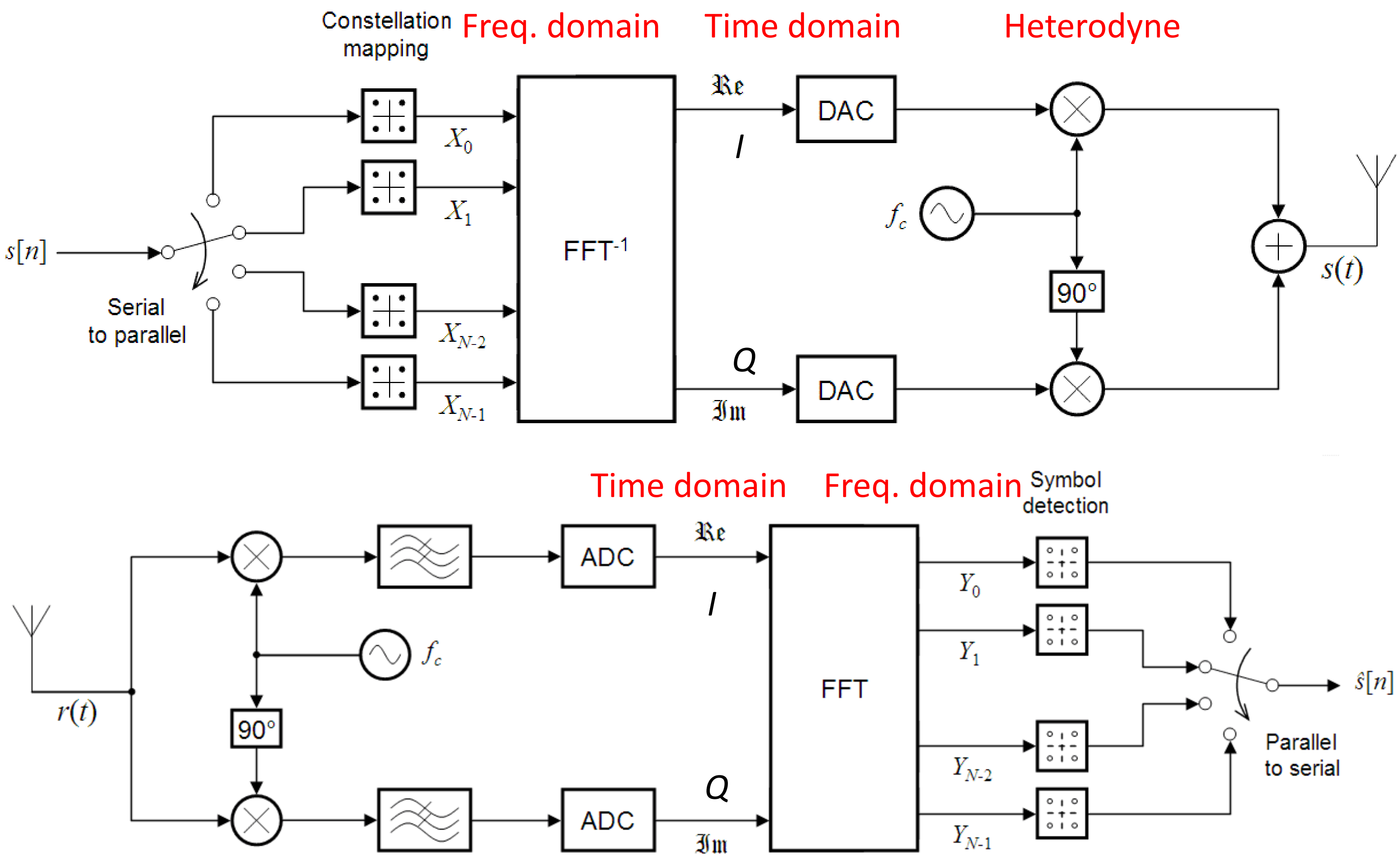


Figure 3.18: Basic elements of a direct-sequence spread spectrum system.

Interference Mitigation 2: OFDM



OFDM: R. W. Chang, Bell Labs, 1966, "Synthesis of band-limited orthogonal signals for multi-channel data transmission". *Bell System Technical Journal*. **45** (10): 1775–1796.

Typical Wi-Fi RX Specification

- **RX sensitivity:**
  - –82dBm at 6Mbps
  - –65dBm at 54Mbps

- **RX signal chain gain:** 30 – 82dB

- **Maximum input power:**
  - 802.11a/g: –30dBm
  - 802.11b: –10dBm

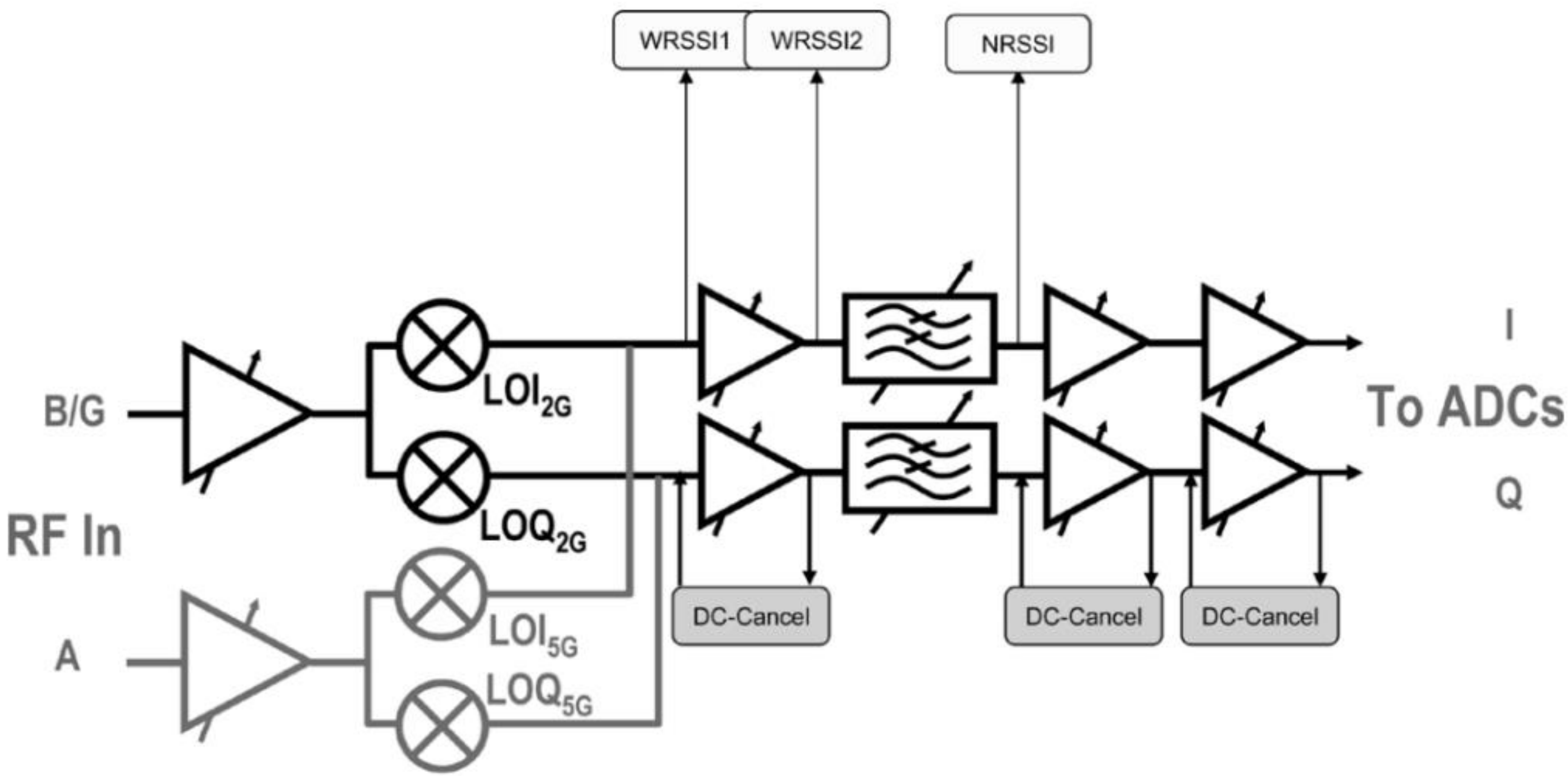
- **NF**: around 6dB

- **BER:** $< 10^{-5}$

“RF Microelectronics”, Behzad Razavi

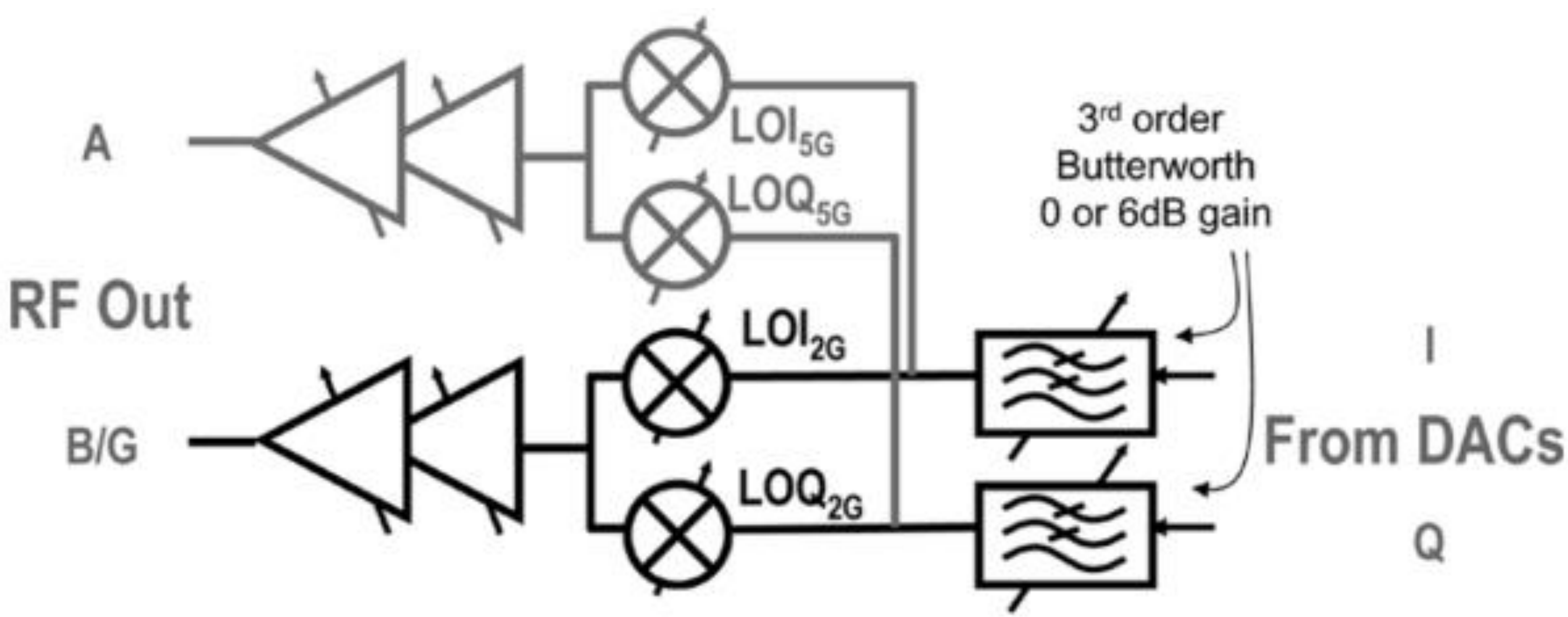
Dual-Band Wi-Fi RX Design

- Used channel signal is amplified by LNA and down converted with associated quadrature mixer
- RSSI (received signal strength indication) used to check if gain is too large



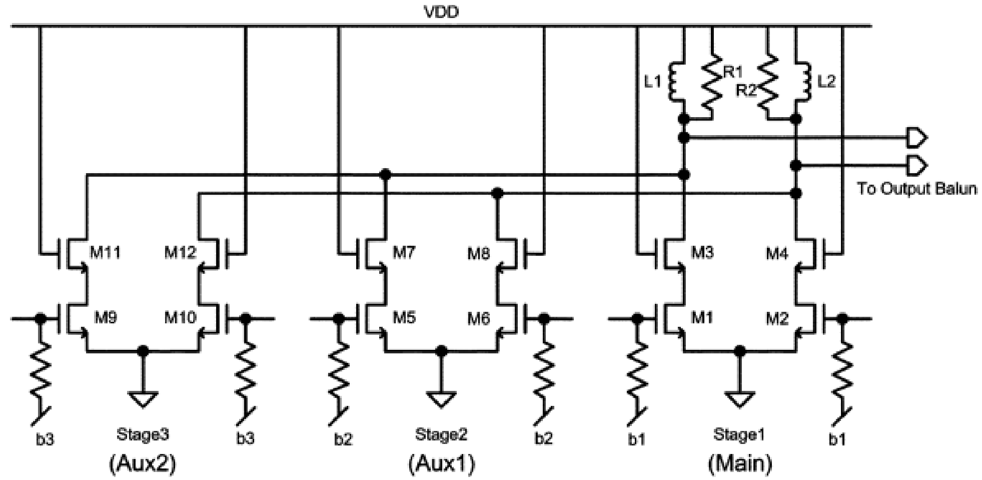
Dual-Band Wi-Fi TX Design

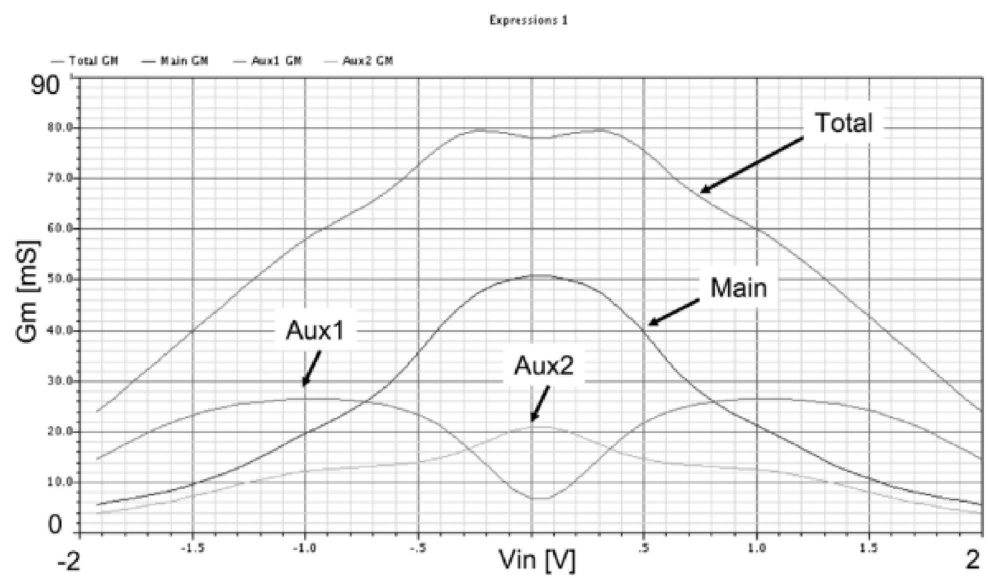
- Baseband DAC outputs are filtered by programmable bandwidth and gain low-pass filters
- Select up-conversion mixers convert baseband to RF
  - Designed for low LOFT (local oscillator feedthrough) and wide gain control
- Mixer output is amplified by two stage variable gain amplifier
  - Output matched to 100Ω differential load



Power Amplifier Design

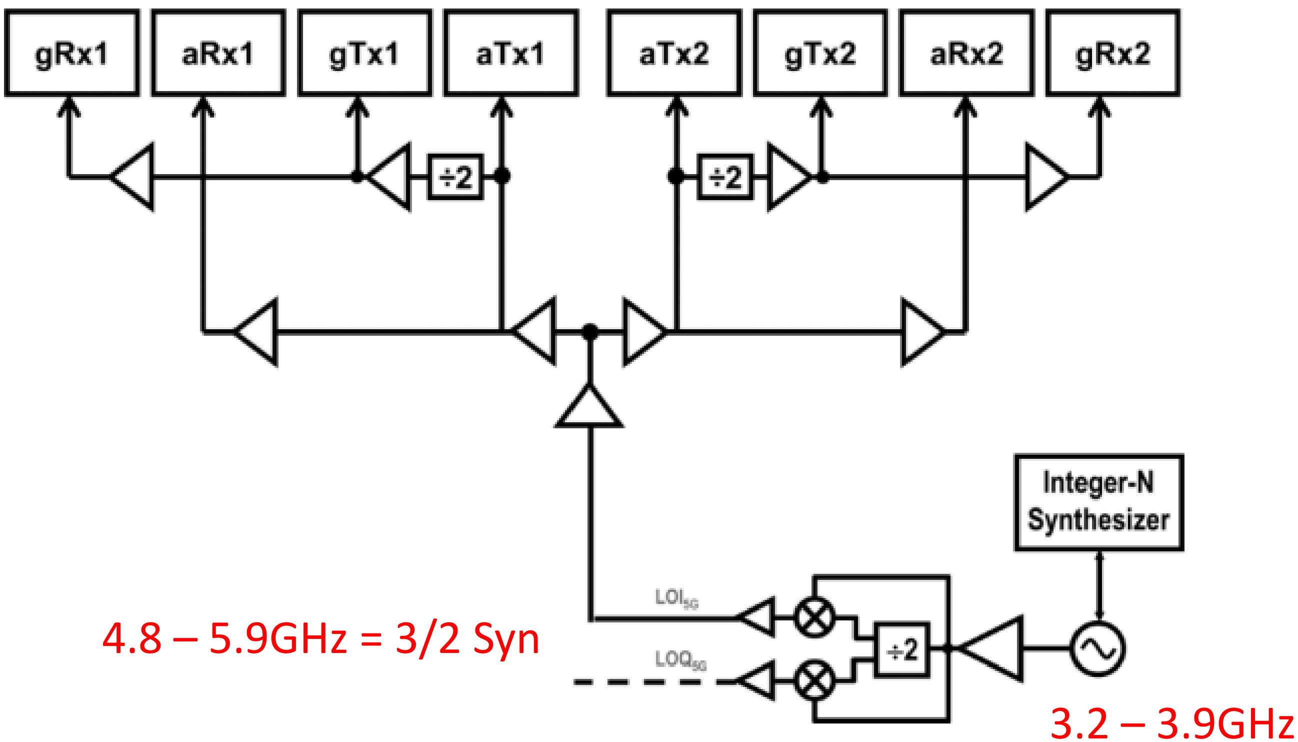
- Parallel amplifier structure for improved linearity
  - Main = Class A
  - Aux 1 = Class AB
  - Aux 2 = Class B
- Aux 1 and Aux 2 are only turned on if input signal is large enough
  - Saves power for smaller signals





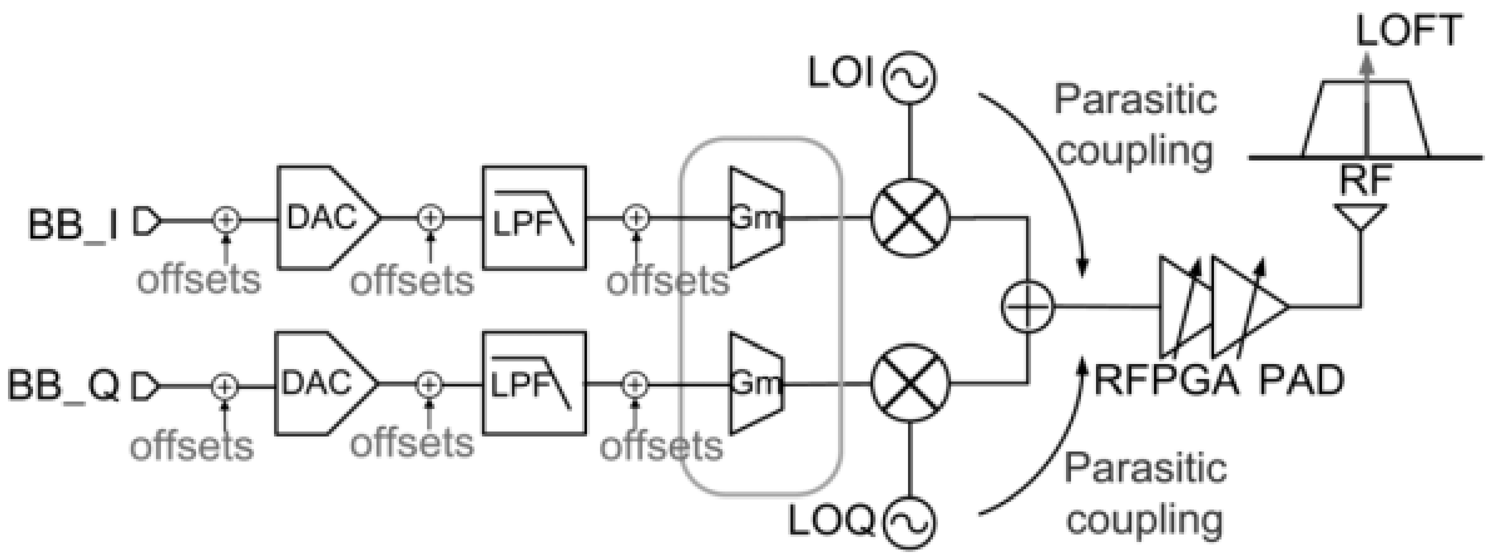
PLL and LO Generation

- VCO Operation Frequencies
  - A-band = 2/3 channel frequency
  - B/G-band = 4/3 channel frequency
- Frequency selection avoids pulling effects/injection locking between VCO and LO signals



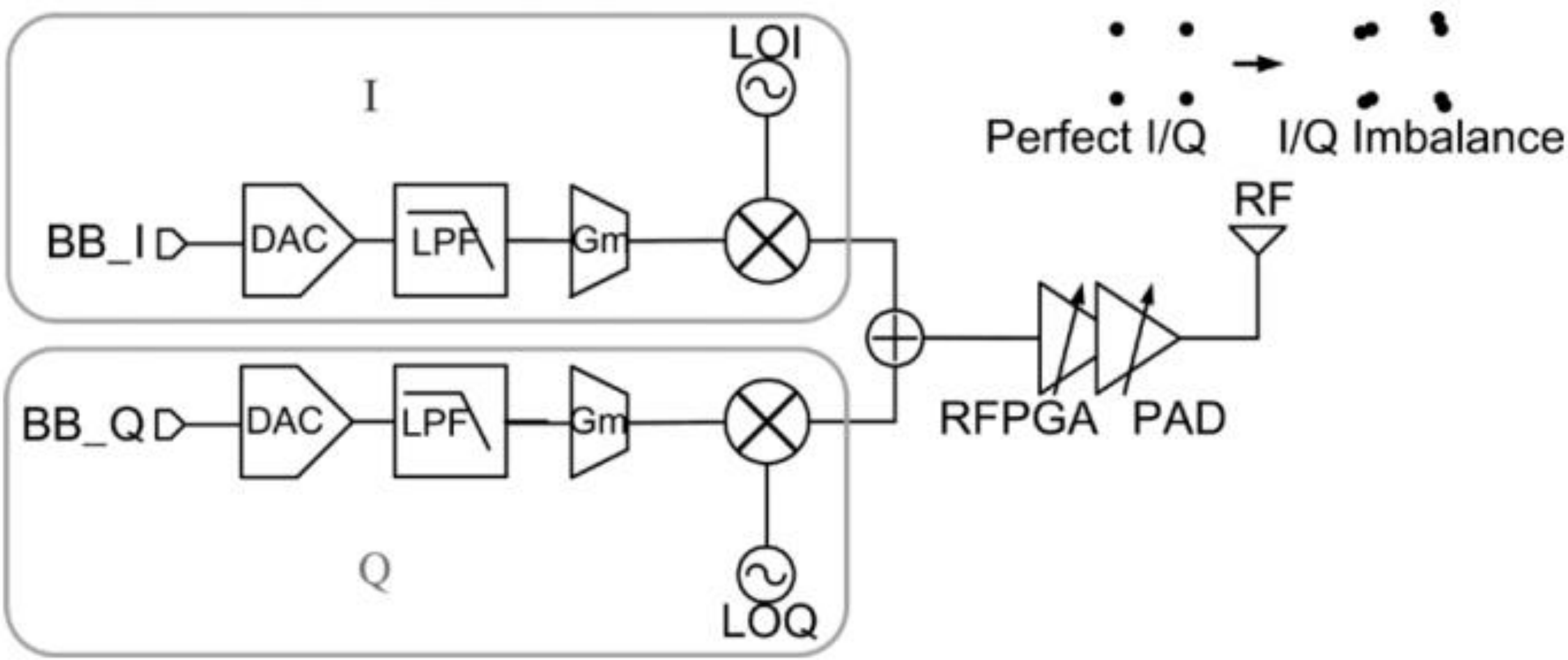
Up-Conversion Offsets and Mismatch: 1

LOFT (LO feed through) in TX appears at LO frequency



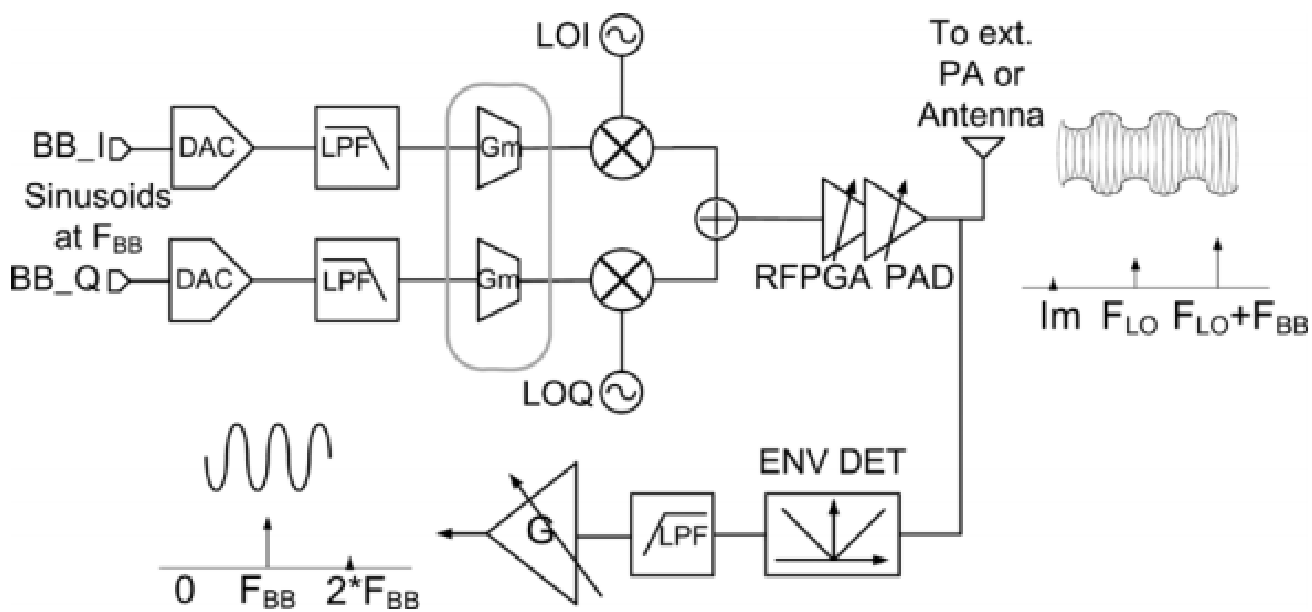
Up-Conversion Offsets and Mismatch: 2

I/Q imbalance as errors in encoding constellation



Possible Self Calibration

- Envelop detector with filtering to measure error
  - LOFT produces strong F_{BB} component
  - I/Q imbalance produces strong $2F_{BB}$ component
- Other harmonics are also produced:
  - Envelope detector circuitry needs to be made linear to prevent harmonic interference

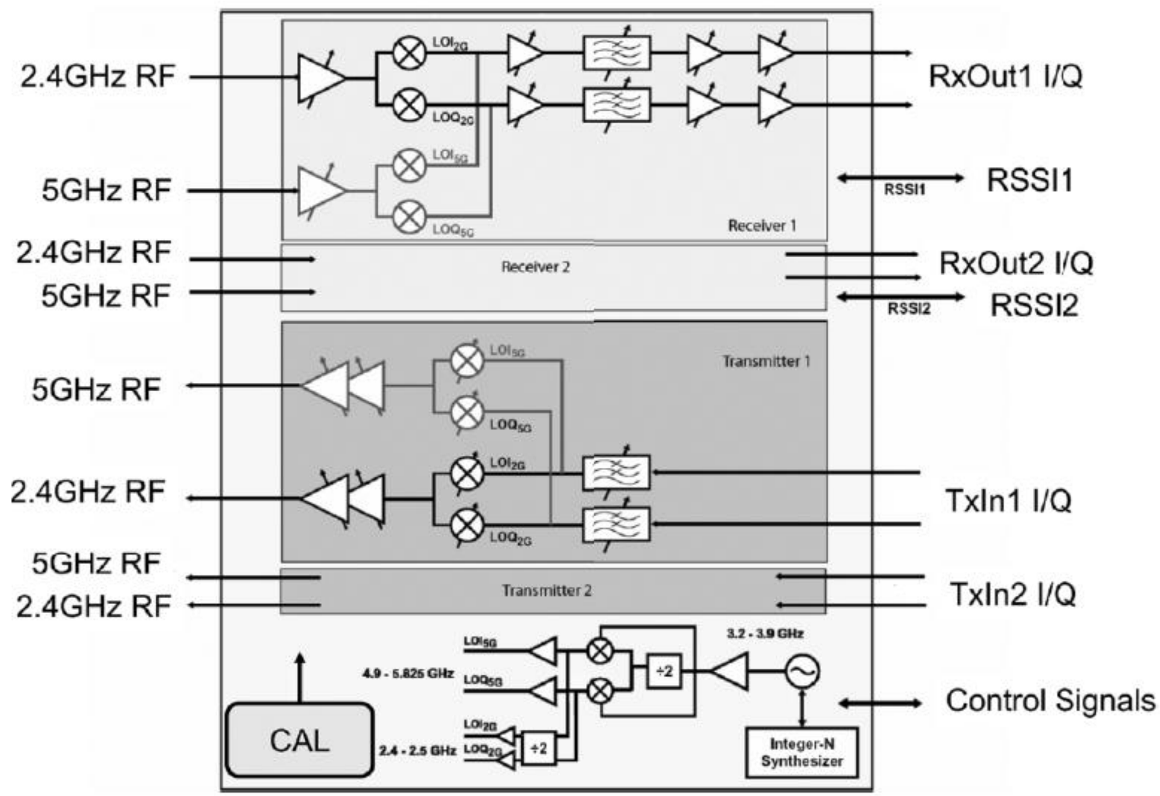


Typical Wi-Fi Transceiver Performance

	Measured	Spec.	
Frequency band (A/G)	2.4-2.5 / 4.8-5.9		GHz
RX max gain (A/G)	>100 / >100		dB
RX min gain (A/G)	5 / 5		dB
RX NF @ max RF gain (A/G)	4 / 4.5		dB
RX IIP3 @ min RF gain (A/G)	+5 / +6		dBm
RX IIP3 @ max RF gain (A/G)	-12 /-10		dBm
RX-RX Isolation (A/G)	>60 / >60	>30	dB
RX LPF BW	5 / 10 / 20		MHz
TX P-1dB (A/G)	+14 / +16		dBm
TX EVM (A/G)	<-40 / <-41	<-30	dB
TX-TX Isolation (A/G)	>35 / >43	>15	dB
In-band PN @ 150KHz offset (A/G)	-108 / <-109	<-100	dBc/Hz
Legacy 54Mbps, chip-referred MRC enabled sensitivity (A/G)	-79 / -78	-65	dBm
EWC MCS15 40MHz channel, std GI, 270Mbps, chip-referred sensitivity	-72 / -72		dBm
Vdd	1.8		V
RX mode total current consumption	275		mA
TX mode total current consumption (both cores active)	280		mA
Technology	0.18um CMOS		
Die size	18		mm^2
ESD HBM performance	> ±2		kV

IEEE 802.11n MIMO

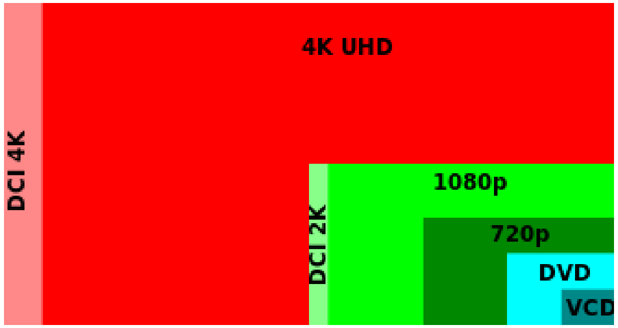
- 2x2 (up to 4x4) MIMO (multiple-input multiple-output) Transceiver
- 2 multiband RX chains
- 2 multiband TX chains
- Spatial isolation for signal chains
- Up to 600Mbps by 4 spatial streams of 40MHz bandwidth with 64-QAM



Arya Behzad et al, 'A Fully Integrated MIMO Multiband Direct Conversion CMOS Transceiver for WLAN Applications (802.11n)', IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 42, NO. 12, DECEMBER 2007

IEEE 802.11ad Gigabit Alliance

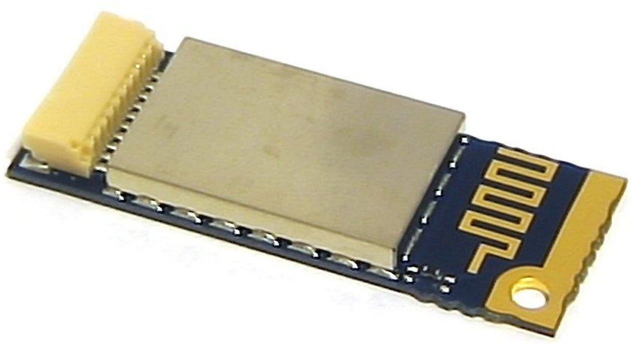
- 60GHz unlicensed ISM bands
- Possible 4 – 14 GHz bandwidth considered by FCC
- Short-range direct line-of-sight wireless transmission
- 7 Gbps ready for real-time uncompressed 4K video streaming (OFDM): 4000×2000 (4K resolution) × 30 (color map) × 20 (frame rate) = 4.8Gbps
  - QPSK: 0.693Gbps at –66dBm sensitivity
  - 64-QAM: 6.76Gbps at –47dBm sensitivity



M. Haidar, "WiFi finally ready for 60GHz", EE Times, April 2016.

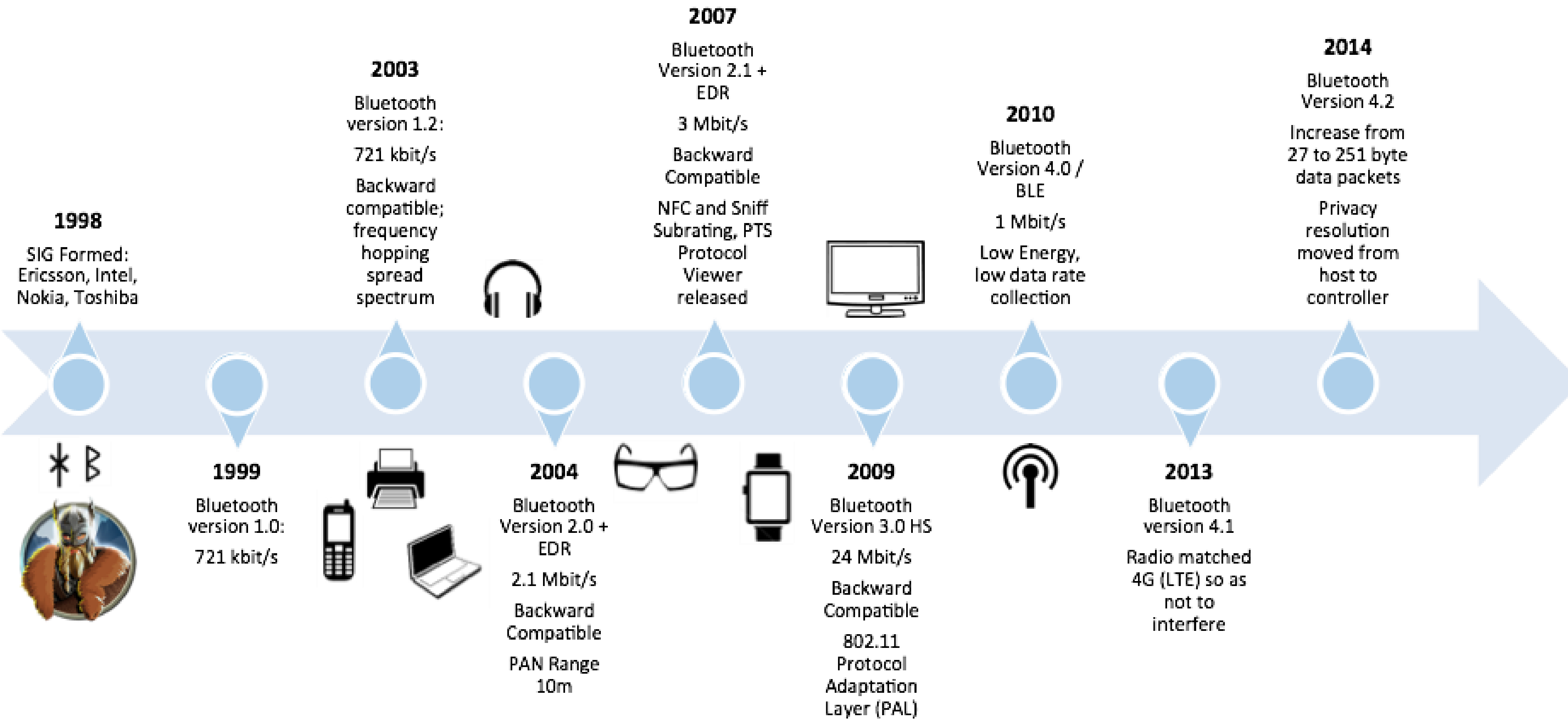
BLUETOOTH

Short Range, Low Data Rate,
Extremely Low Power



Bluetooth card: 14×36×4 mm

Brief Bluetooth History



Danish King, “Harald Bluetooth”, united Danish tribes in 10th century. In the similar way, Bluetooth was proposed to unite the “wireless personal area network” (WPAN) or “piconet”.

Bluetooth Channel Assignment

- Packet-based protocol with master-slave structure.
- One master can communicate up to 7 slaves in a “piconet”.
- Data channels from slave will synchronize with advertising channel from master.

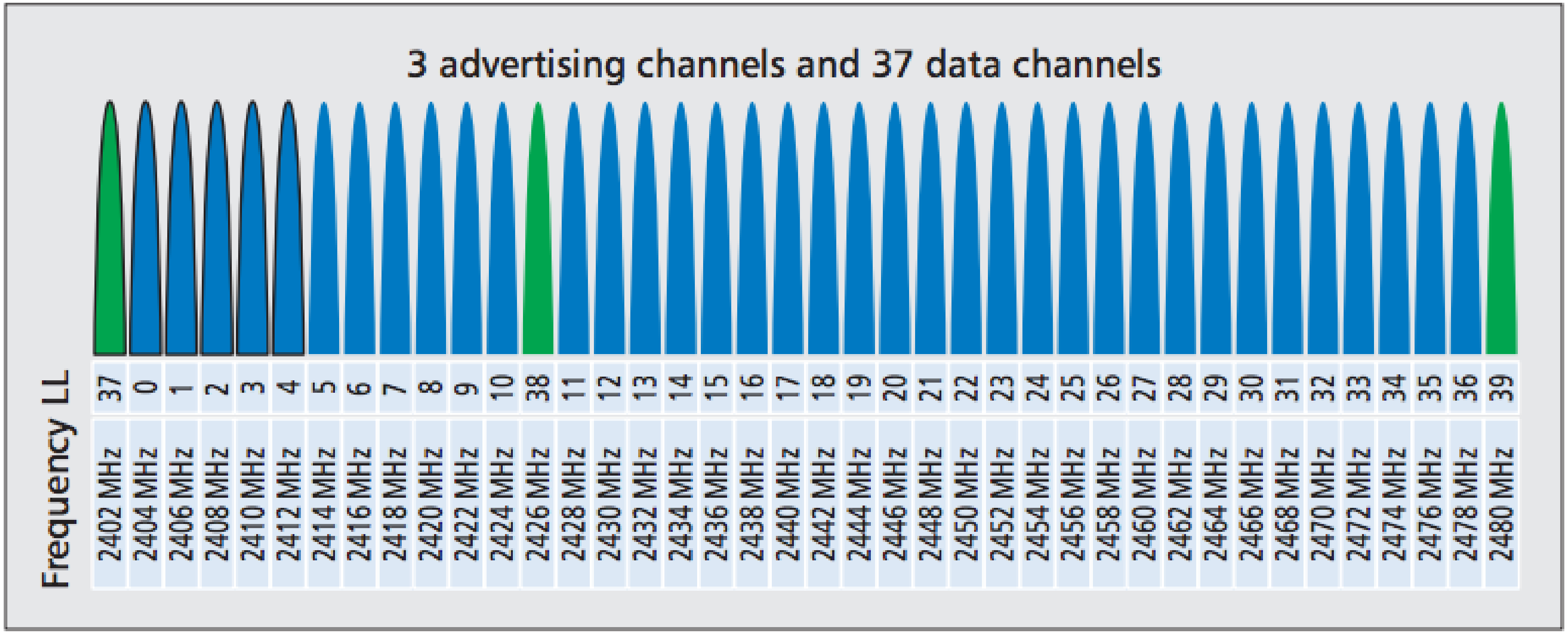
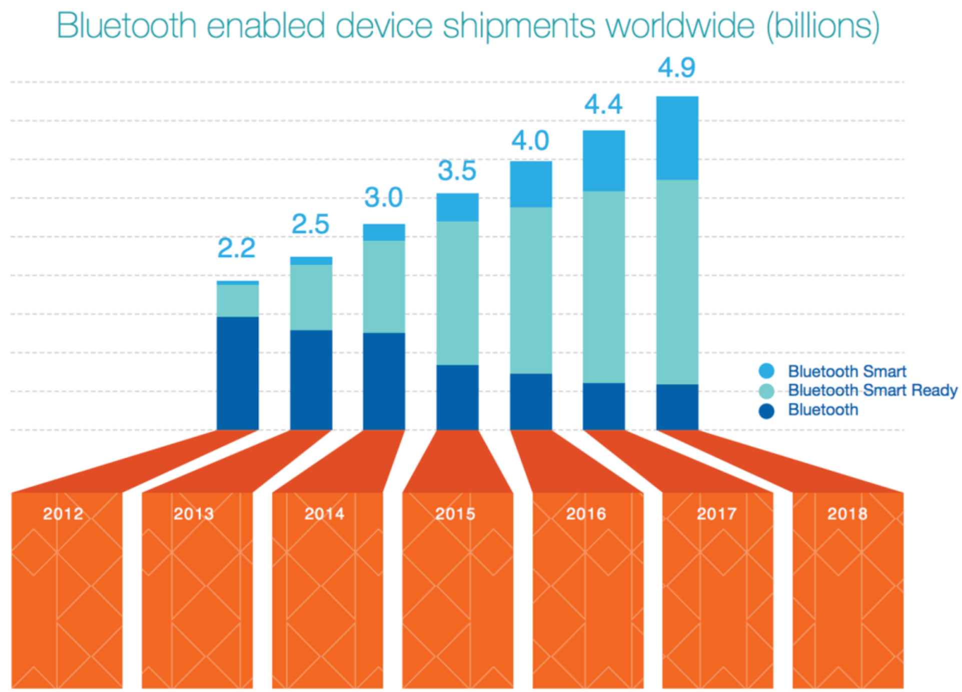


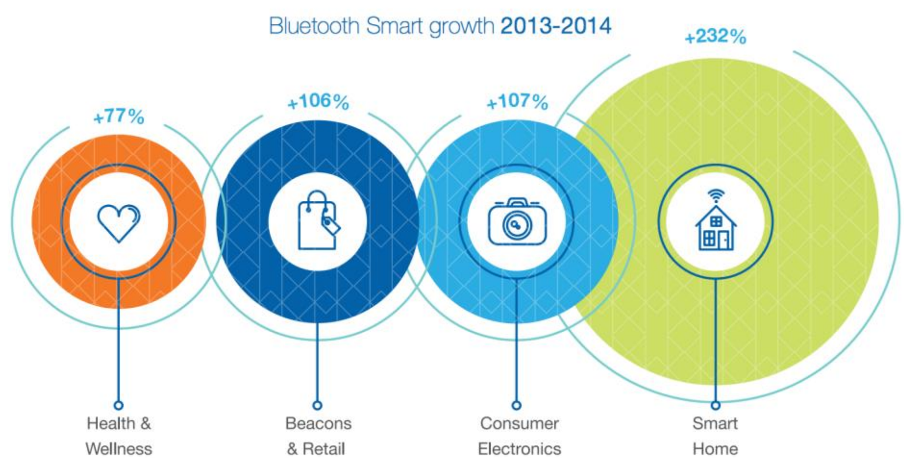
Figure 1. The channel plan of Bluetooth Low Energy.

IEEE Wireless Communications • December 2014

Bluetooth Market and Applications

- Market application need with IoT, wearables, beacons, health & fitness
- Present market leaders: In 2014, Nordic, TI, and CSR owned 95% of Bluetooth Smart ICs shipped
- 2016 - Bluetooth standard for all mobile phones





Bluetooth SIG - Annual Report 2014 - 5

FCC and ETSI Regulations on Bluetooth (1)

- Band and bandwidth of operations: 2400 to 2483.5 MHz portion of ISM band - applies globally as well
- Cannot cause harmful interference to other radio devices within the same 2.4GHz ISM band
- Max transmitter output power (into antenna) is 20 dBm or 0.1 watt

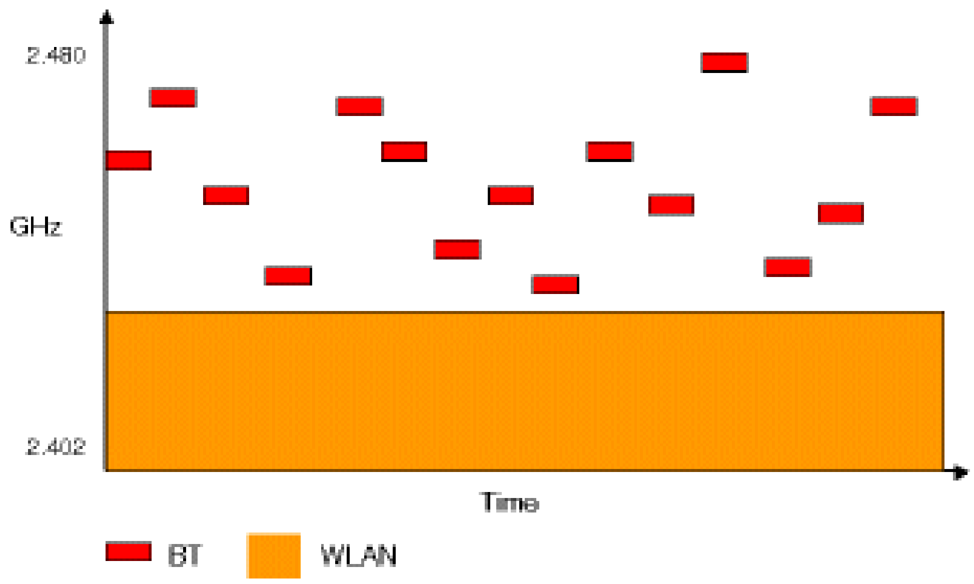
	Min	Max	Operating Range
Power Class 1	1mW (0dBm)	100mW (20dBm)	100 meters
Power Class 2	0.25mW (–6dBm)	2.5mW (4dBm)	10 meters
Power Class 3		1mW (0dBm)	1 meter
Power Class 4		0.5mW (-3dBm)	0.5 meter

FCC and ETSI Regulations on Bluetooth (2)

- 3.5MHz channel with 2MHz guard band at each side.
- Applies for all combinations of power level and antenna assembly
- FHSS (frequency hopping spread spectrum) Modulation: use at least 15 non-overlapping channels, separated by the BW as measured at 20 dB below peak power
- For adaptive frequency hopping (AFH): must be capable of operating over a minimum of 90% of the 2.4-2.4835 GHz band. At any 0.4s interval, a minimum of 20 channels or hopping channels must be used
- Other types of modulation considered equivalent to FHSS and DSSS modulations

Air Protocol for Multiple Access

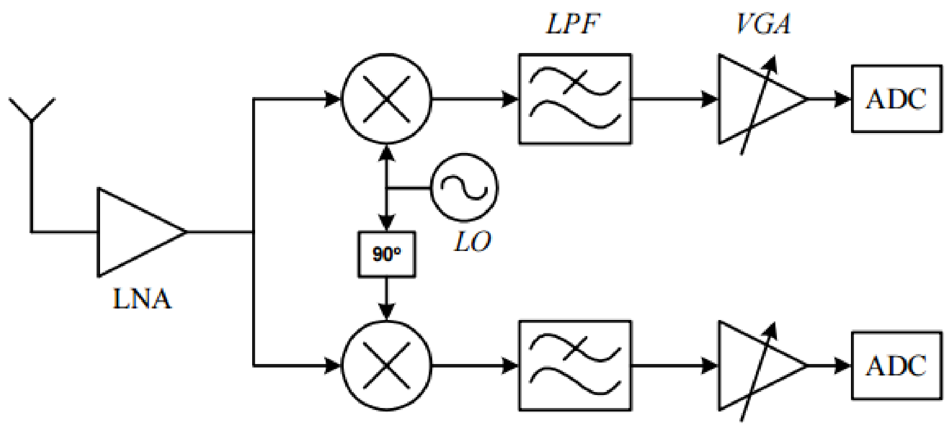
- Bluetooth Pairing: Acknowledgement/Encryption
- Piconet (Master/Slave)
- Adaptive Frequency Hopping (AFH) Spread Spectrum
  - Given 1 MHz bandwidth channels → 79 channels, ~1600 changes/sec
- Round Robin scheduling



Transmitter and Receiver Isolation

- Half duplex implementation: master/slave communicate over the same frequency channel with Time Division Duplex TDD):
  - TX/RX switch with variable time ideal for Bluetooth since communication time is asymmetric
- Coupled with frequency hopping and encryption, Bluetooth can be secure
- Low IF of ~ 2 MHz: This selection leads to in-band image frequencies. Tradeoffs between dealing with DC offset or with image interference

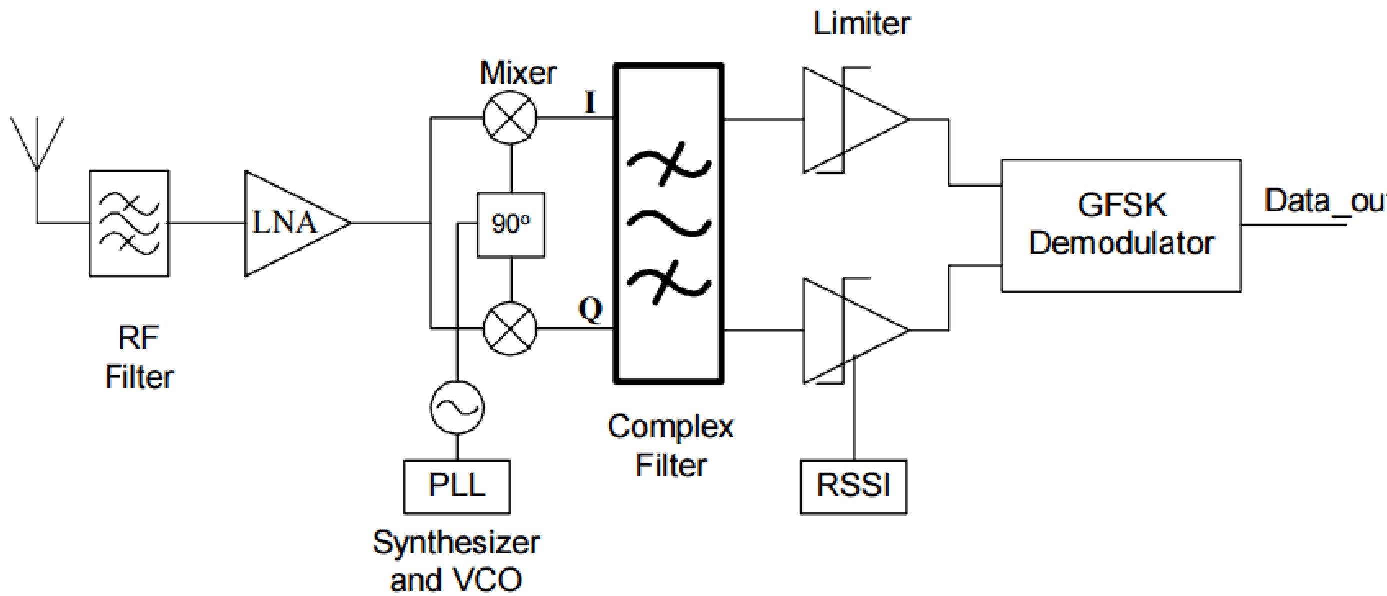
Common Receiver Architectures (1)
Direct Conversion



- DC offset from LO & interferer leakage
- Flicker noise
- Even-order intermodulation and distortion
- I/Q mismatch
- Fewer components: Lower power consumption

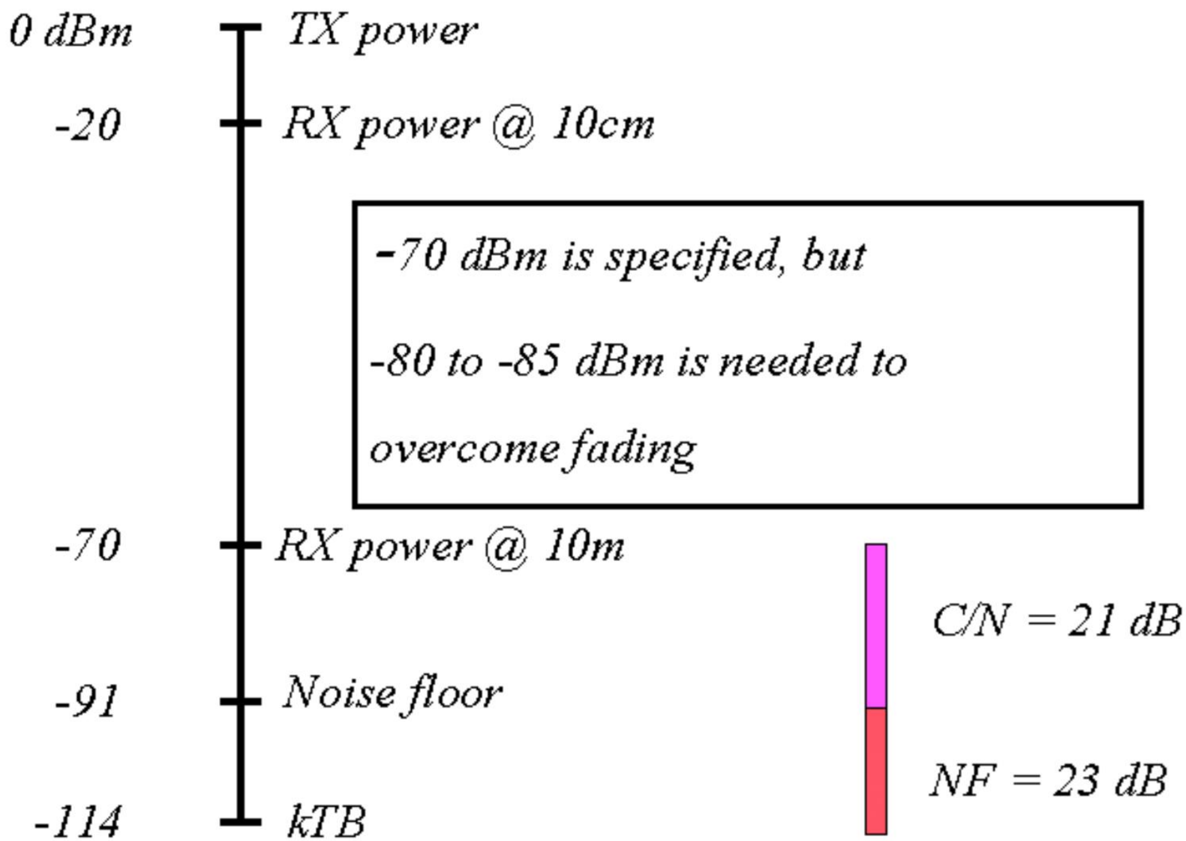
Common Receiver Architectures (2)

Low-IF



- DC offset and Flicker Noise greatly alleviated
- Folded-back interference

Typical Tx and Rx values in Bluetooth



LNA in Low-Power Transceivers

- Robust input matching: 50 Ohm input impedance to provide termination for preceding external components
- High gain: Since the LNA is the first block of the entire receiver, high gain helps to reduce overall noise figure
- Low noise: NF of LNA sets lower bound of system NF
- Sufficient linearity, low power consumption

Common LNAs for 2.4 GHz Band

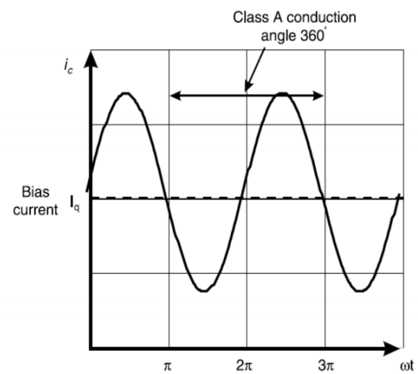
(Typical Values 2.4-2.5 GHz)	Maxim Integrated MAX2644	Microchip SST12LN01
Gain	**18.7 dB**	14 dB
Noise Figure	**1.9 dB**	2.0 dB
IIP3	0.5 dBm	**3 dBm**
P1dB	-13 dBm	**-5.5 dBm**
Power Consumption	**2.45 mW**	6.05 mW
Applications	WLAN, Bluetooth, Home RF, 2.4 GHz ISM Band Radio & Cordless Phones	WLAN, Bluetooth, Wireless Networks

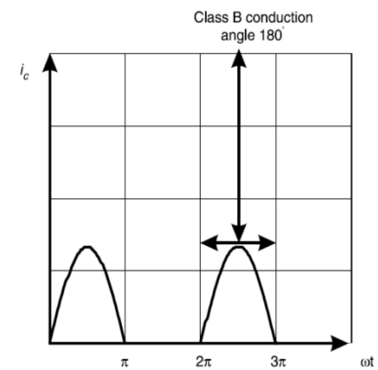
Power Amplifier

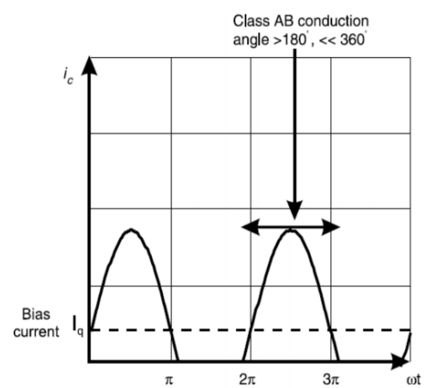
- RF PA consumes most of the power in TX
- Linear amplifier class determined by voltage bias
- Bluetooth can use multi-stage amplifiers

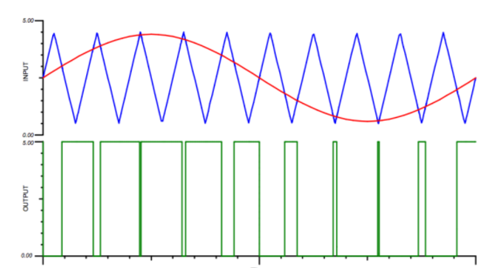
	Ideal Efficiency	Linearity	Practical efficiency	Process
Class A	50%	Good	35%	SOI 0.5μm CMOS [8]
Class AB	50% - 78.5%	Good	45%	0.35μm CMOS [9]
Class B	78.5%	Moderate	49%	PHEMT [10]
Class C	78.5% - 100%	Poor	55%	0.6μm CMOS [11]
Class E	100%	Poor	62%	0.35μm CMOS [12]
Class F	100%	Poor	80%	PHEMT [10]

http://www.ee.ust.hk/~analog/thesis/power_amplifier_for_bluetooth.pdf









http://www.ti.com/lit/ug/slau508/slau508.pdf

PA Example: Microchip: SST12LP17E

- 2.4 GHz high-efficiency, fully-matched PA module
- Input/Output ports matched to 50Ω internally
- Meets 802.11g spectral mask up to 21.5 dBm

Frequency Range	2.4 GHz - 2.5 GHz
Power Gain	28 dB
Power Added Efficiency; Pout = 21.5dBm 802.11g	28%
ICC: DC Input Current @ 17dBm	100 mA
Linearity @ 18dBm	3% EVM
Dynamic Range	>15 dB

EVM: error vector magnitude

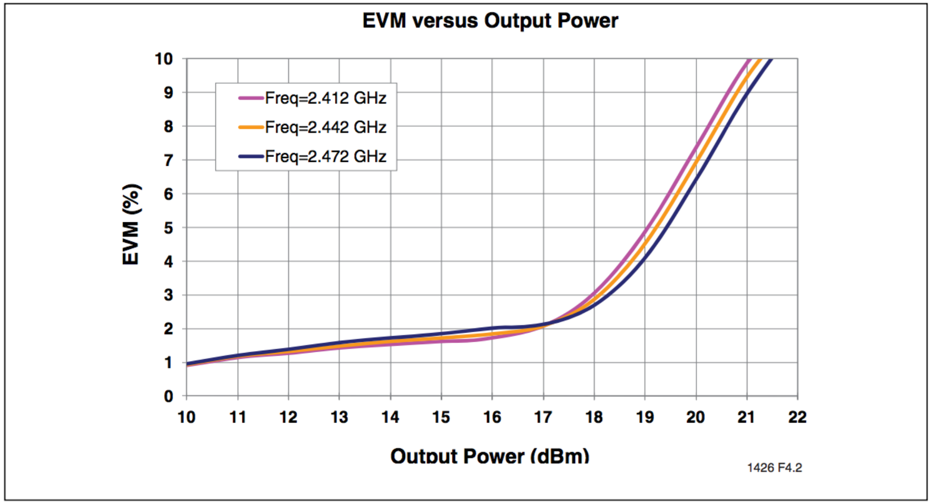


Figure 4: EVM versus Output Power

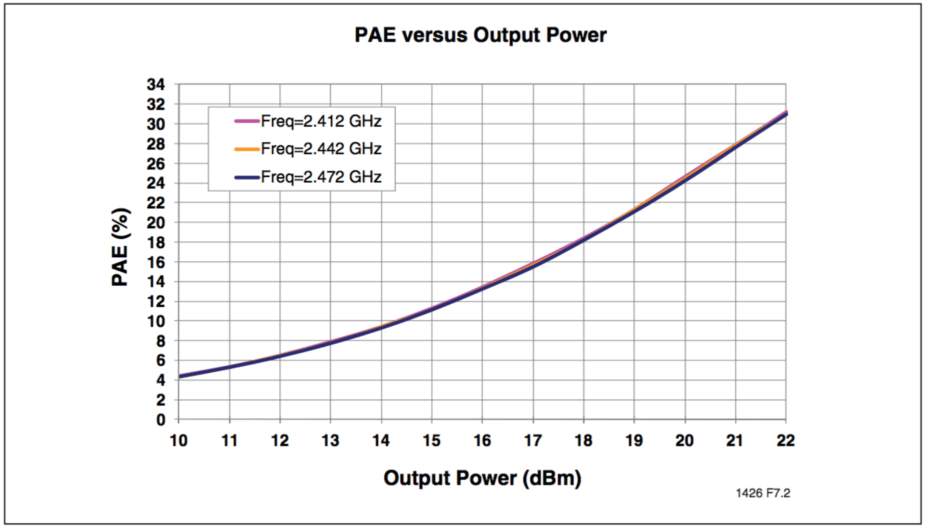
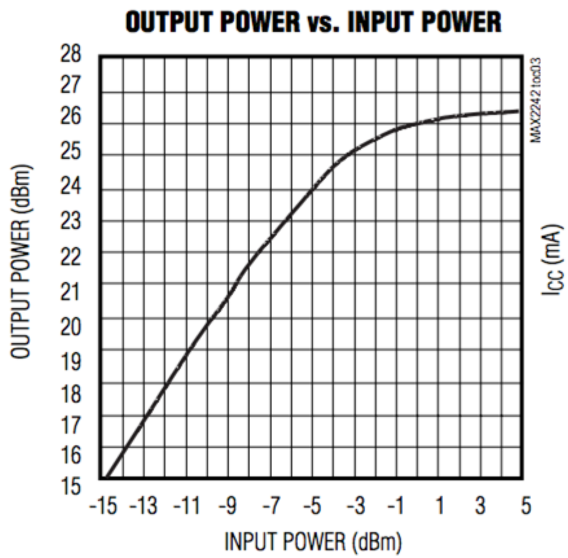


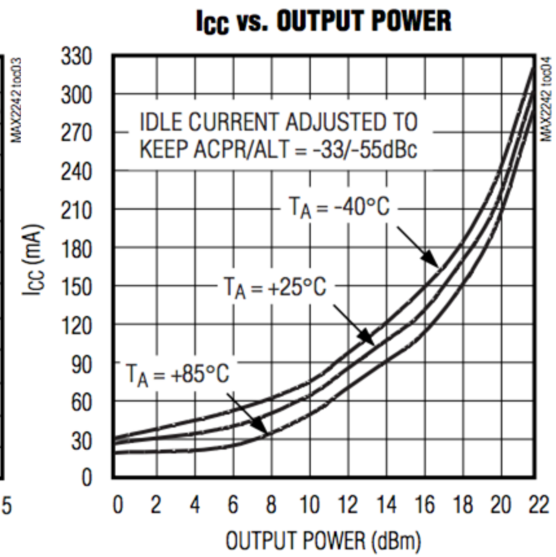
Figure 7: PAE versus Output Power

PA Example: Maxim: MAX2242

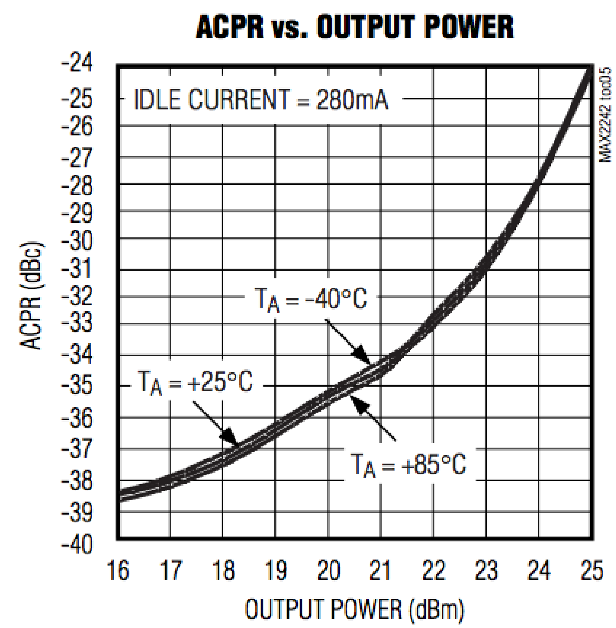
- Low-voltage linear Power Amplifier
- Designed for 2.4 GHz ISM-band wireless LAN applications, Bluetooth, 802.11b
- 3-stage Class AB PA
- 22.5dBm linear output power (ACPR<-33dBc 1st lobe, <-55dBc 2nd lobe)

Frequency Range	2.4 GHz - 2.5 GHz
Power Gain	28.5 dB
Power Added Efficiency	16%
DC Input Current @ Pout = 22 dBm	300 mA
Dynamic Range	20 dB



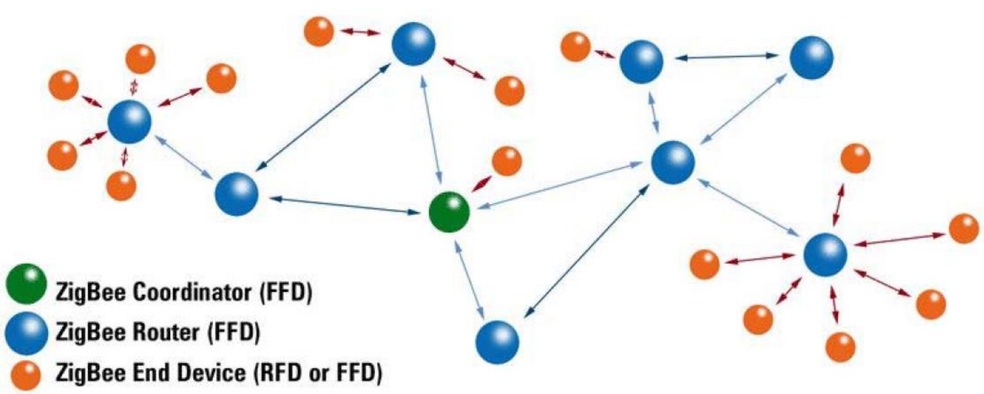


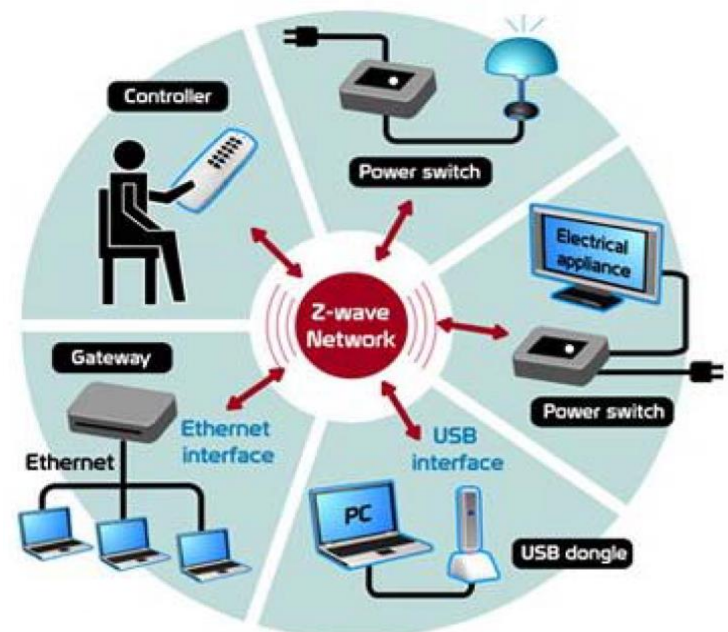
ACPR: Adjacent channel power ratio (dBc)



Other Short-Range Network Protocols

- **Zigbee**: for long-range, low data-rate control, such as robotics and quadcopters.
- **Z-Wave**: for short-range INDOOR, low data-rate appliance and room control connection in the 900 MHz range.

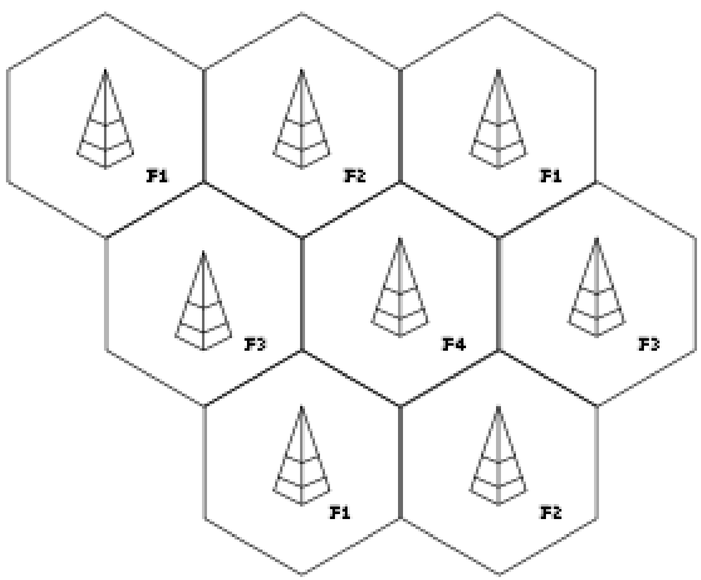


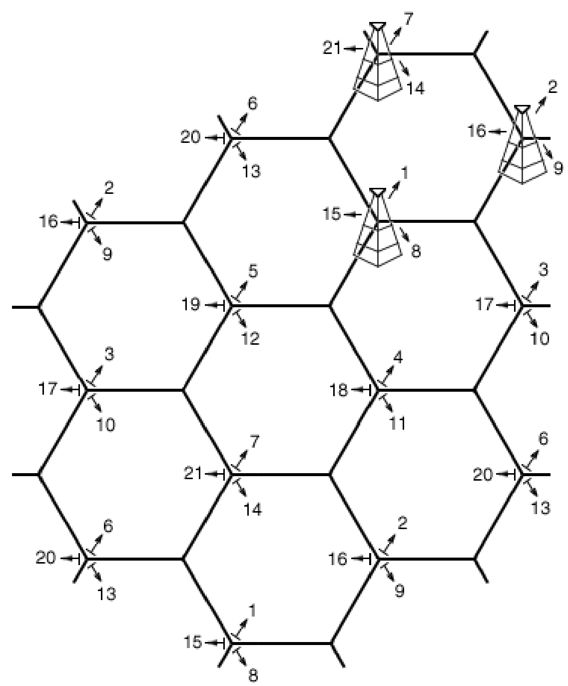


Cellular Networks 3G, 4G and 5G

Cellular Networks

- A cellular network is a full communication network where the last link is wireless. Maximal frequency usage and quality of service (QoS) in each radio cell.
- The radio coverage needs to be long-range (1 – 40 km), full duplex, and reliable network for voice and data.
- Dynamic allocation: cell breathing for load balance.





Cellular Network Characteristics

- FCC regulates 50 dBm EiRP or 57 dBm ERP (antenna)
- Frequency reuse in non-adjacent cells
- Control handover for moving units (together with load balance)

Band capacity ↔ Coverage distance

Macrocell	> 2km (2 – 40km)
Microcell	< 2km
Picocell	< 200m
Femtocell	< 10m

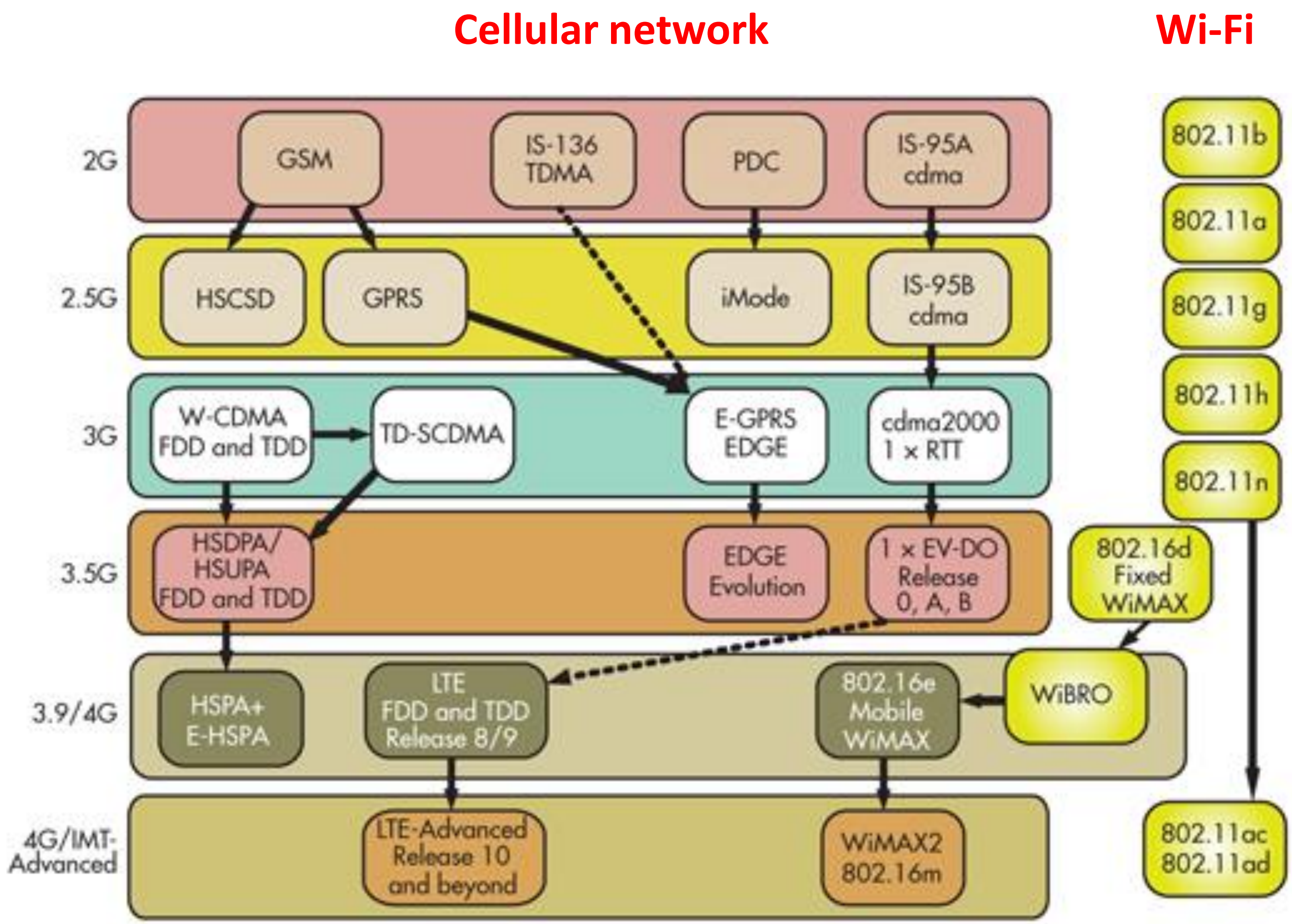
Freq. (MHz)	Cell Radius (km)	Relative capacity
450	49	1
950	27	3.3
1800	14	12.2
2100	12	16.2

Cellular Network Evolution

2G: TDMA
TDD

3G: CDMA; GSM
TDD and FDD

4G: IMT-Advanced;
WiMAX; LTE; OFDM
802.16



http://electronicdesign.com/content/evolution-lte

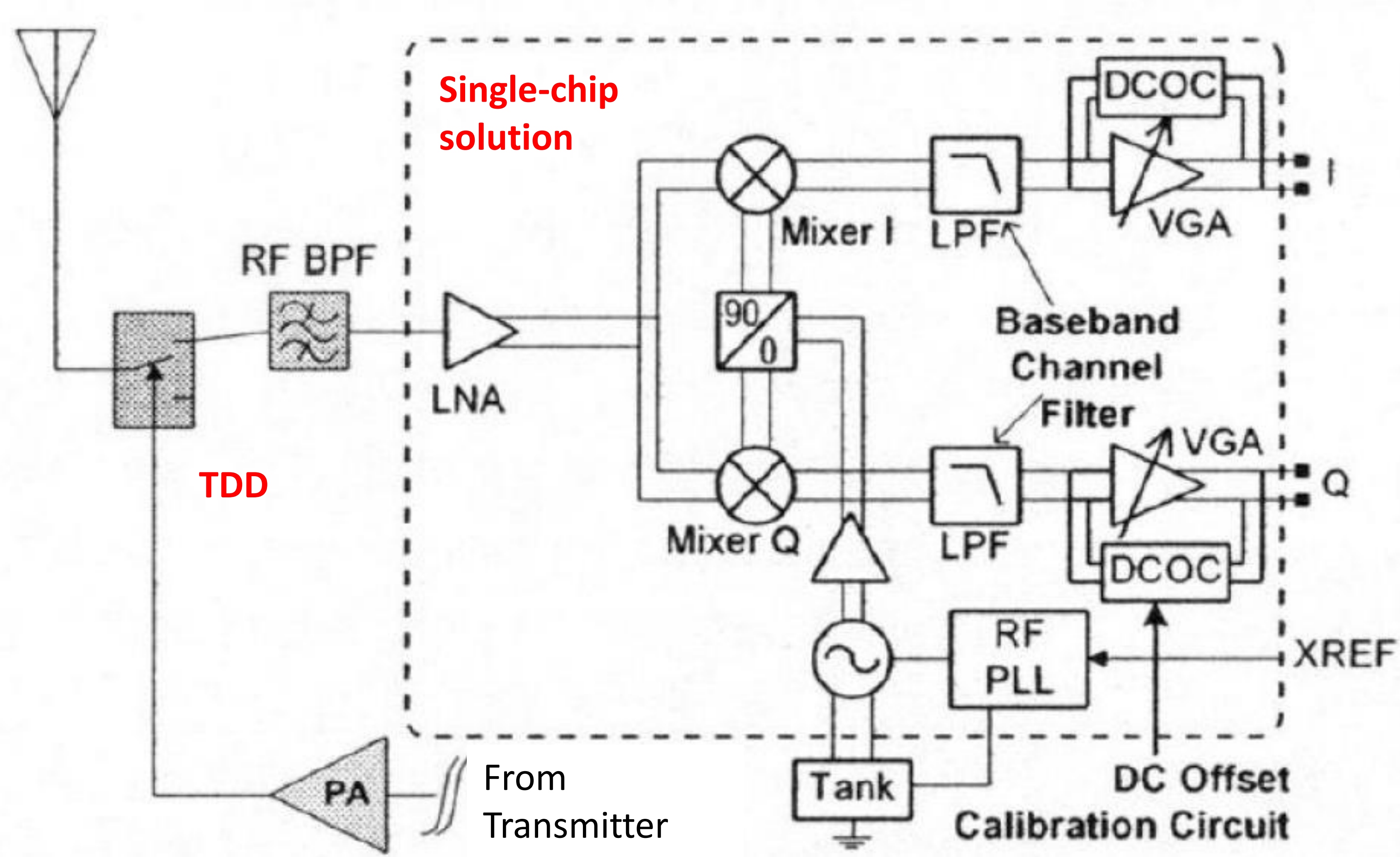
3G Cellular Network Regulation Examples

Band (MHz)	Uplink Freq. (MHz)	Downlink Freq. (MHz)	Channel Bandwidth (MHz)	Main Regions
2100	1920 – 1980	2110 – 2170	5, 10, 15, 20	EU, Asia, Africa
1900	1850 – 1910	1930 – 1990	1.4, 3, 5, 10, 15, 20	America
900	880 – 915	925 – 960	1.4, 3, 5, 10	EU and Asia
850	824 – 849	869 – 894	1.4, 3, 5, 10	America

USA: FCC (Federal Communication Commission)
EU: ECC (Electronic Communications Committee)
ITU: International Telecommunication Union

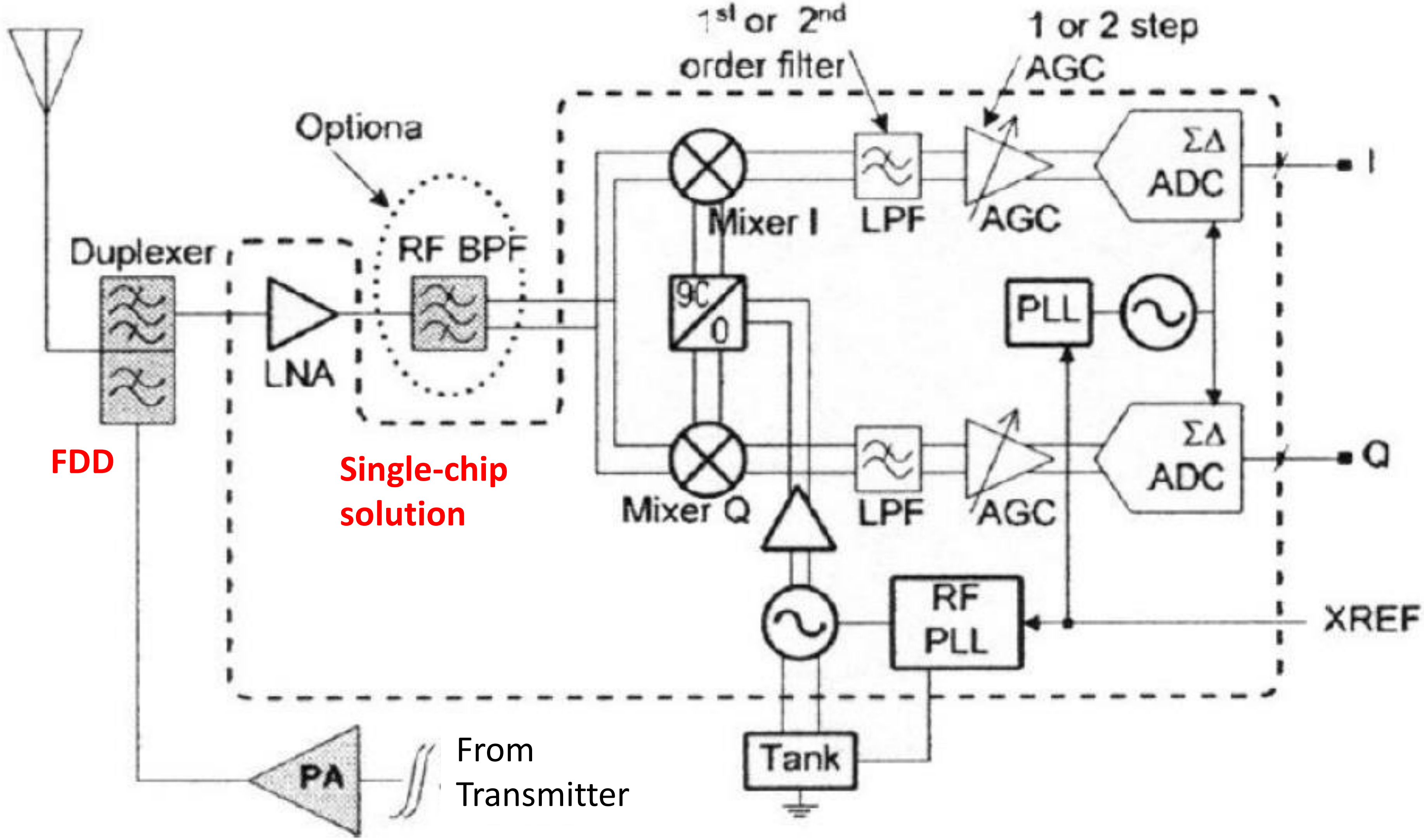
3G Receiver Example 1

Direct Conversion with DC Offset Cancellation (DCOC)

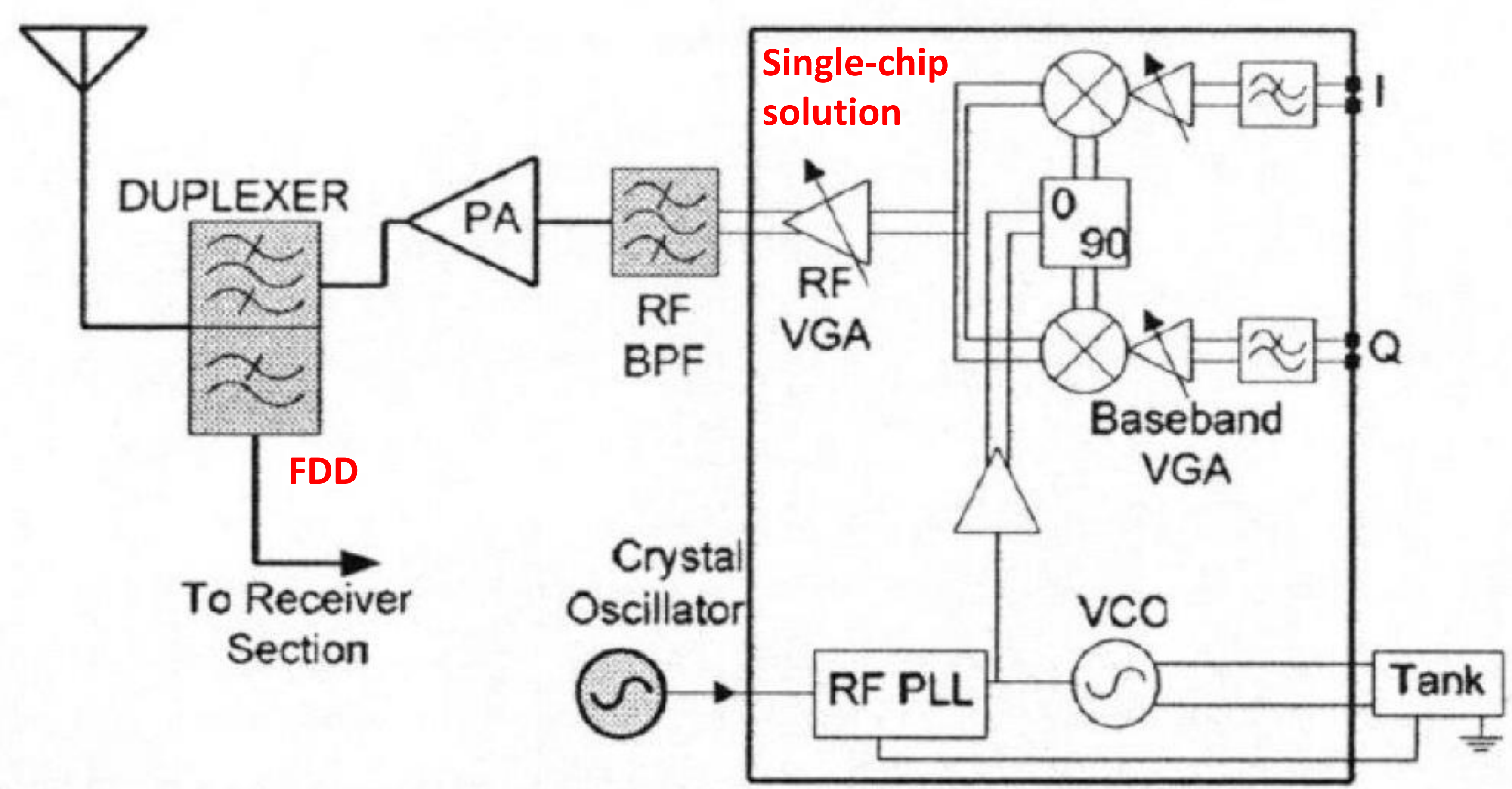


3G Receiver Example 2

Fast Sampling ΣΔ ADC



3G Transmitter Example 2
Direct Modulation



Typical 3G Asymmetric Link Budget Example

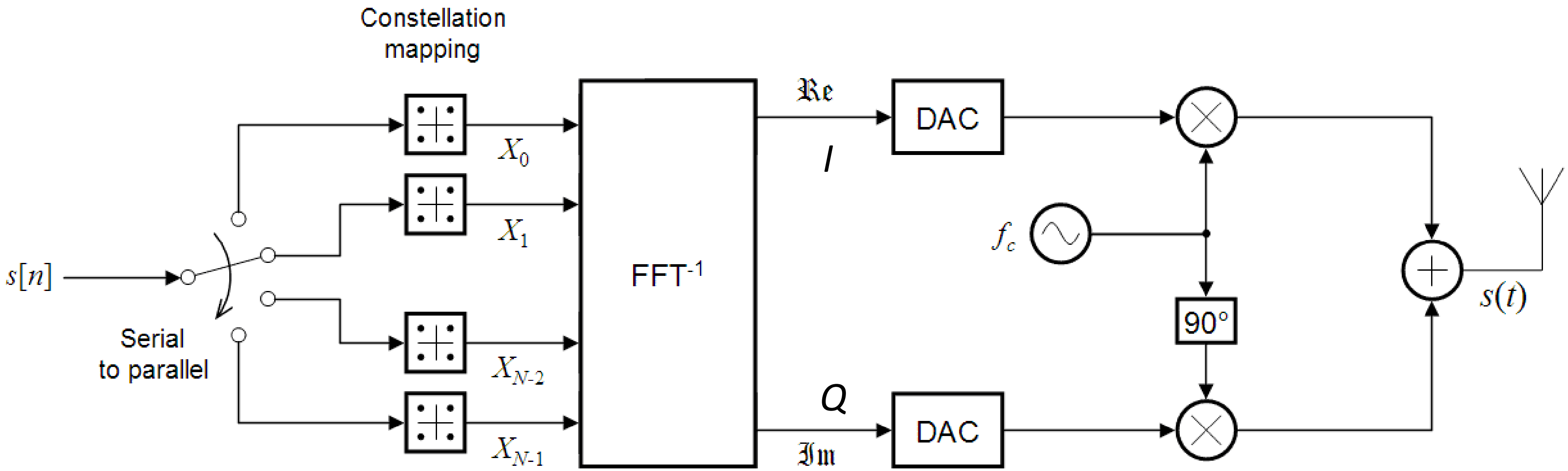
- Base station (TX) to handset (RX) downlink budget: 139dB
  - TX: ERP 43dBm (20W); antenna: 13dBi
  - RX: Antenna 3dBi; receiver sensitivity –80dBm
  - Base station TX-to-RX isolation: 153 dB
- Handset (TX) to base station (RX) uplink budget: 139dB
  - TX: ERP 13dBm (20mW); antenna: 3dBi
  - RX: Antenna 13dBi; receiver sensitivity –110dBm
  - Handset TX-to-RX isolation: 93dB

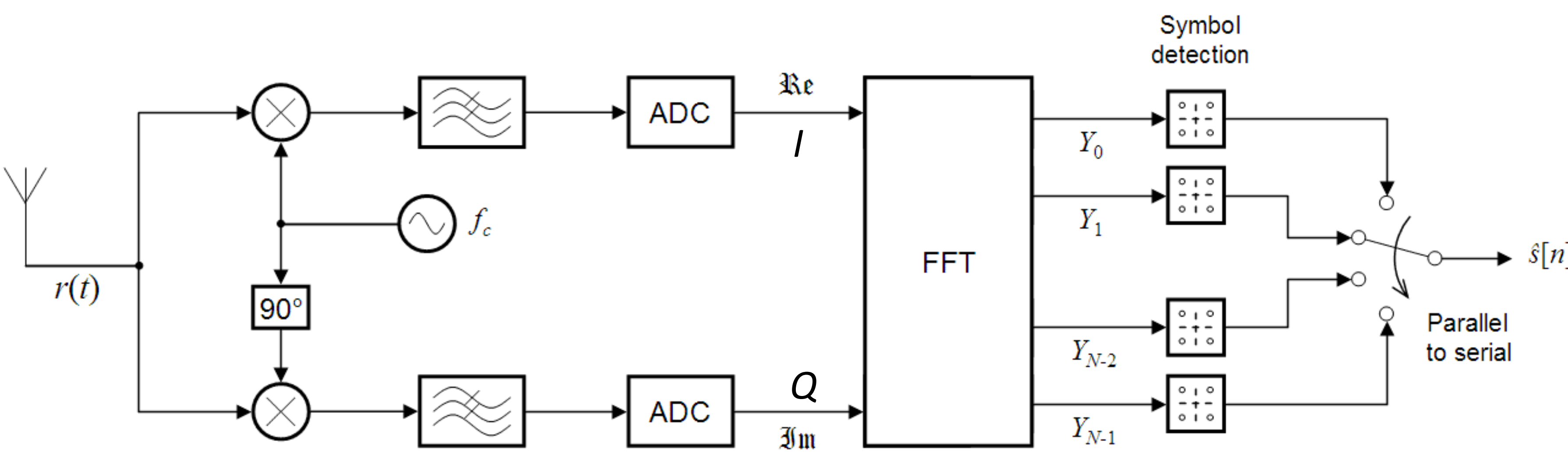
FCC and OSHA Safety Regulation on Human Body

- Radiation < –2.3dBm/cm^2 or 0.58mW/cm^2 integrated over 500MHz – 5GHz
- Specific absorption rate (SAR): 1.6W/kg

https://www.fcc.gov/consumers/guides/human-exposure-radio-frequency-fields-guidelines-cellular-and-pcs-sites

4G Transceiver Example: OFDM





Typical 4G Asymmetric Link Budget Example

- Base station (TX) to handset (RX) downlink budget: 179dB
  - TX: ERP 47dBm (50W); ant.: 18dBi; internal cable/filter loss: 4dB
  - RX: Ant. 2dBi; receiver sensitivity –118dBm; internal loss: 2dB
  - Base station TX-to-RX isolation: 153 dB
- Handset (TX) to base station (RX) uplink budget: 172dB
  - TX: ERP 37dBm (5W); ant.: 2dBi; internal loss: 2dB
  - RX: Ant. 18dBi; receiver sensitivity –121dBm; internal loss: 4dB
  - Handset TX-to-RX isolation: 93dB

Larger link budget gives better chances for higher data rate!

Typical 4G LNA Examples

	Infineon BGA7H1N6	Infineon BGA711N7
Gain (dB)	12.5	17
Noise Figure (dB)	0.6	1.1
IIP_{IM3} (dBm)	6	–2
$I_{1dBcomp}$ (dBm)	–4	–10

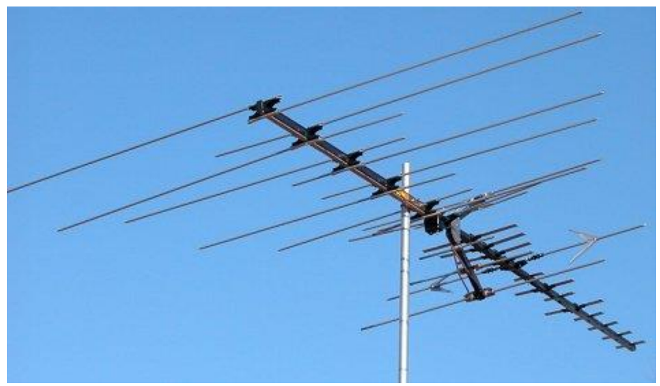
Note: GaAs or GaN pHEMT gives LNA and PA higher OIP_{IM3} (around 10dB for GaAs and 15dB for GaN) but much more expensive and much higher static power consumption

5G Expectation

- Around 2020 deployment
- Data rates about 10 – 100 Mb/s with 1,000 – 10,000 users in macrocells
- Data rates > 100Mb/s for microcells (e.x. metro areas)
- Data rates > 1Gb/s for picocells (e.x. same office floor)
- Massive simultaneous connection (> 10^5) to sensor network and IoT (Internet of Things)
- Spectral efficiency higher than 4G
- Improved coverage
- Improved signaling efficiency (Joule/bits)
- < 1 ms latency (improved from LTE)
- Additional bands of 28G, 37G and 39G.

Broadcasting TV

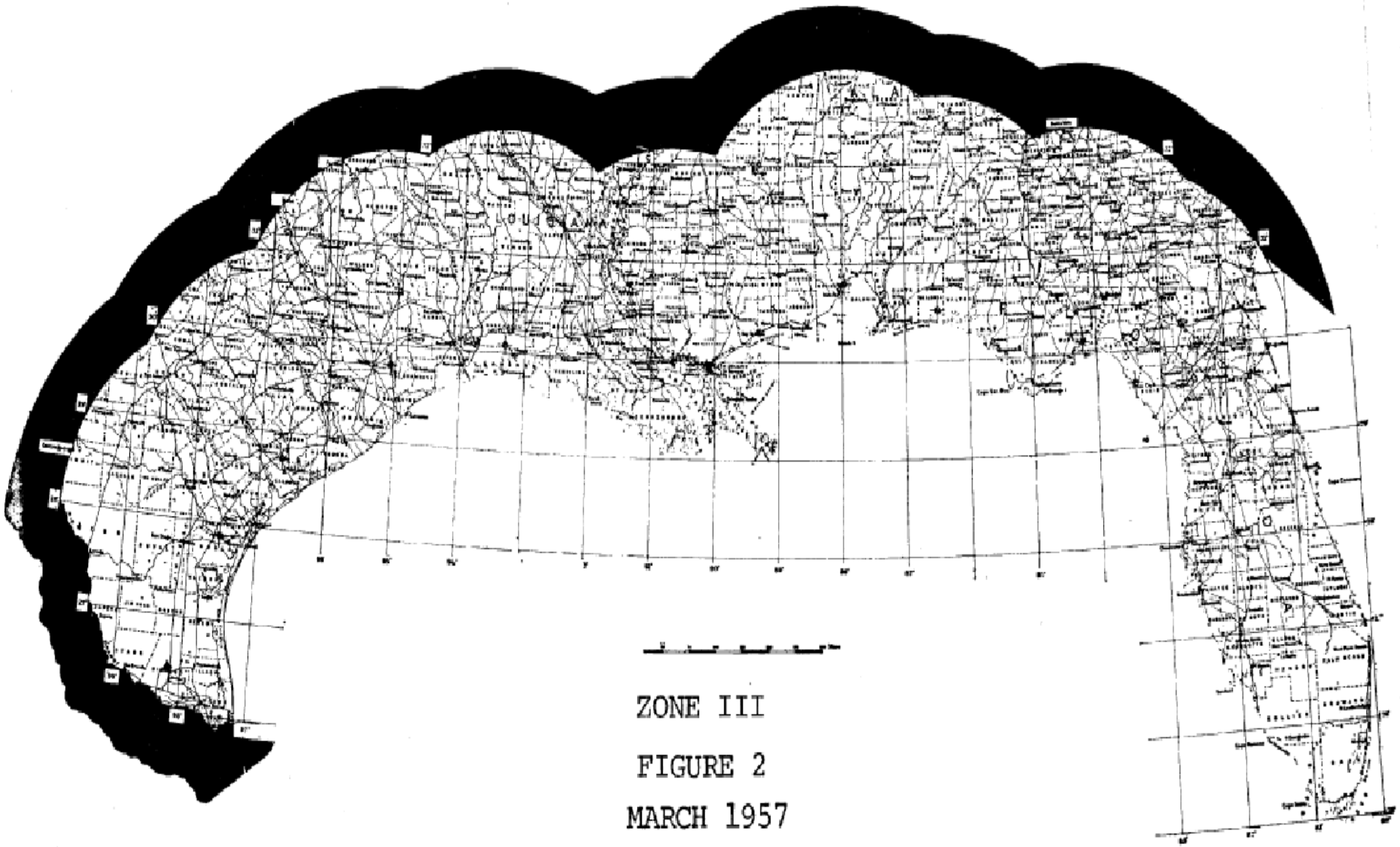
Berlin TV Broadcasting Tower



VHF/UHF TV Receiving Antenna

Analog and Digital TV

FCC Regulations: Zoning Example



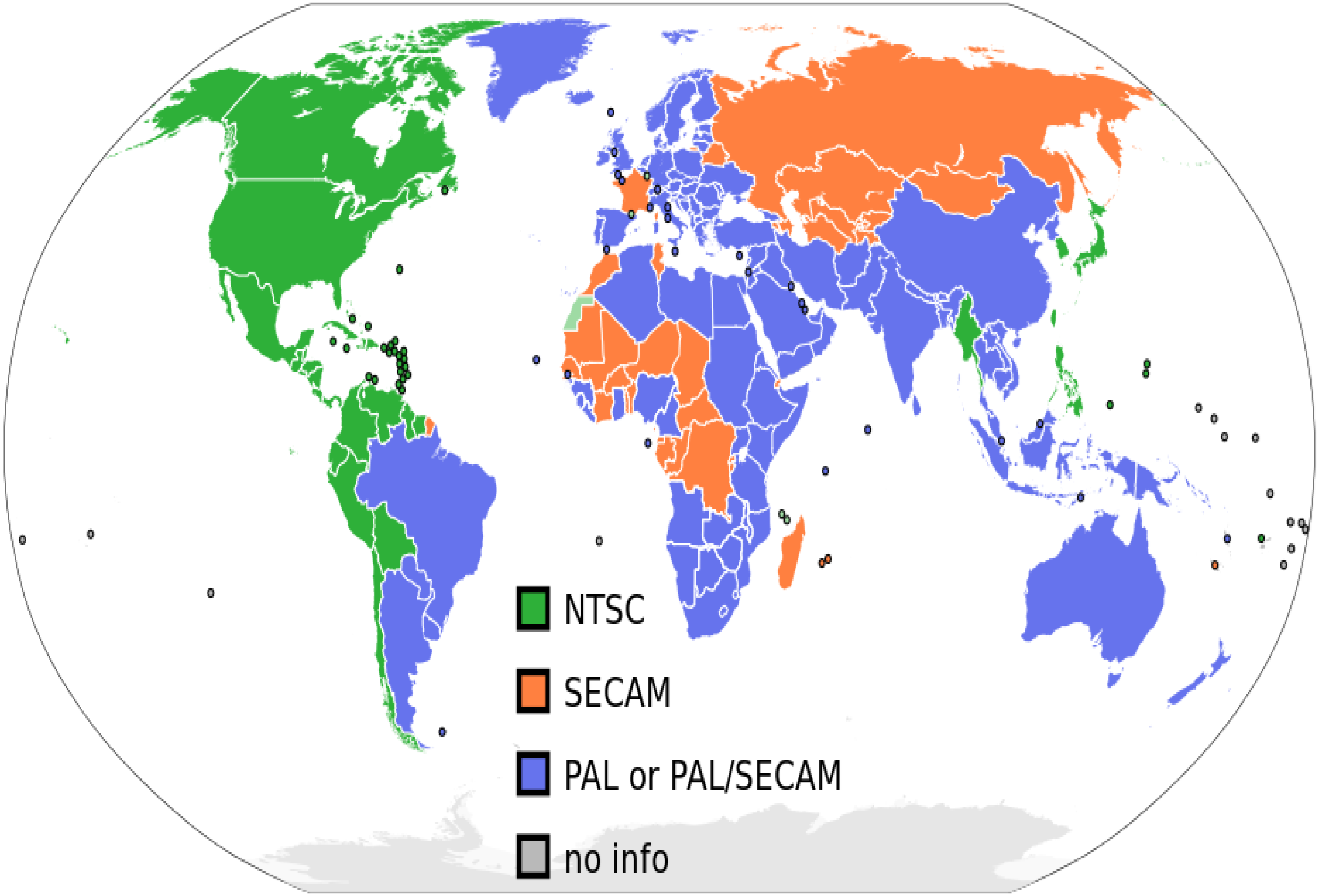
FCC: Power and Height Regulation

<table>
<tr><th colspan="4">FCC Power and Height Requirements for TV Transmitters</th></tr>
<tr><th></th><th>Ch 2-6 (VHF)</th><th>Ch 7-13 (VHF)</th><th>Ch 14-69 (UHF)</th></tr>
<tr><td>Zone I</td><td>ERP: 20dBk (analog);
16dBk (digital)
HAAT: 305m
Co-channel dist: 272km</td><td>ERP: 25dBk (analog);
22dBk (digital)
HAAT: 305m
Co-channel dist: 272km</td><td rowspan="2">ERP: 36dBk (analog);
30dBk (digital)
HAAT: 610m
Co-channel dist: 330km</td></tr>
<tr><td>Zones II-III</td><td>ERP: 20dBk (analog);
16dBk (digital)
HAAT: 610m
Co-channel dist: 353km</td><td>ERP: 25dBk (analog);
22dBk (digital)
HAAT: 610m
Co-channel dist: 353km</td></tr>
</table>

- HAAT: Height above average terrain
- To reduce interference, in general, HAAT↑, ERP↓

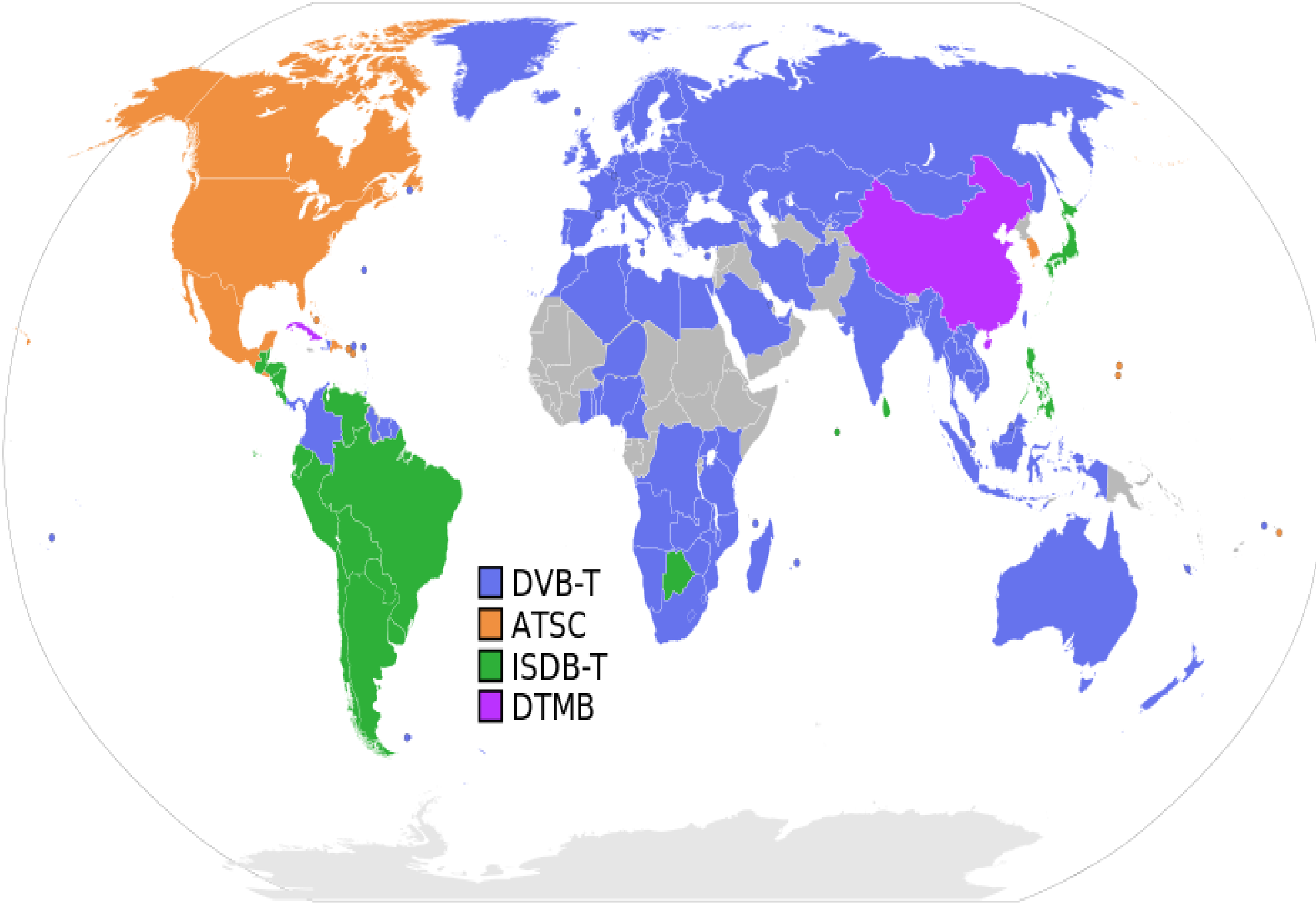
- dBm: mW reference
- dBW: W
- dBk: kW

Analog TV Encoding Systems of the World



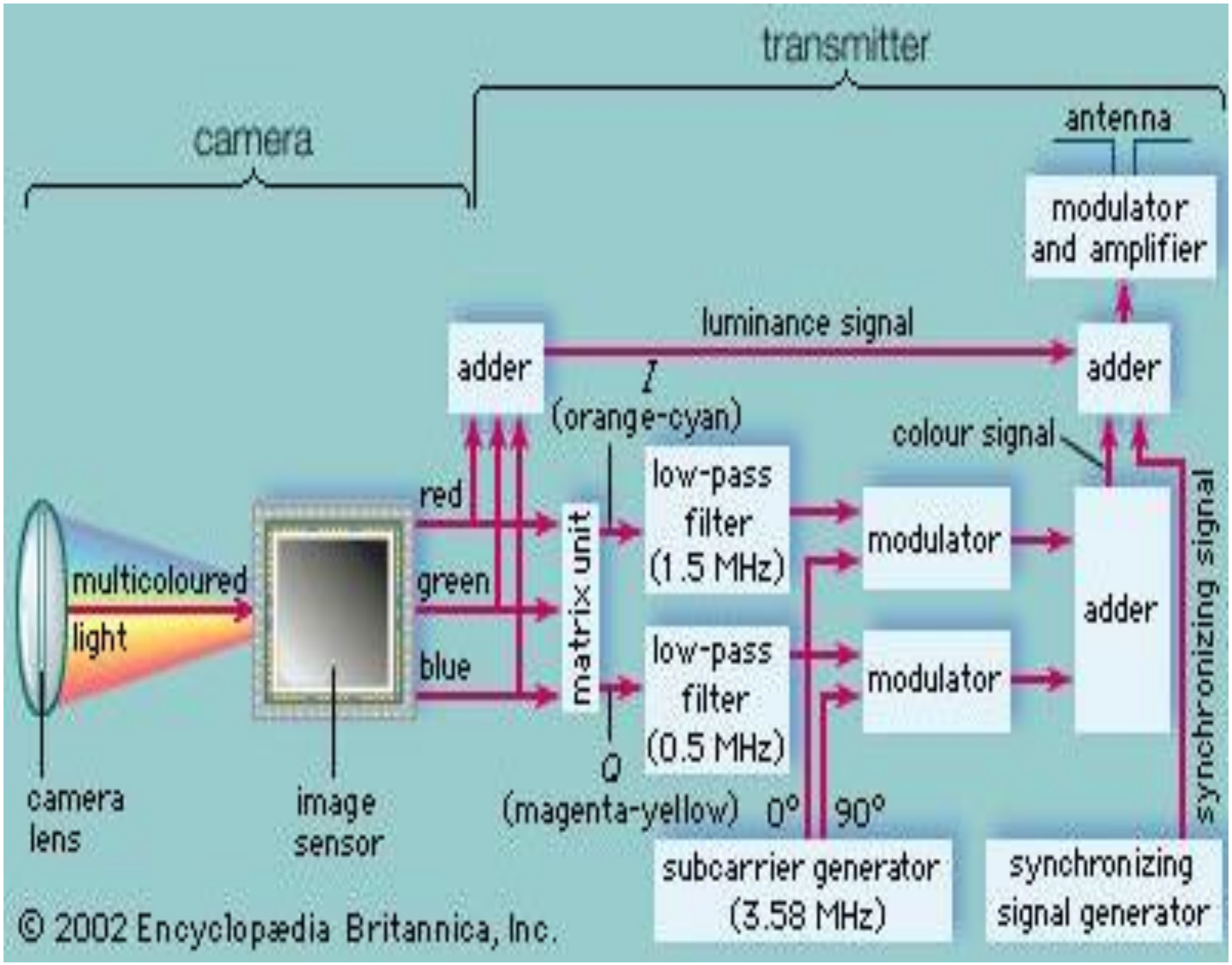
https://en.wikipedia.org/wiki/Broadcast_television_systems#/media/File:PAL-NTSC-SECAM.svg

Digital TV Encoding Systems of the World

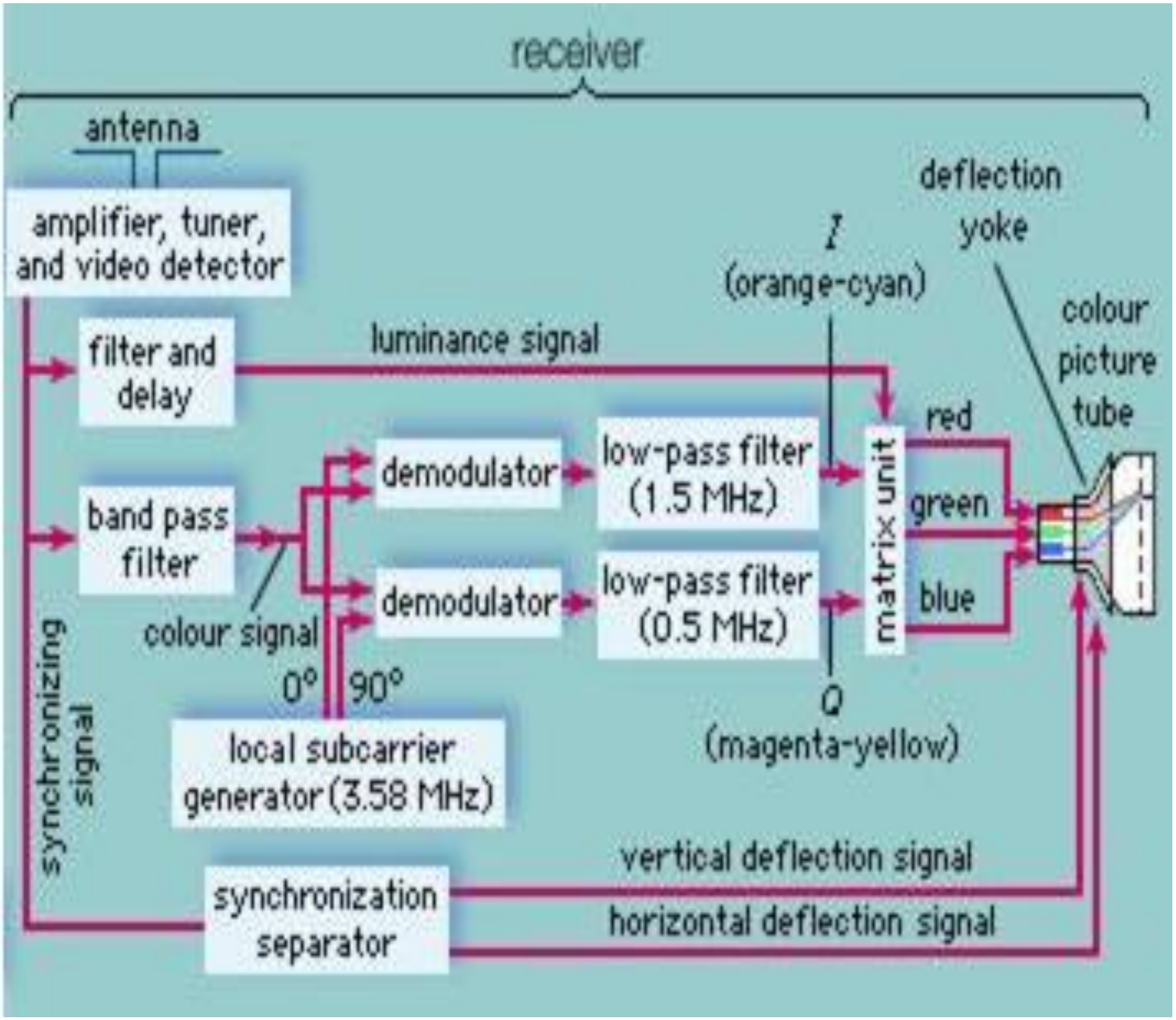


https://en.wikipedia.org/wiki/Broadcast_television_systems#/media/File:Digital_broadcast_standards.svg

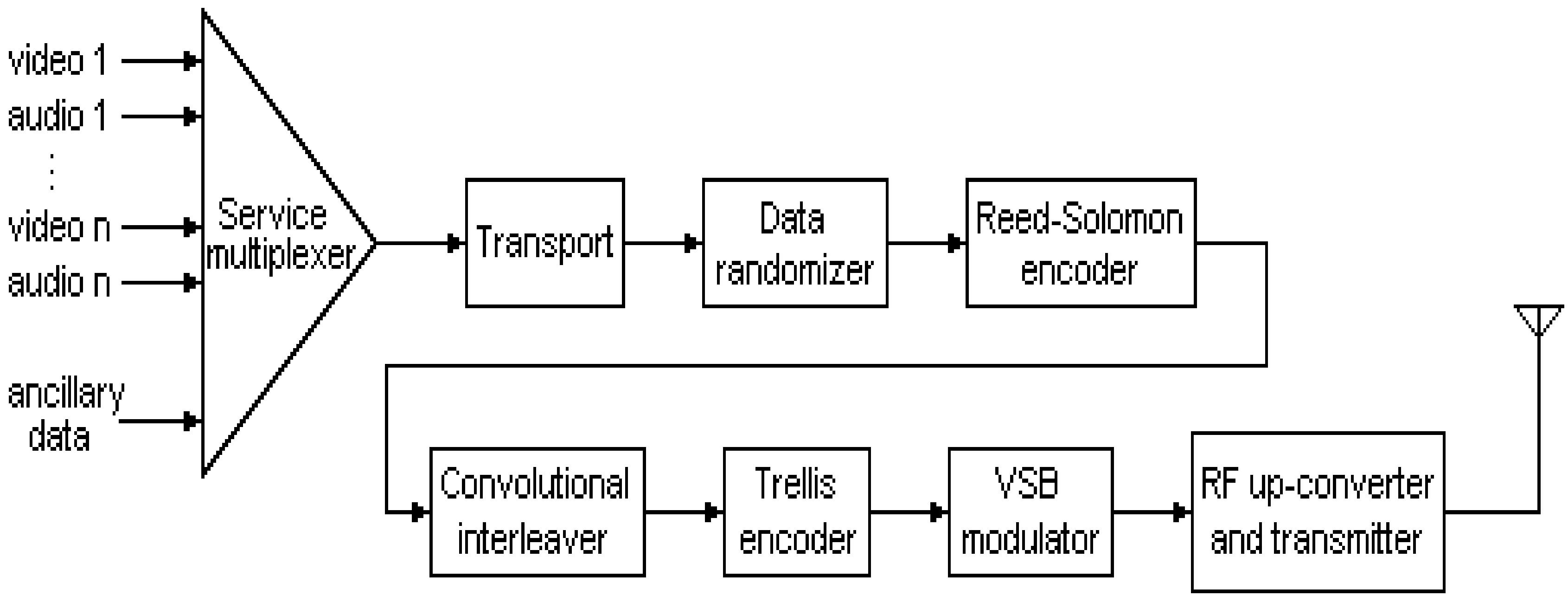
NTSC Transmitter Block Diagram



NTSC Receiver Block Diagram



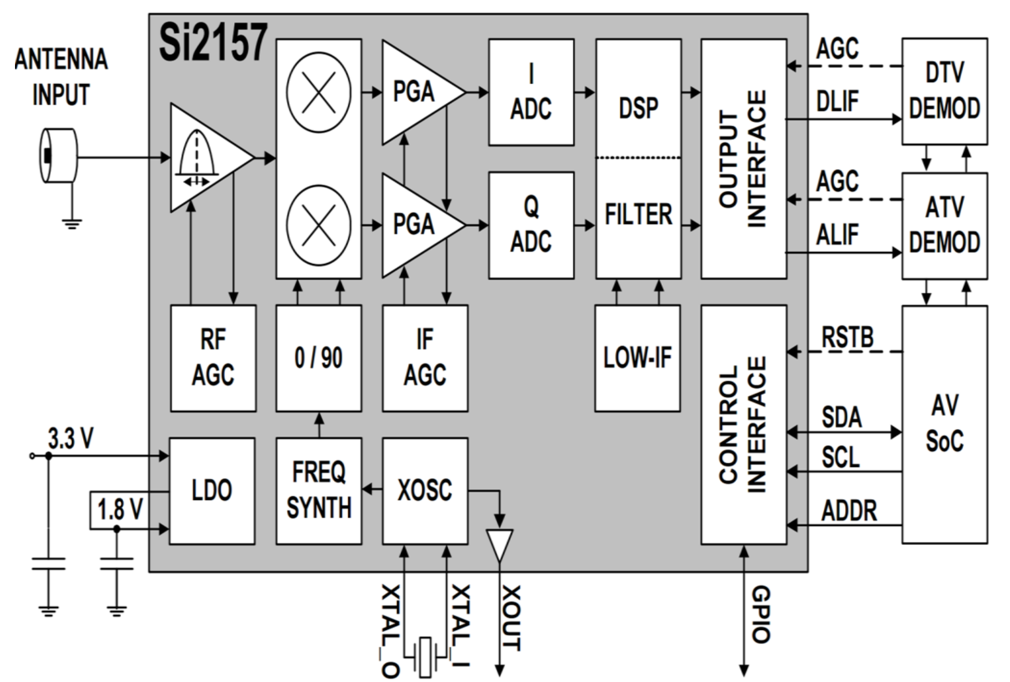
ATSC TV Transmitter



Hybrid Digital/Analog Receiver: SI2157

- Frequency Synthesizer digitally adjustable for LO selection.
- All IF demodulation and filtering done digitally after I and Q ADCs.
- NTSC, PAL/SECAM, ATSC or DVB-T compatible.
- Multiple demodulators can share one front end, enabling set top boxes that support many standards.

- AGC: automatic gain control
- LDO: low dropout regulator (DC supply)
- XOSC: external oscillator
- PGA: programmable gain amplifier
- DLIF: digital link IF
- ALIF: analog link IF

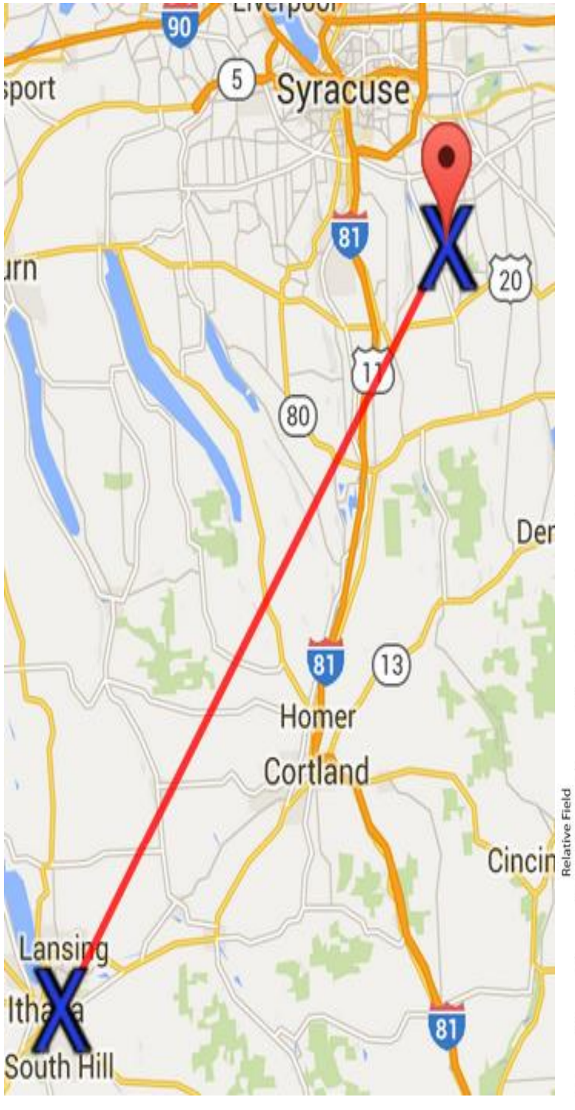


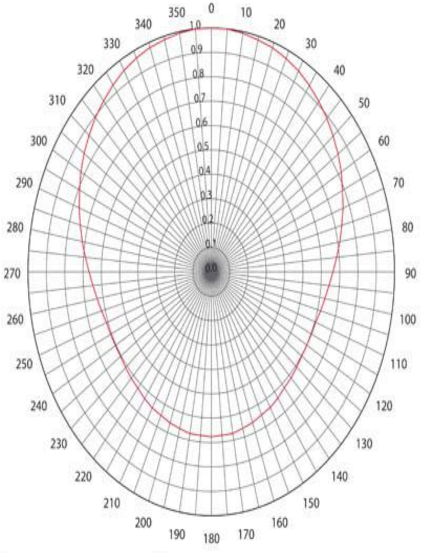
Si2157 TV Tuner Specification

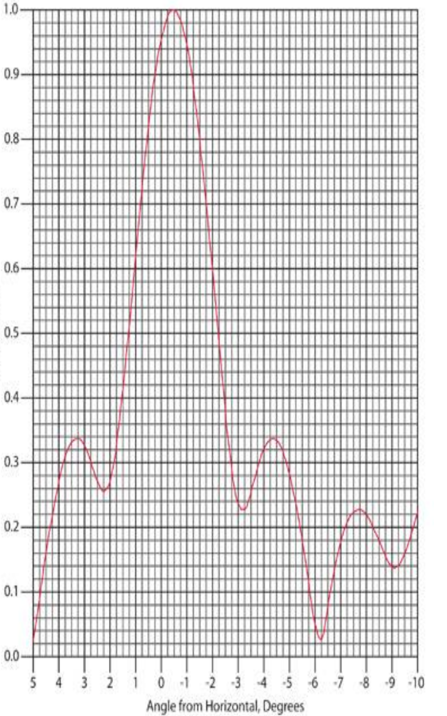
Parameter	Typical values
Supply voltage	1.8V & 3.3V, or 3.3V only
Power consumption	496mW
RF input frequency	42MHz to 870MHz (including FM)
NF	4dB
Broadband IIP3	5dBm
Inband IIP3	–6dBm
LO phase noise at 860MHz	–100dBc/Hz at 1kHz; –100dBc/Hz at 10kHz; –132dBc/Hz at 1MHz
IF spurious distortion	–72dB
IF center frequency	4MHz – 7MHz

Example TV Link Budget

- ATSC transmission from ABC affiliate, WSYR-TV in Syracuse, to a dipole antenna on top of Duffield Hall.
- Distance from WSYR-TV to Duffield hall is 67,147m. Azimuthal angle is 214°. Zenith angle is -.314°.
- TX Azimuthal gain is -1.66dBi, Elevation gain is 14.2dBi. Total antenna gain is 12.54dBi
- Frequency: 500MHz

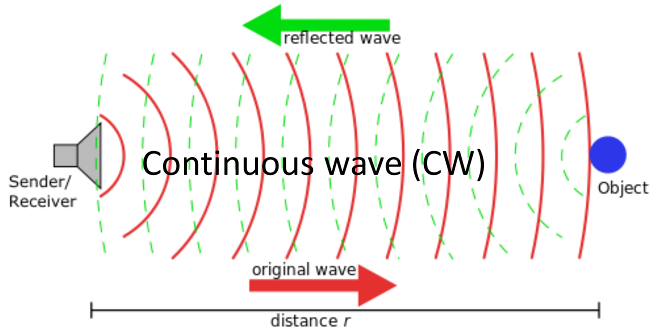


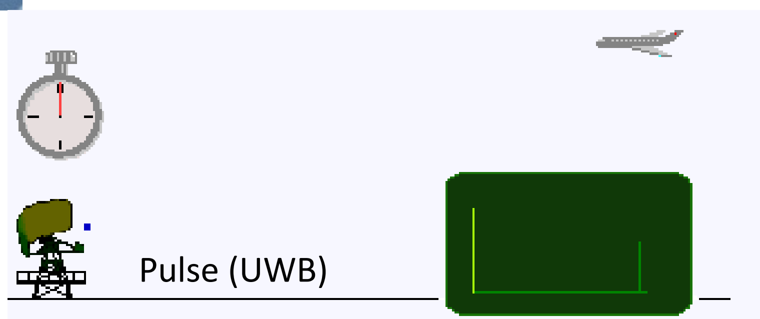


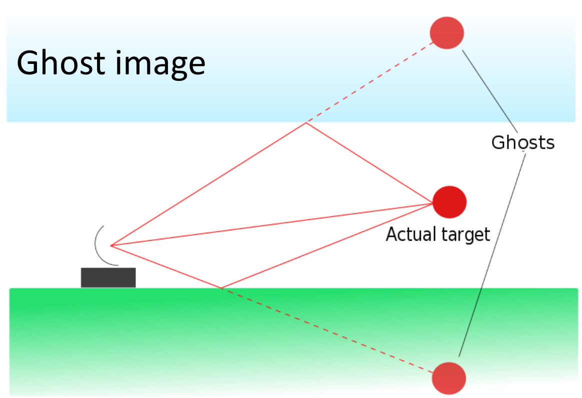


Radar and RFID

Radar: From More Than 100 Years Ago





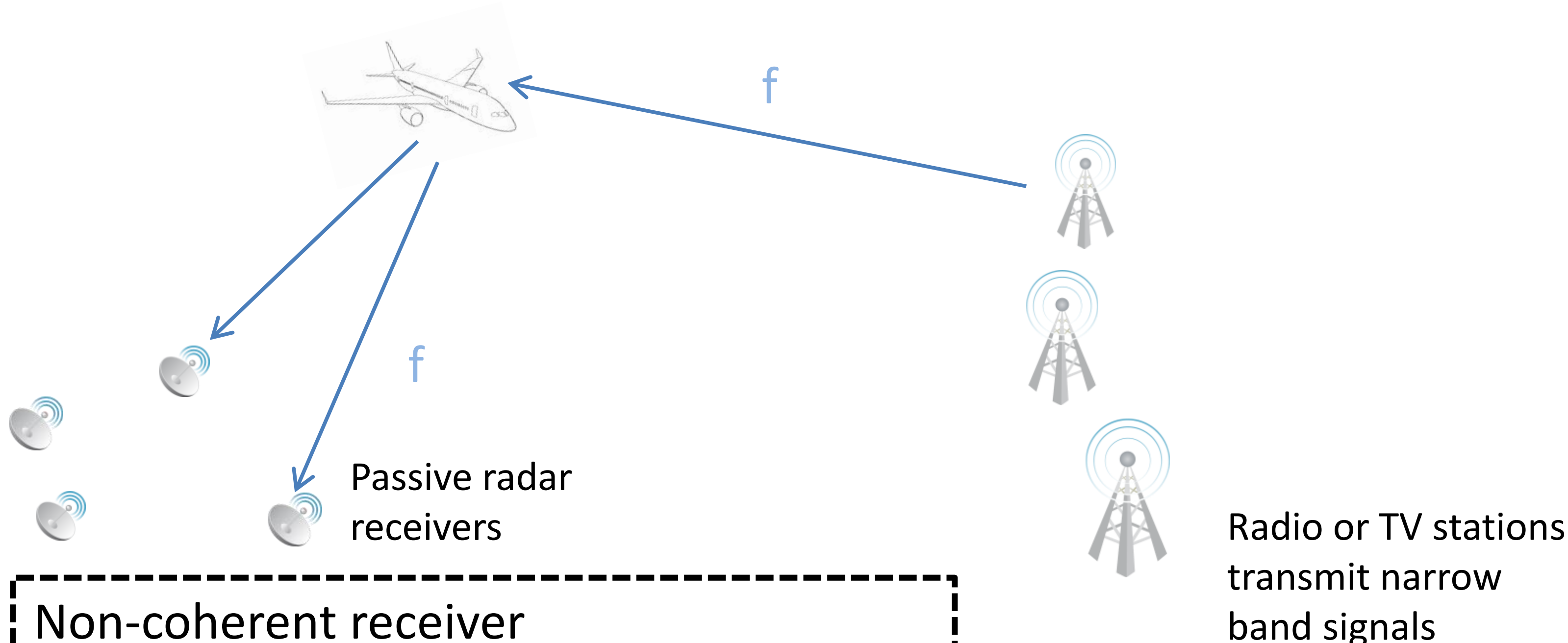


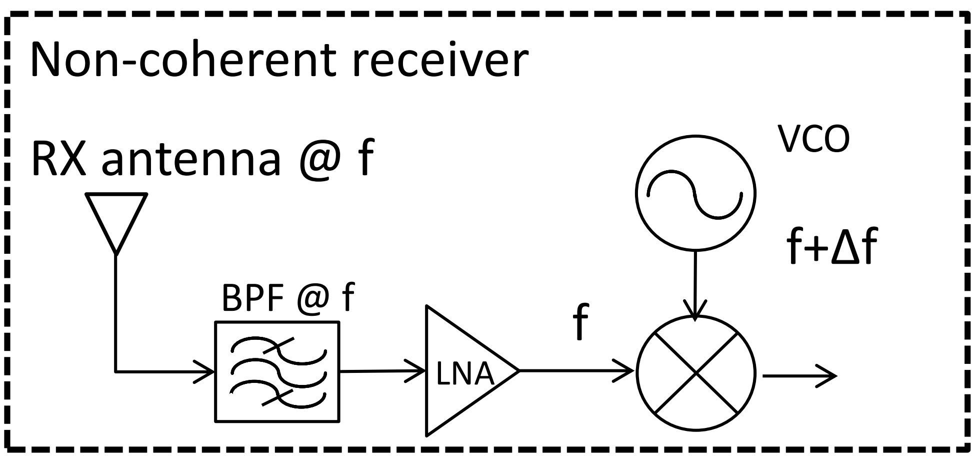
RADAR: Radio Detection and Ranging

Hertz (1886)
Hülsmeyer (1904)
Tesla (1917)
World War II period

This is nearly impossible for indoor in radar history.

Multi-Static Passive Radar (MSPR)

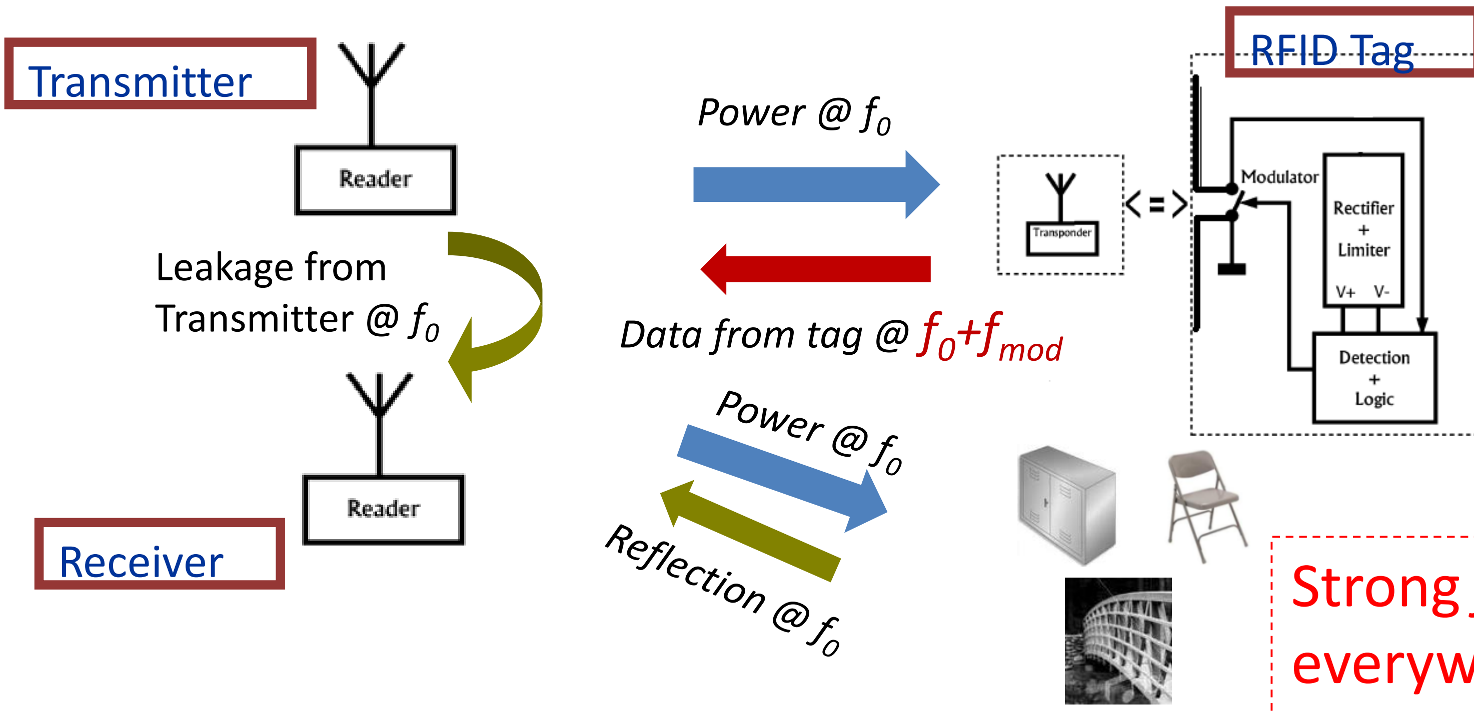




- Y. Wu and D. C. Munson, “Multi-static passive radar imaging using the smoothed pseudo winger-ville distribution,” *IEEE ICIP*, 2001.
- M. Cetin and A. D. Lanteman, “Region-enhanced passive radar imaging,” *Radar, Sonar and Navigation, IEE Proceedings*, 2005.
- C. Liu, et al, “The distributed passive radar 3D imaging and analysis in wavenumber domain, ” *Proc. IEEE ICSP*, 2010.

Passive RFID Tags < $0.1

Conventional backscattered passive RFID



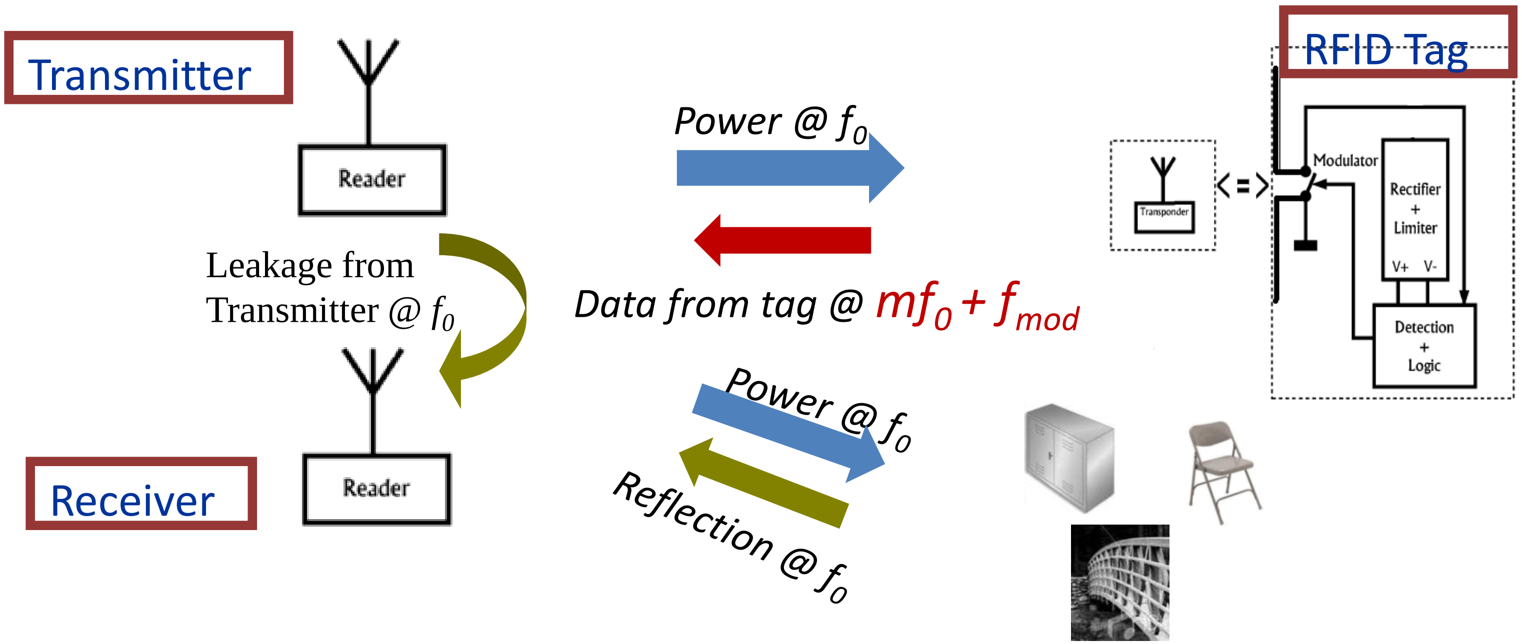
Strong f_0 everywhere for indoors, even near resonance

Conventional Passive RFID System

Backscattering Modulation

- Biggest Challenge: Self and multi-path interference

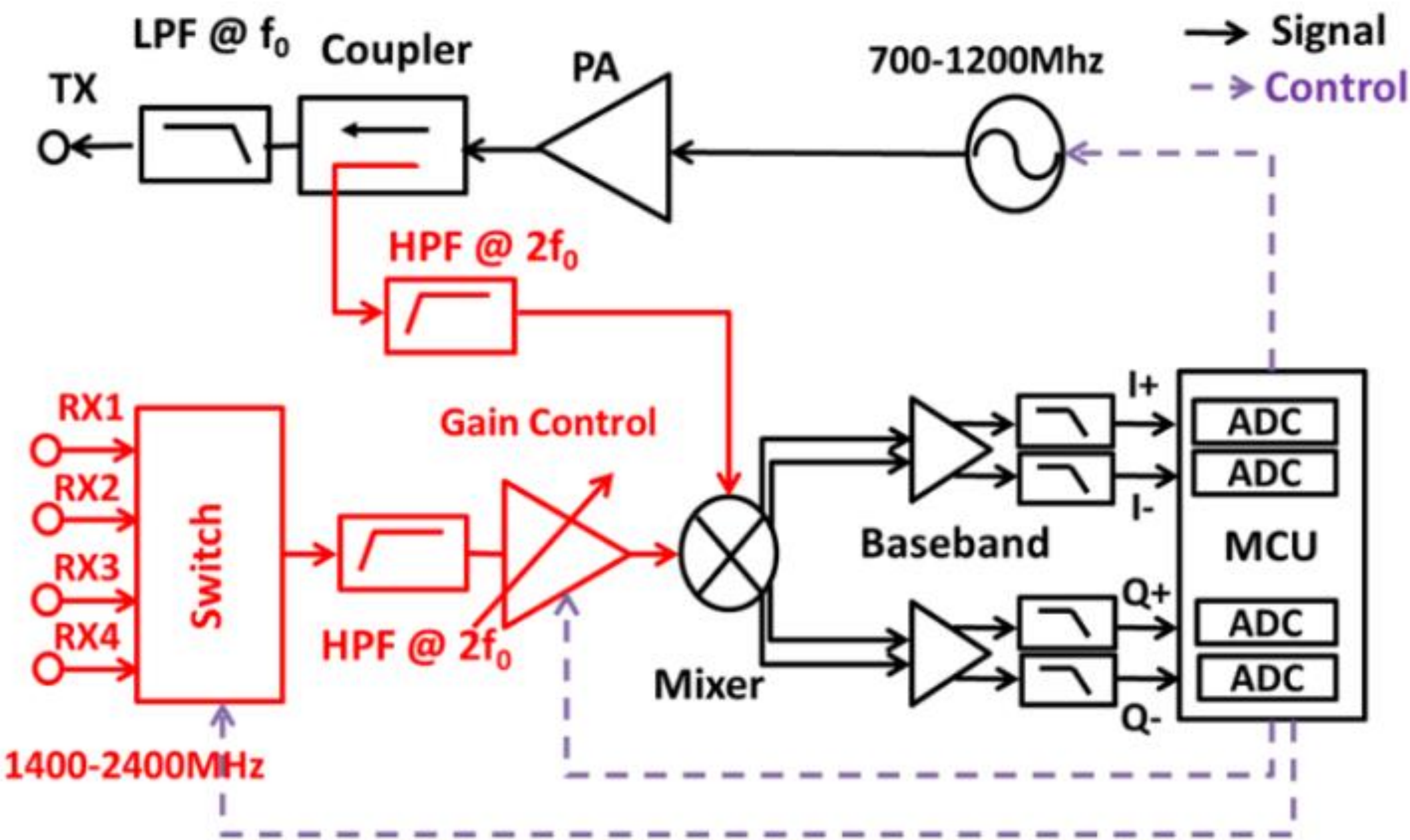
Harmonic passive RFID tags



- Downlink: f_0; Uplink: $mf_0 + f_{mod}$
- Each harmonic tag has a unique ID
- Reduction of noises and interferences to achieve millimeter and millisecond resolution

No strong mf_0 for indoors; No resonance; No regulation; But uplink has multi-path

Harmonic RFID Reader



What Have We Learned?

- History of 802.11 variants
- System level specifications and modulation schemes in Wi-Fi and Bluetooth
- Cellular network designs
- FCC and ETSI regulation differences
- Safety standards
- Tradeoffs in component selection