TSEK38: Radio Frequency Transceiver Design
Lecture 1: Course Introduction

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LINKÖPING UNIVERSITY

Objectives of the course

- Understand wireless communication standards at the physical layer.
- Strengthen the knowledge of RF transceiver architectures (TSEK02).
- Learn design methods and techniques for RF front-end design at the system level.
- Get familiar with professional design tools (Keysight ADS).

Scope of interest

- Physical layer of wireless communication systems.
- Focus on RX/TX RF front-end and signal processing between the antenna and A/D or D/A converters at baseband.
- Functional level modeling of RX/TX building blocks (no detailed circuits).
- Design of RX/TX front-ends in terms of predefined conditions and tests (aimed at interference, noise, and signal purity).

Organization of the course 2019

- Lectures 9 x 2h (w4-8).
- Laboratory work 4 x 4h (w6-7). ADS, lab manual.
- Project work: RF transceiver design
  - Part 1. Synthesis by analytical model (hand calc),
  - Part 2. Simulation and verification in ADS.
- Project seminar 4 x 2h (w7-9) = support for project work.
- A project task will be assigned to each student. Do not work together.

- Course book: Qizheng Gu, RF System Design of Transceivers for Wireless Communication, Springer 2005. (Available as ebook through LiU library.)

Lecture schedule

w4:
- Le1: Introduction (Ch 1)
- Le2: Fundamentals of RF system modeling (Ch 2)
- Le3: Superheterodyne TRX design (Ch 3.1)

w5:
- Le4: Homodyne TRX design (Ch 3.2)
- Le5: Low-IF TRX design (Ch 3.3)

w6:
- Le6, Le7: Systematic synthesis (calculations) of RX (Ch 5)

w7-8:
- Le8, Le9: Systematic synthesis (calculations) of TX (Ch 6)

Staff

- Ted Johansson
- Docent, Adjunct Professor
- Integrated Circuits and Systems (EKS), ISY
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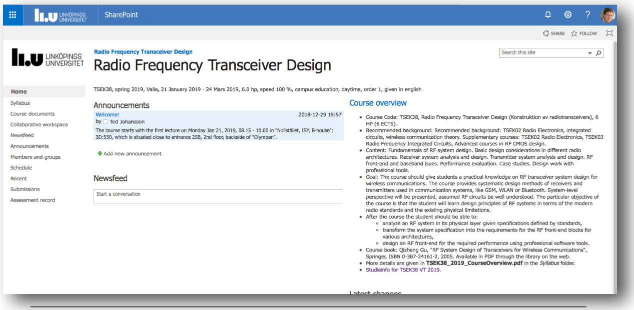
- Lectures, labs, project work, examiner.

Lisam Course Room

- https://liuonline.sharepoint.com/sites/TSEK38/TSEK38_2019VT_FU



Lisam Course Room

- https://liuonline.sharepoint.com/sites/TSEK38/TSEK38_2019VT_FU

- You have to register to reach the course room!
- If you can not reach the course room, please email me (ted.johansson@liu.se)!

Lisam Course Room

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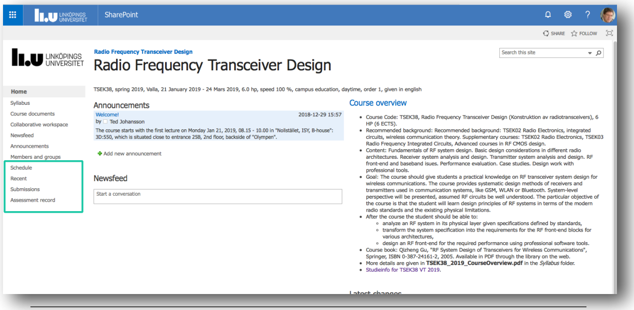

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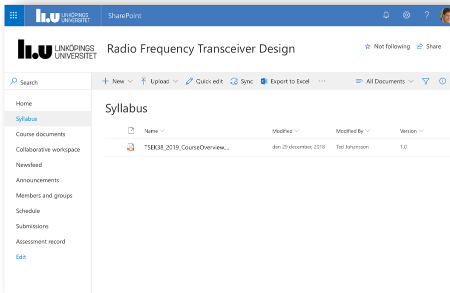
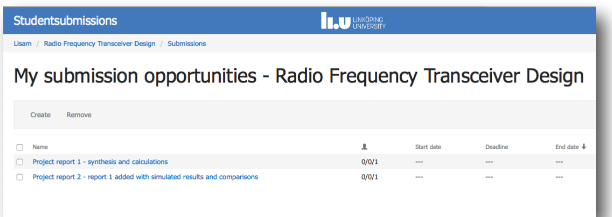
- All course details can be found in this Folder/Document



Lisam Course Room

- This is where you will upload the Project Reports

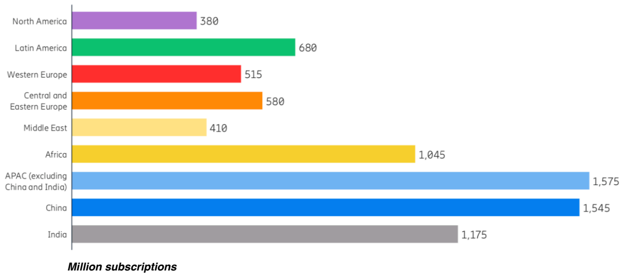


Outline of lecture 1

- Wireless communication today
- Some wireless standards
- Communication radio examples
- Architectures: the big picture

Gu: Chapter 1

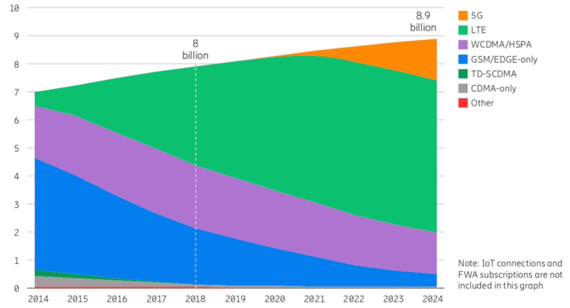
Mobile subscriptions Q3 2018: 7.9 billion!



"Additional readings" folder

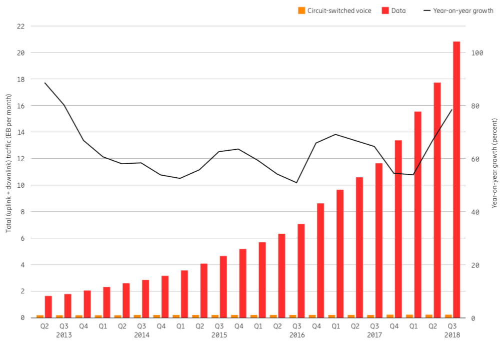
Source: Ericsson Mobility Report, Nov 2018

Mobile subscriptions by technology

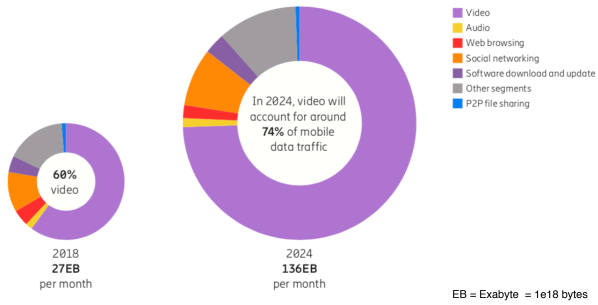


Billion subscriptions. Source: Ericsson Mobility Report, Nov 2018

Data traffic growth

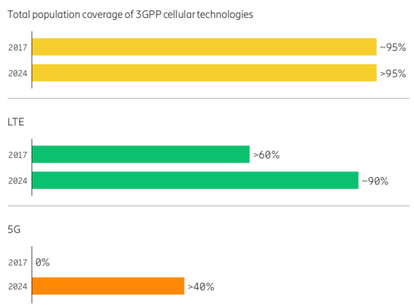


Mobile data traffic



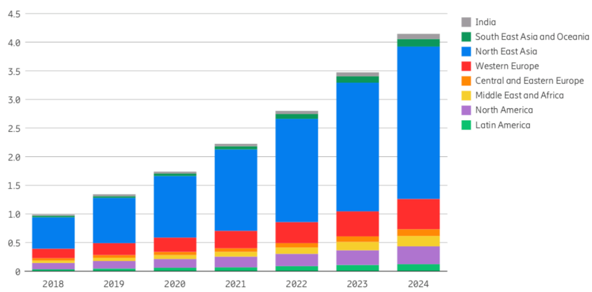
EB = Exabyte = 1e18 bytes

World population coverage by technology

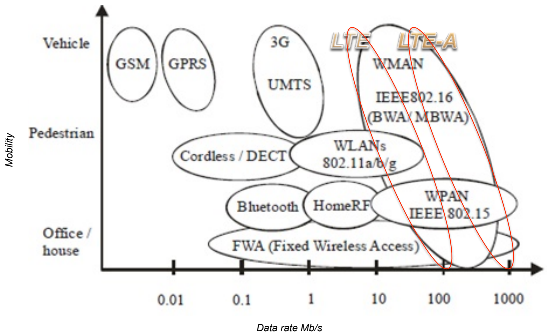


3GPP = GSM + WCDMA + LTE

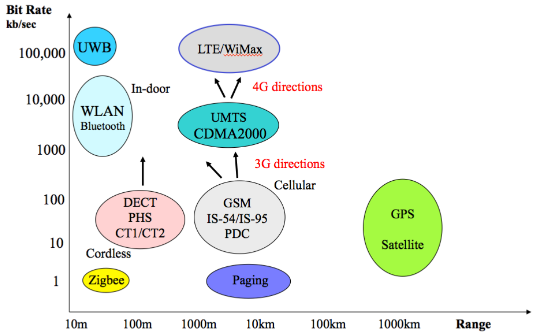
Cellular IoT connections per region (billion)



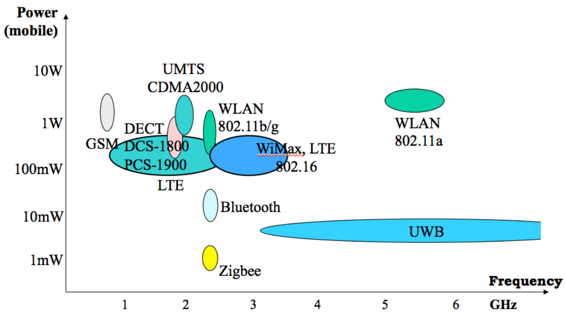
There is a standard for almost any need!



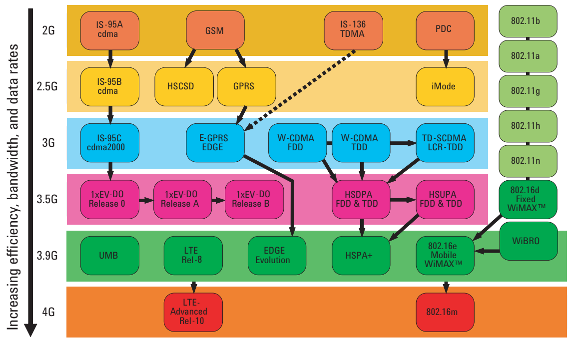
Wireless Communication Systems/Standards



Wireless Communication Systems



Wireless evolution 1990-2010+



Examples of Standards

Standard	Access Scheme/Dupl	Frequency band (MHz)	Channel Spacing	Frequency Accuracy	Modulation Technique	Rate (kb/s)	Peak Power (uplink)
GSM	TDMA/FDMA/ TDD	890-915 (UL) 935-960 (DL)	200 kHz	90 Hz	GMSK	270.8	0.8, 2, 5, 8 W
DCS-1800	TDMA/FDMA/ TDD	1710-1785 (UL) 1805-1850 (DL)	200 kHz	90 Hz	GMSK	270.8	0.8, 2, 5, 8 W
DECT	TDMA/FDMA/ TDD	1880-1900	1728 kHz	50 Hz	GMSK	1152	250 mW
IS-95 cdmaOne	CDMA/ FDMA/ FDD	824-849 (RL) 869-894 (FL)	1250 kHz	N/A	OQPSK	1228	N/A
Bluetooth	FHSS/TDD	2400-2483	1 MHz	20 ppm	GFSK	1000	1,4,100 mW
802.11b (DSSS)	CDMA/TDD	2400-2483	20 MHz	25 ppm	QPSK/CCK	1, 2, 11 Mb/s	1 W
WCDMA (UMTS)	W-CDMA/TD-CDMA/F/TDD	1920-1980 (UL) 2110-2170 (DL)	5 MHz	0.1 ppm	QPSK, 16/64QAM	3840 (max)	0.125, 0.25, 0.5, 2W
LTE	OFDMA (DL) SC-FDMA (UL) FDD/TDD	700-2700	scalable to 20MHz	4.6 ppm /32 ppm 0.1 ppm (BS)	QPSK, 16/64QAM	DL/UL 300/75 Mb/s	Scalable with BW to 250 mW

Example: WLAN 802.11ac

- Operating freq.: 4.9-5.9 GHz (different bands in the different parts of the world).
- Optional 160 MHz and mandatory 80 MHz channel bandwidth. (cf. 802.11n: 40 MHz)
- More MIMO spatial streams: Support for up to eight spatial streams. (802.11n: four)
- Modulation:
  - Up to 256-QAM (802.11n: 64-QAM).
  - Some vendors offer a non-standard 1024-QAM mode, providing 25% higher data rate compared to 256-QAM.
- Beamforming with standardized sounding and feedback for compatibility between vendors (non-standard in 802.11n made it hard for beamforming to work effectively between different vendor products).
- Coexistence mechanisms for 20, 40, 80, and 160 MHz channels, 11ac and 11a/n devices.

[Wikipedia]

Example: WLAN 802.11ac

All rates assume 256-QAM, rate 5/6:

Scenario	Typical client form factor	PHY link rate	Aggregate capacity (speed)
One-antenna AP, one-antenna STA, 80 MHz	Handheld	433 Mbit/s	433 Mbit/s
Two-antenna AP, two-antenna STA, 80 MHz	Tablet, laptop	867 Mbit/s	867 Mbit/s
One-antenna AP, one-antenna STA, 160 MHz	Handheld	867 Mbit/s	867 Mbit/s
Three-antenna AP, three-antenna STA, 80 MHz	Laptop, PC	1.27 Gbit/s	1.27 Gbit/s
Two-antenna AP, two-antenna STA, 160 MHz	Tablet, laptop	1.69 Gbit/s	1.69 Gbit/s
Four-antenna AP, four one-antenna STAs, 160 MHz (MU-MIMO)	Handheld	867 Mbit/s to each STA	3.39 Gbit/s
Eight-antenna AP, 160 MHz (MU-MIMO) • one four-antenna STA • one two-antenna STA • two one-antenna STAs	Digital TV, Set-top Box, Tablet, Laptop, PC, Handheld	• 3.39 Gbit/s to four-antenna STA • 1.69 Gbit/s to two-antenna STA • 867 Mbit/s to each one-antenna STA	6.77 Gbit/s
Eight-antenna AP, four 2-antenna STAs, 160 MHz (MU-MIMO)	Digital TV, tablet, laptop, PC	1.69 Gbit/s to each STA	6.77 Gbit/s

[Wikipedia]

Example: Bluetooth

- Wireless personal area network (WPAN)
- Wire-replacement communications protocol primarily designed for low-power consumption, with a short range based on low-cost transceiver microchips in each device.
- Uses the unlicensed 2.4 GHz ISM band (2402-2480 MHz, or 2400-2483.5 MHz)
- Frequency-hopping spread spectrum (FHSS), 1MHz channel, 79 channels.
- Radio part developed by Ericsson, Lund.

Bluetooth version	Maximum speed[citation needed]	Maximum range[citation needed]
3.0	25 Mbit/s[18]	10 meters (33 ft)
4.0	25 Mbit/s[19]	60 meters (200 ft)[20]
5	50 Mbit/s	240 meters (800 ft)

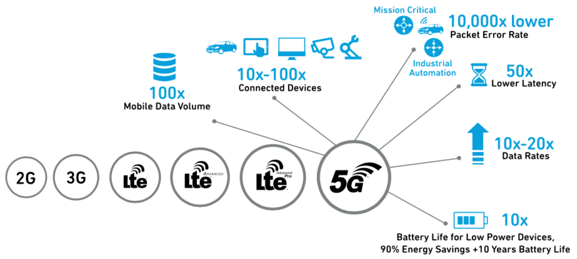
[Wikipedia]

Example: Global Positioning System (GPS)

- 24 satellites send timing data, full operation in 1995.
- Receive only at 1575.24 MHz.
- **GPS** satellites continuously transmit their current time and position. A GPS receiver monitors multiple satellites and solves equations to determine the precise position of the receiver and its deviation from true time. Four satellites must be in view of the receiver for it to compute four unknown quantities (three position coordinates and clock deviation from satellite time).
- The Russian Global Navigation Satellite System (**GLONASS**) was developed contemporaneously with GPS, but suffered from incomplete coverage of the globe until the mid-2000s. GLONASS can be added to GPS devices, making more satellites available and enabling positions to be fixed more quickly and accurately, to within two meters.
- There are also the European Union **Galileo** positioning system, China's **BeiDou** Navigation Satellite System, India's **NAVIC** and Japan's **Quasi-Zenith** Satellite System.

[Wikipedia]

Example: 5G



"Additional readings" folder

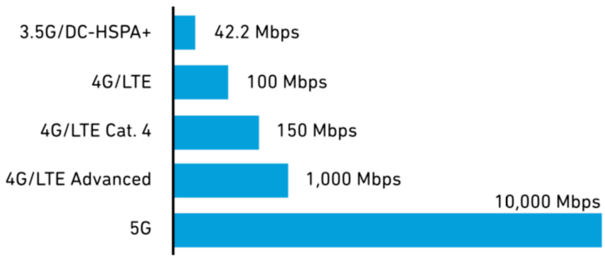
Source: 5G RF for dummies (Corvo)

5G

	4G (Today, Before Further Developments)	5G
Latency	10 ms	Less than 1 ms
Peak data rates	1 Gbps	20 Gbps
Number of mobile connections	8 billion (2016)	11 billion (2021)
Channel bandwidth	20MHz 200kHz (for Cat-NB1 IoT)	100MHz below 6GHz 400MHz above 6GHz
Frequency band	600MHz to 5.925 GHz	600MHz–mmWave (for example, 28GHz, 39GHz, and onward to 80 GHz
Uplink waveform	Single-carrier frequency division multiple access (SC-FDMA)	Option for cyclic prefix orthogonal frequency-division multiplexing (CP-OFDM)
User Equipment (UE) transmitted power	+23 decibel-milliwatts (dBm) except 2.5GHz time-division duplexing (TDD) Band 41 where +26dBm, HPUE is allowed IoT has a lower power-class option at +20dBm	+26dBm for less than 6GHz 5G bands at and above 2.5GHz

Source: 5G RF for dummies (Corvo)

Downlink speeds by technical generation

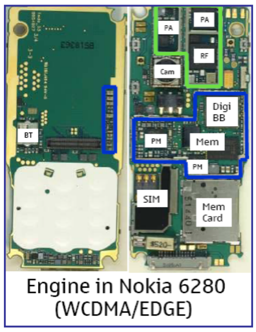


Communication radio examples

- Cellular handsets use many modules to maintain different functions and operation modes
  - RF front-end
  - Analog BB
  - Digital BB
  - Memory
  - Power management
  - I/O
  - Media players, GPS, WLAN, Bluetooth, …

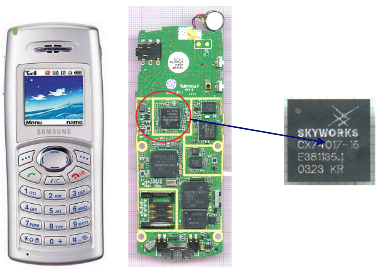
Communication radio examples: Nokia 6280

2005:
- 3 G phone
- TriBand GSM (900/1800/1900 MHz) and WCDMA (2100 MHz).
- 6 MB of built-in memory and the option to expand up to 2 GB via the use of a miniSD card.
- Two cameras, a rear two megapixel camera with an 8x digital zoom and flash, and a front-mounted VGA camera for video calling only.
- Bluetooth



Communication radio examples: Samsung SGH-100

- (2008): multi-band GSM, GPRS, EDGE. No WLAN, BT, …

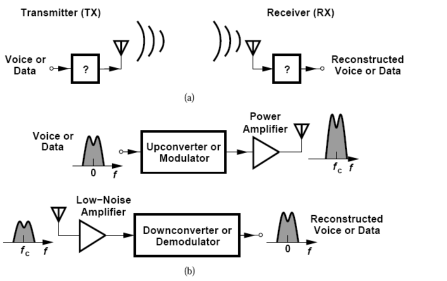


Communication radio examples: iPhone 5

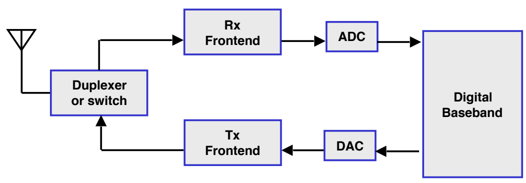
The Big Picture: RF Communication

TX: Drive antenna with high power level

RX: Sense small signal (amplify with low noise)

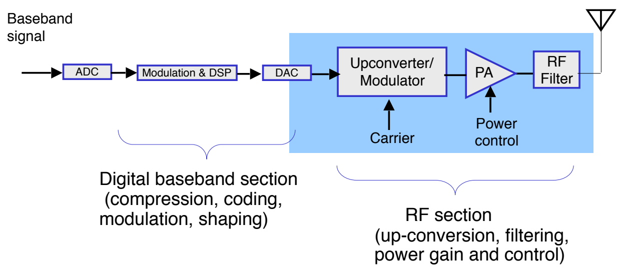


RF Transceiver at glance



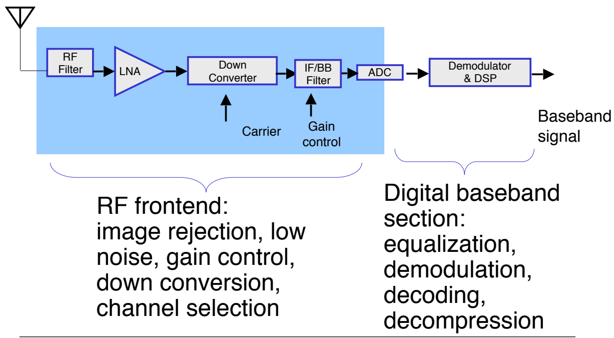
- RF frontend – analog, high frequencies
- Baseband - digital today (DSP), low frequencies
- Mostly common antenna – duplexer/switch (full/half duplex)

Digital Transmitter



Tradeoff between power efficiency and spectral efficiency

Digital Receiver



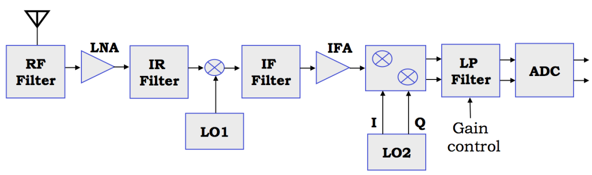
Basic receiver and transmitter architectures

- Heterodyne Receiver
- Homodyne (Zero-IF Receiver)
- Low-IF Receiver

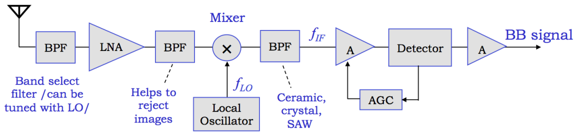
- One-step Transmitter
- Two-step Transmitter
- Polar Transmitter

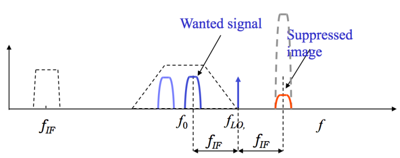
Heterodyne double conversion receiver

- Double conversion - tradeoffs less severe: good sensitivity and selectivity, good image rejection
- Discrete IR and IF filters not easy to integrate
- Low impedance of those filters raise power dissipation in LNA and first mixer (matching for off-chip needed)



Heterodyne receiver

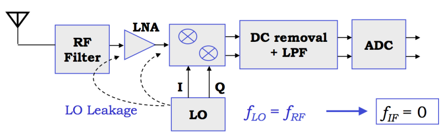




The trade-off between selectivity and sensitivity can be mitigated with better filters or double conversion superheterodyne

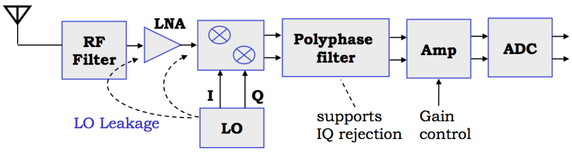
Homodyne receiver (Zero-IF)

- Direct conversion.
- Fewer components, image filtering avoided – no IR and IF filters.
- Large DC offset can corrupt weak signal or saturate LNA (LO mixes itself), notch filters or adaptive DC offset cancellation – eg. by DSP baseband control.
- Flicker noise (1/f) can be difficult to distinguish from signal.
- Channel selection with LPF, easy to integrate, noise-linearity-power tradeoffs are critical, even-order distortions low-freq. beat: differential circuits useful.



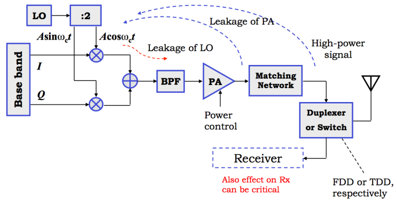
Low-IF receiver

- Tradeoff between heterodyne and homodyne.
- DC offset and 1/f do not corrupt the signal, like in the homodyne, still DC offset must be removed - saturation threat.
- Image problem reintroduced - close image!
- Still even-order distortions can result in low-frequency beat: differential circuits useful but not sufficient



One-step (direct conversion) transmitter

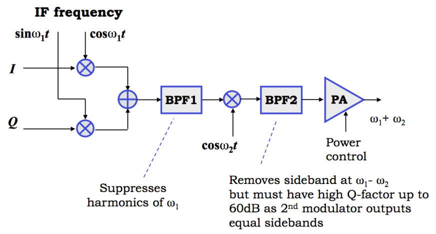
- Up-conversion is performed in one step, $f_{LO} = f_c$
- Modulation, e.g. QPSK can be done in the same process
- BPF suppresses harmonics
- LO must be shielded to reduce corruption
- I and Q paths must be symmetrical and LO in quadrature, otherwise crosstalk



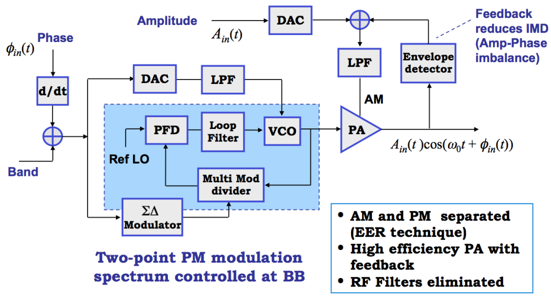
Two-step transmitter

Advantage:

- Better IQ matching since ω_1 is lower
- Carrier far from LO frequency

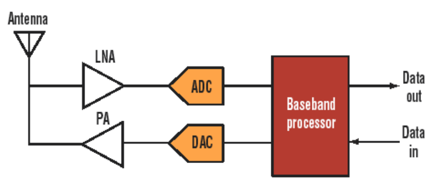


Multi-standard flexible polar TX



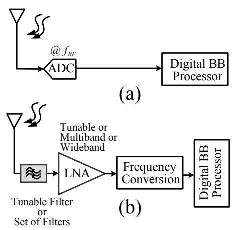
- AM and PM separated (EER technique)
- High efficiency PA with feedback
- RF Filters eliminated

SDR – Software Defined Radio



1. In the ideal software-defined radio, the antenna connects directly to the LNA and ADC, or the PA and DAC. The processor handles all radio functions, filtering, up/downconversion, modulation/demodulation, and digital baseband.

SDR – Software Defined Radio



(a) Ideal SDR Receiver (b) Practical SDR Receiver.

Summary: Overview receiver and transmitter architectures

- Many wireless communication systems (mobile, cordless, WLAN, GPS, …) coexist.
- Variety of transceiver architectures represent different trade-offs in performance.
- Digital baseband makes A/D and D/A conversion compulsory.
- Design of a receiver part more critical than of a transmitter, especially for full-duplex.