Overview: Trends and Implementation Challenges for Multi-Band/Wideband Communication

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What is RFIC?

- Any integrated circuit used in the frequency range: 100 MHz to 3 GHz (till 6GHz can sometimes be considered RF). Currently we are having mm-wave circuits in Silicon (17GHz, 24GHz, 60GHZ, and 77GHz)

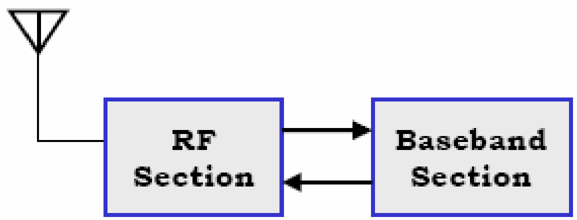
- Generally RFIC's contain the analog front end of a radio transceiver, or some part of it.

- RFIC's can be the simplest switch, up to the whole front end of a radio transceiver.

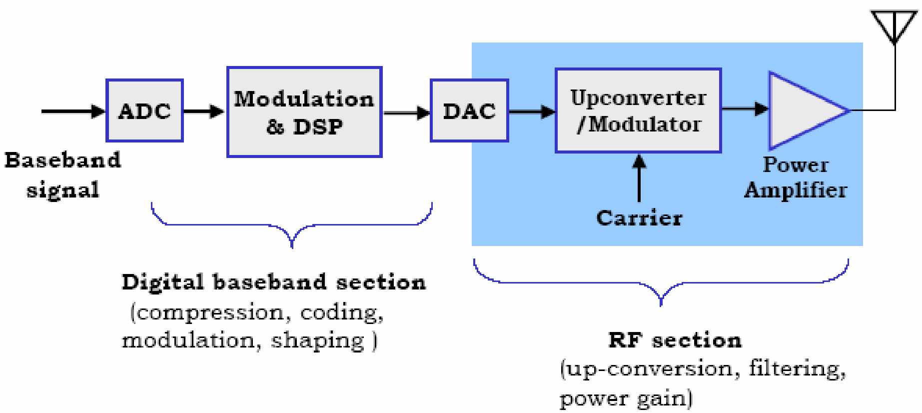
- RFIC's are fabricated in a number of technologies: Si Bipolar, Si CMOS, GaAs HBT, GaAs MESFET/HEMT, and SiGe HBT are today's leading technologies.

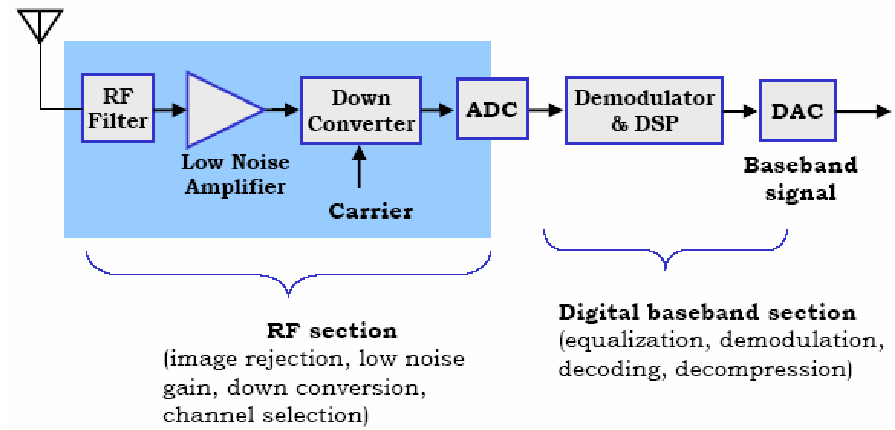
We are going to design in either CMOS, or SiGe.

Basic Wireless Transceivers



- RF Section – analog, high frequencies
- Baseband Section - mostly digital today (DSP), low frequencies





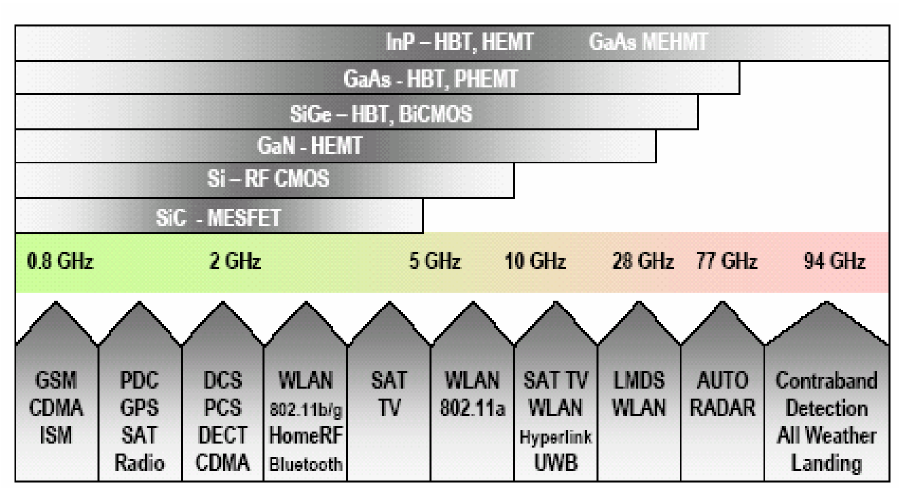
RF Transmitter

RF Receiver

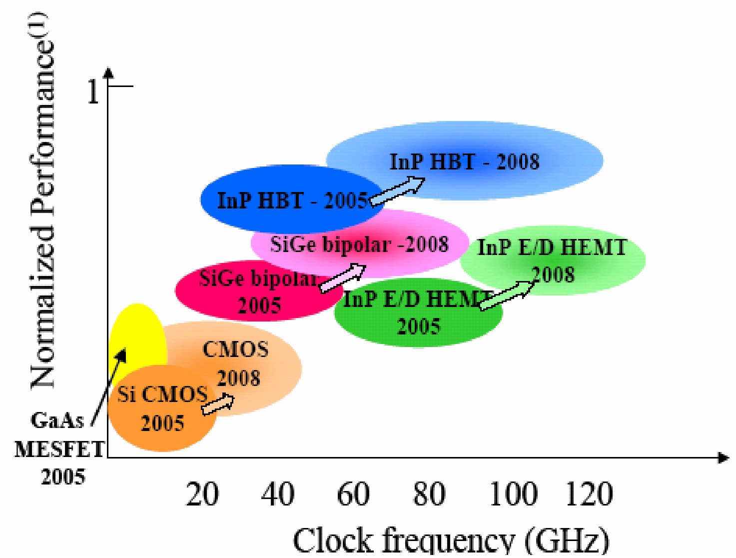
The last 10 years in wireless systems

- New Transmitter / Receiver Architectures
- CMOS/BiCMOS RF Circuit Design in sub 100nm CMOS
- Low-Power A/D and D/A in CMOS
- Power-optimized DSP architectures and circuits
- New Approaches for Low-Noise On-chip Freq Synthesis
- Control of Chip, Package Parasitic RF Paths
- IP Libraries, Design Environment, and Synthesis Tools for Custom Radios

Where we are in terms of technology?



Source: International roadmap for semiconductors ITRS 2005



The metric for performance depends on the class of circuit. It can include dynamic range, signal-to-noise, bandwidth, data rate, and/or inverse power.

Application-specific wireless node implemented in a low cost technology (CMOS) can provide programmability, low cost and low power solution

The next 10 years !!

1. Spectrum Utilization/expansion- critical for ubiquitous wireless
2. Universal radio/SW radio- critical for system designability
3. Micropower radios- critical for ubiquitous/autonomous sensing

Spectrum Utilization

a. New bands – Use scaled CMOS Technology to exploit unused bands (60 GHz Radios)

b. Underlay Sharing – limit power to reduce interference and compensate by the use of wide bandwidths (UWB Radios)

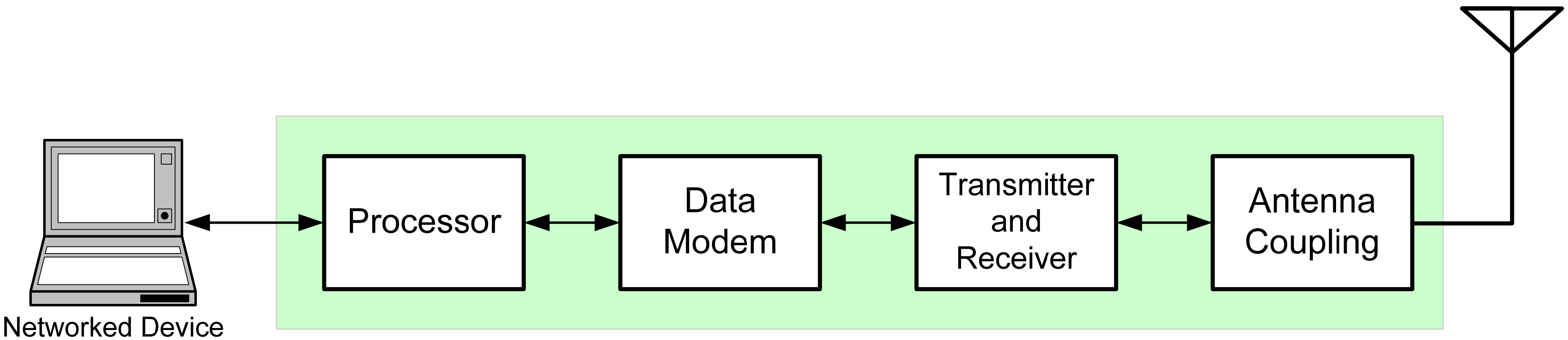
c. Overlay Sharing – Sense primary users and use vacant bands, time slots or locations – “white space” (Cognitive Radios)

Introduction to Cognitive Radio

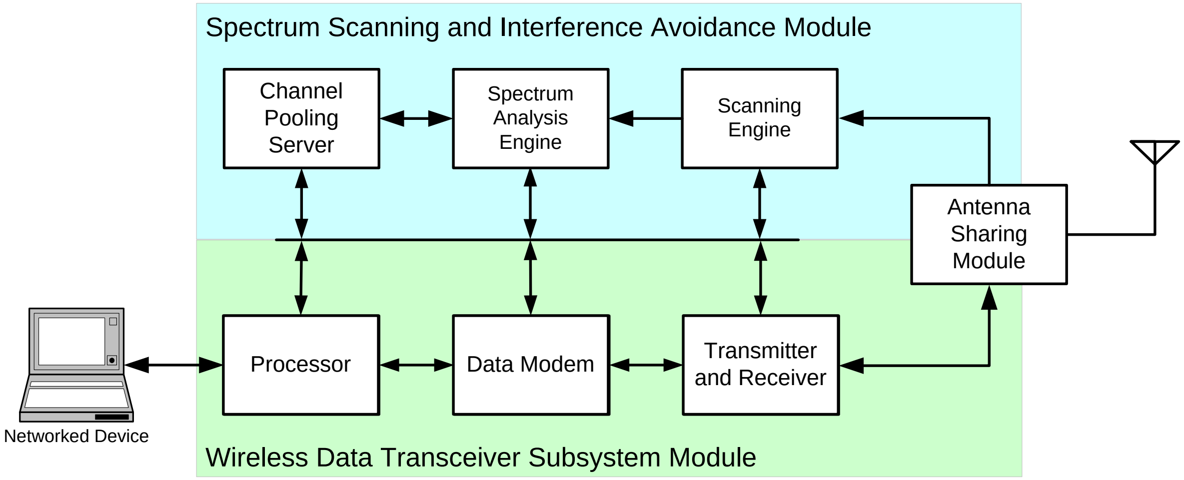
- A Cognitive Radio (CR) can be defined as “a radio that senses and is aware of its operational environment and can dynamically adapt to utilize radio resources in *time, frequency and space* domains on a real time basis, accordingly to maintain connectivity with its peers while not interfering with licensed and other CRs”.
- Cognitive radio can be designed as an enhancement layer on top of the Software Defined Radio (SDR) concept.

Introduction to Cognitive Radio-2

- Basic Non-Cognitive Radio Architecture:



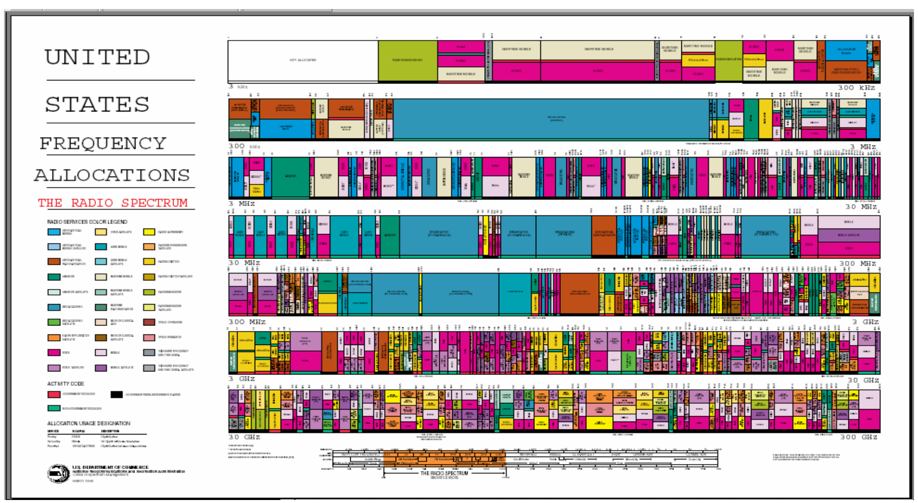
- Cognitive Radio architecture:

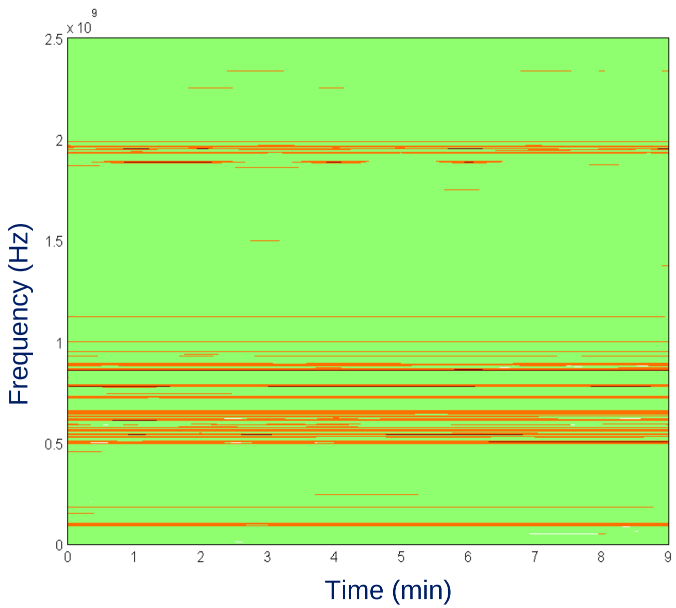


Window of Opportunity

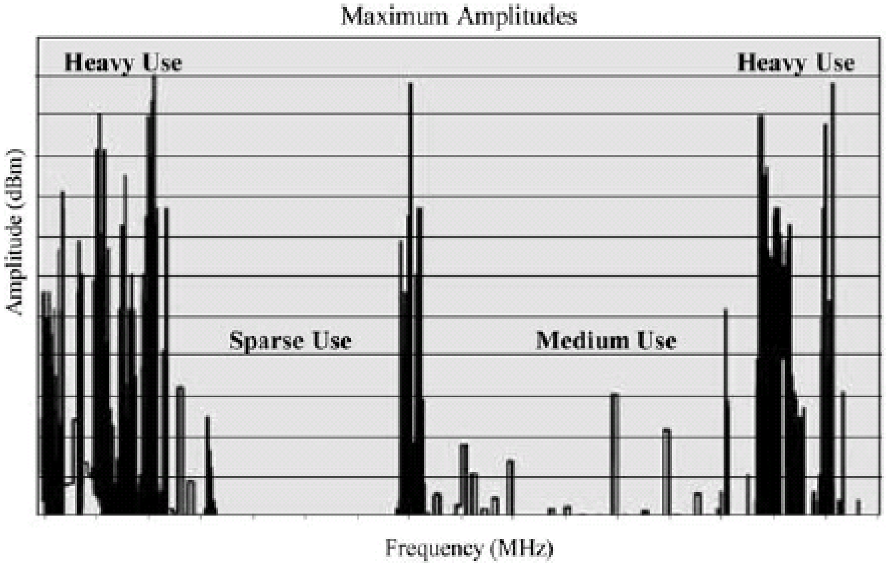
- Existing spectrum policy forces spectrum to behave like a fragmented disk
- Bandwidth is expensive and good frequencies are taken
- Unlicensed bands – biggest innovations in spectrum efficiency

- Recent measurements by the FCC in the US show 70% of the allocated spectrum is not utilized
- Time scale of the spectrum occupancy varies from msecs to hours

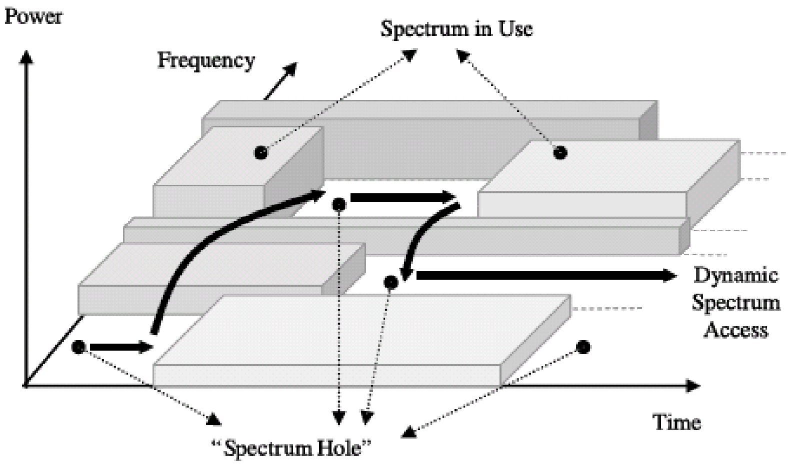




CR Definitions



Spectrum utilization.



- Today “spectrum“ is regulated by governmental agencies, e.g. FCC)
- “Spectrum“ is assigned to users or licensed to them on a long term basis normally for huge regions like whole countries
- Doing so, resources are wasted
- Vision: Resources are assigned where and as long as they are needed, spectrum access is organized by the network (i.e. by the end users)
- A CR is an autonomous unit in a communications environment. In order to use the spectral resource most efficiently, it has to
  - be aware of its location
  - be interference sensitive
  - comply with some communications etiquette
  - be fair against other users
  - keep its owner informed
- CR should
  - <u>Sense</u> the spectral environment over a wide bandwidth
  - <u>detect</u> presence/absence of primary users
  - <u>Transmit</u> in a primary user band only if detected as unused
  - <u>Adapt</u> power levels and transmission bandwidths to avoid interference to any primary user

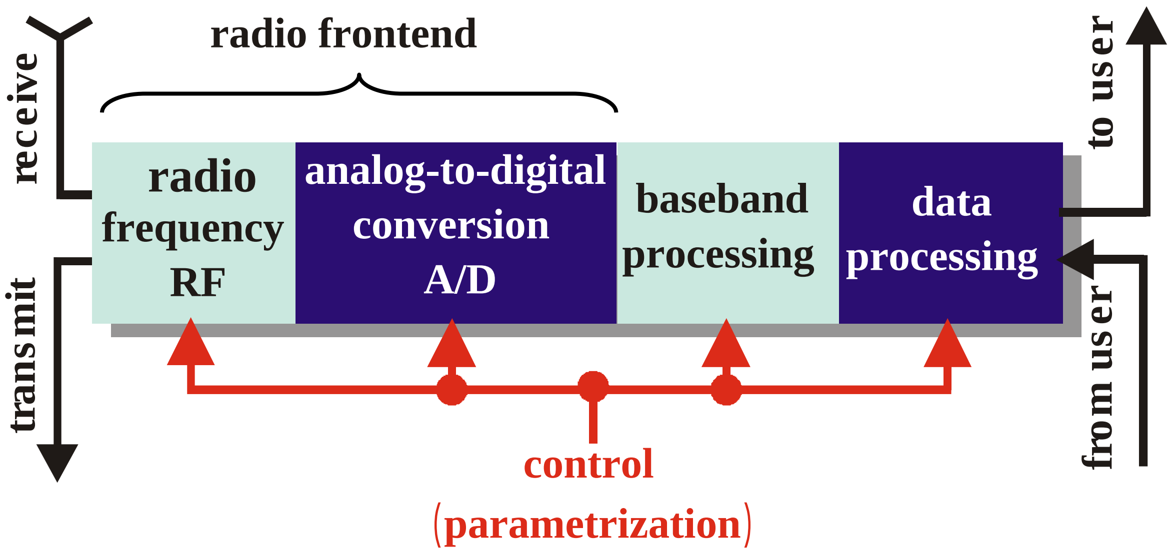
CR Definitions

Digital Radio (DR): The baseband signal processing is invariably implemented on a DSP.

Software Radio (SR): An ideal SR directly samples the antenna output.

Software Defined Radio (SDR): An SDR is a presently realizable version of an SR: Signals are sampled after a suitable band selection filter.

Cognitive Radio (CR): A CR combines an SR with a PDA



1) According to J. Mitola, 2000

Cognitive radio Functions

Sensing Radio

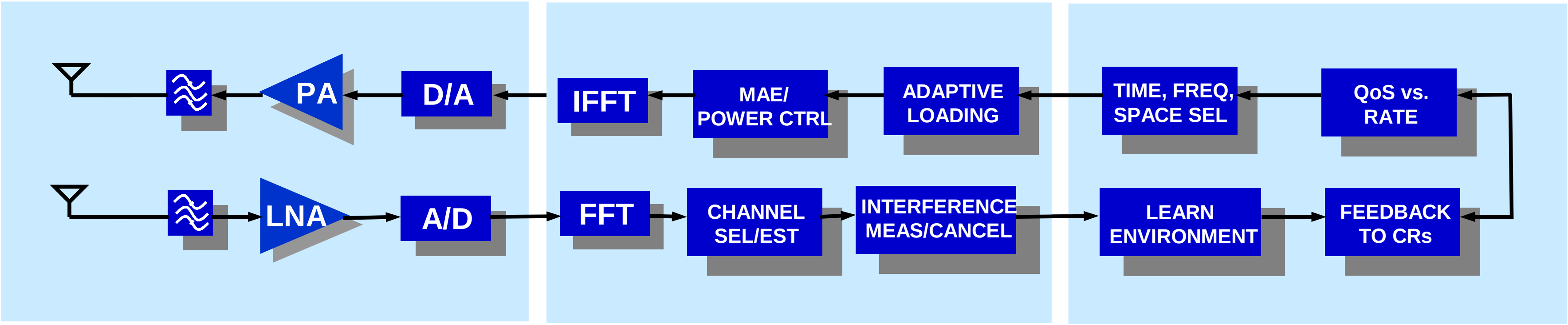
- Wideband Antenna, PA and LNA
- High speed A/D & D/A, moderate resolution
- Simultaneous Tx & Rx
- Scalable for MIMO

Physical Layer

- OFDM transmission
- Spectrum monitoring
- Dynamic frequency selection, modulation, power control
- Analog impairments compensation

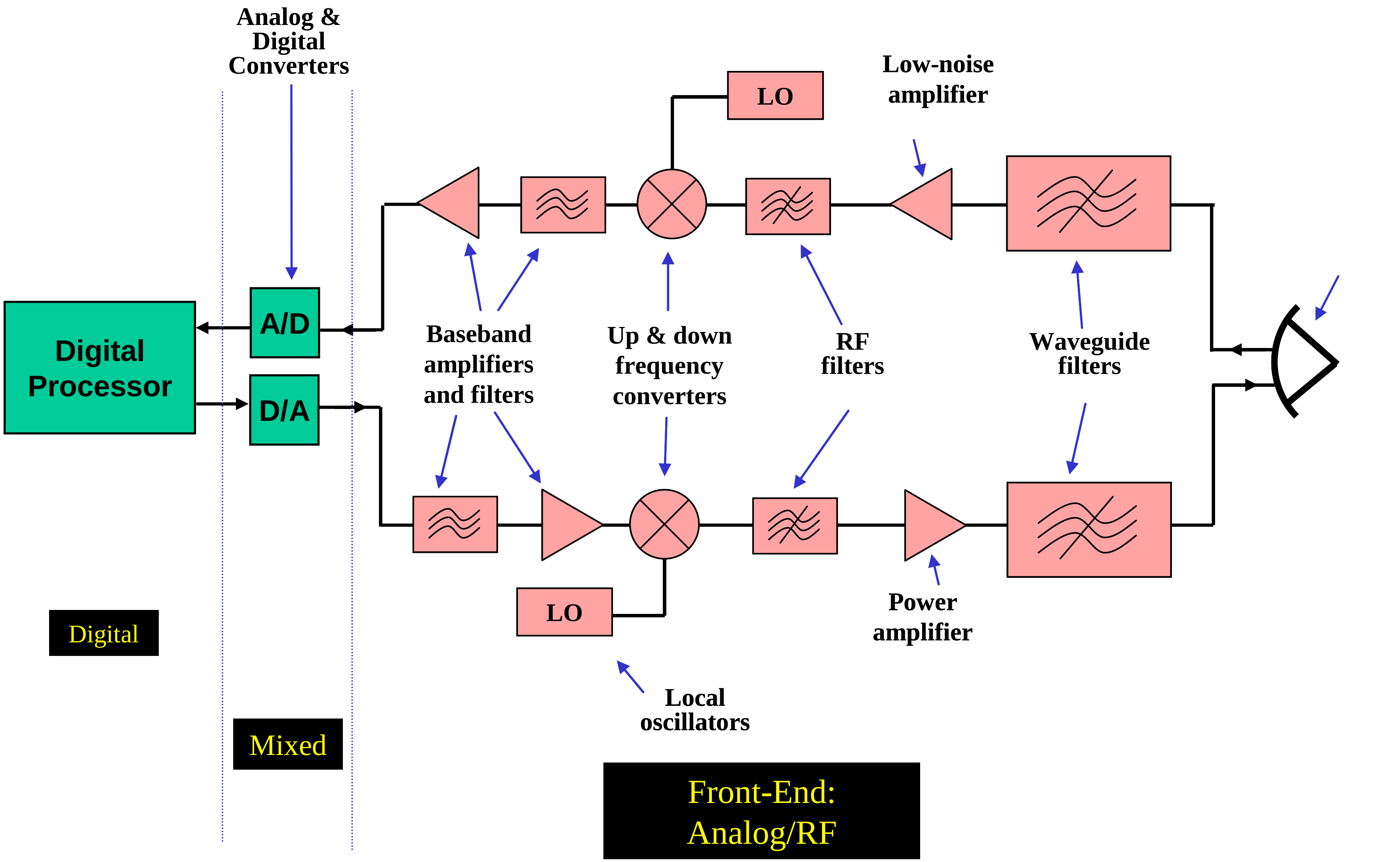
MAC Layer

- Optimize transmission parameters
- Adapt rates through feedback
- Negotiate or opportunistically use resources

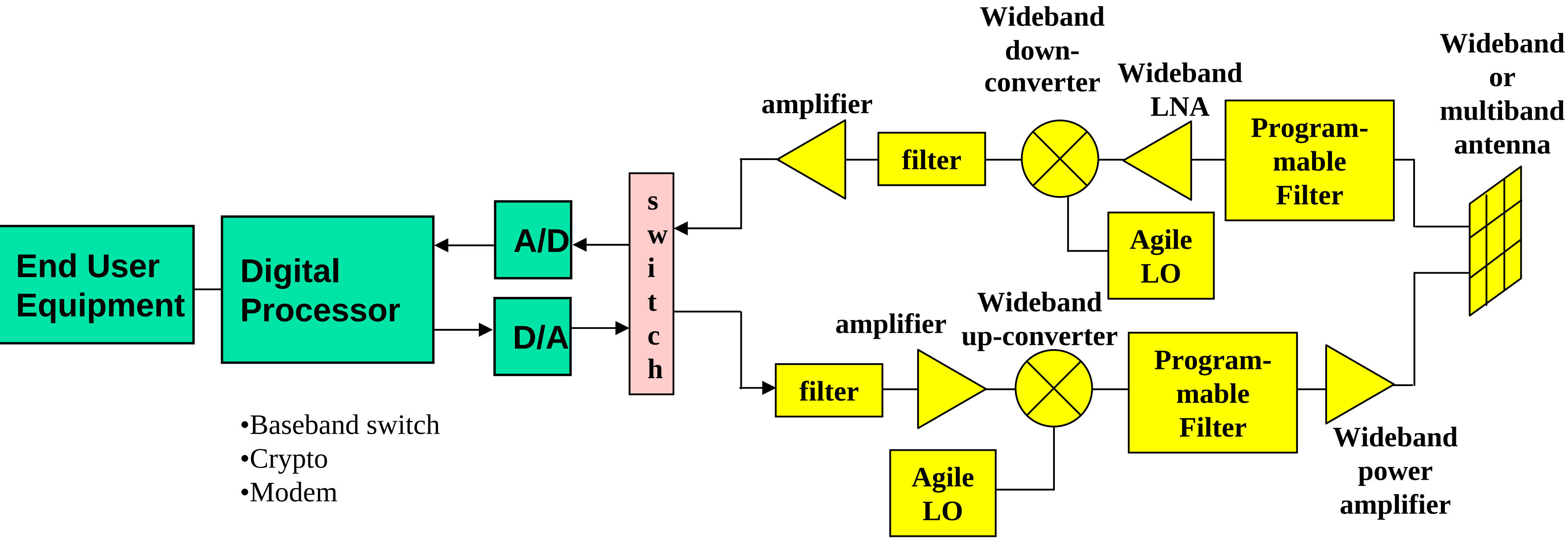


RF/Analog Front-end
Digital Baseband
MAC Layer

RF Front-End Schematic



RF Front-End Challenges



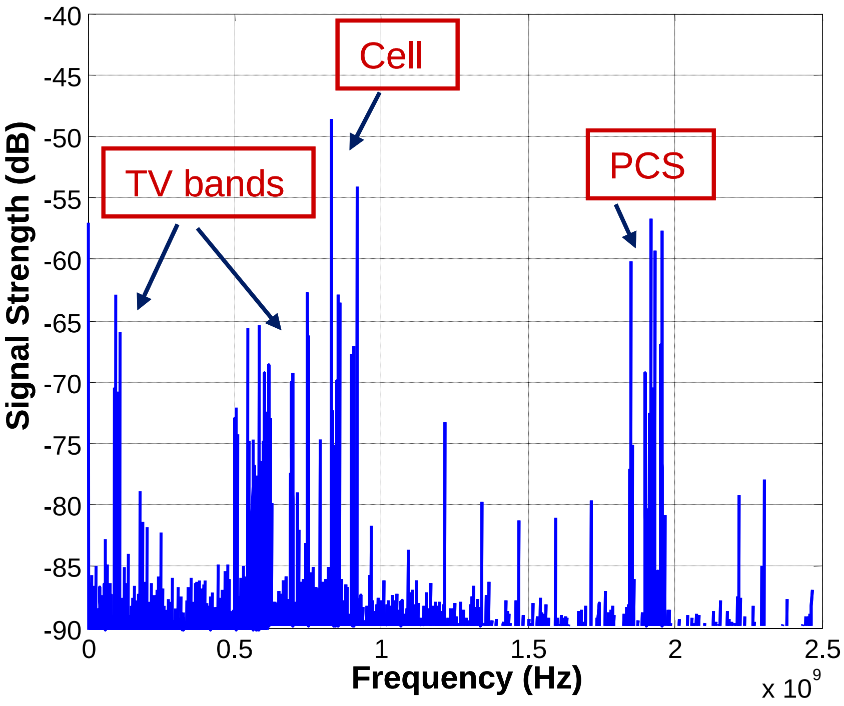
- Baseband switch
- Crypto
- Modem

Motivation

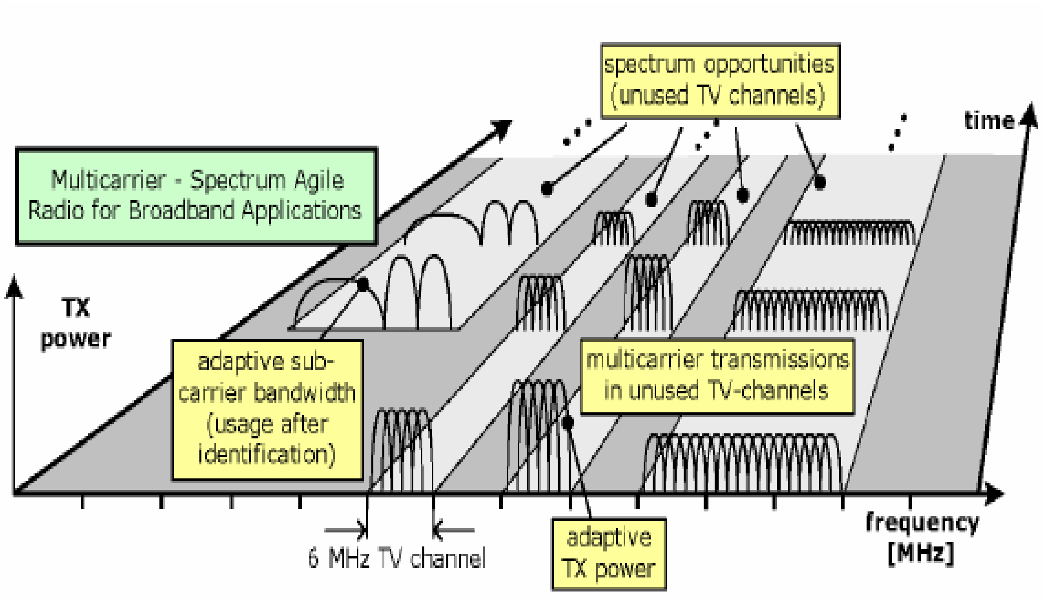
- Intelligence and military application require an application-specific low cost, secure wireless systems.
- **An adaptive spectrum-agile MIMO-based wireless node will require application-specific wireless system:**
  - **Reconfigurable Radio (operating frequency band, bit rate, transmission power level, etc)**
  - **Wide frequency coverage and agility**
  - **Work independent of commercial infrastructure**
  - **Large instantaneous bandwidth**

System Challenges

- A/D converter:
  - High resolution
  - Speed depends on the application
  - Low power ~ 100mWs
- RF front-end:
  - Wideband antenna and filters
  - Linear in large dynamic range
  - Good sensitivity
- Interference temperature:
  - Protection threshold for licensees



System Challenges



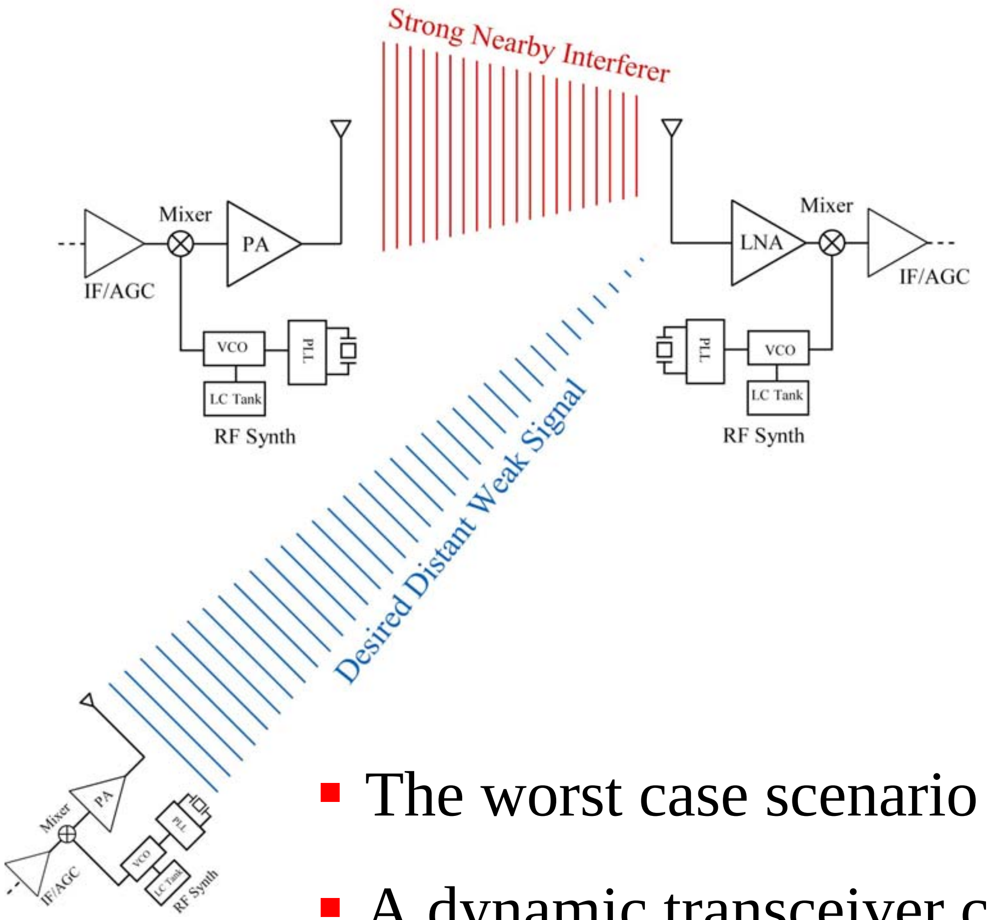
Receiver

- Wideband sensing
- Different primary use
- Channel uncertainty between CR and primary user

Transmitter

- Wideband transmission
- Adaptation
- Interference with primary user

Dynamic Operation: Near-Far Problem



- High power consumption due to simultaneous requirement of high linearity in RF front-end *and* low noise operation
- The conflicting requirements occur since the linearity of the RF front-end is exercised by a strong interferer while trying to detect a weak signal

- The worst case scenario is a rare event.
- A dynamic transceiver can schedule gain/power of the front-end for optimal performance

Advantages of CR

- Cognitive radios are expected to be powerful tools for mitigating and solving general and selective spectrum access issues (e.g. finding an open frequency band and effectively utilizing it).
- Improves current spectrum utilization (Fill in unused spectrum and move away from occupied spectrum).
- Improves wireless data network performance through increased user throughput and system reliability.
- More adaptability and less coordination required between wireless networks.

UWB Systems

Basics of UWB Signaling

Basics

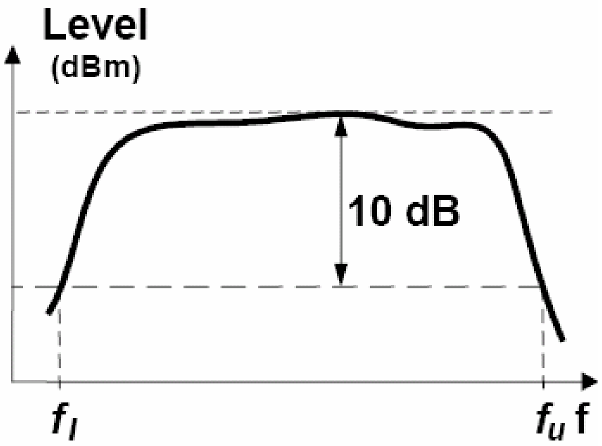
Fractional bandwidth

$$B_f = \frac{B}{f_c} = \frac{2\cdot(f_u - f_l)}{(f_u + f_l)} > 20\%$$

or

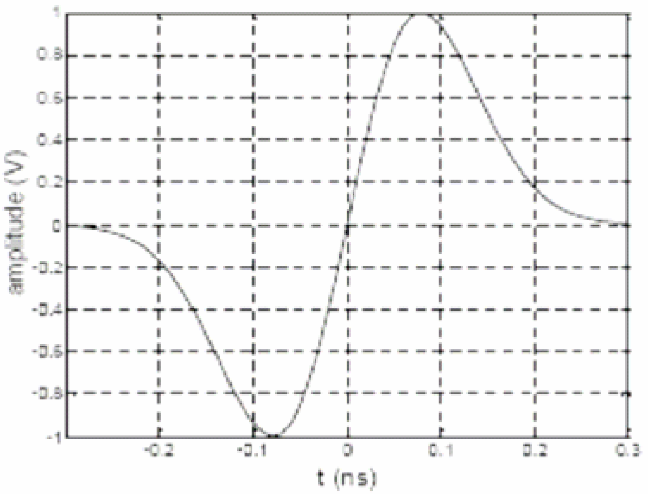
Absolute bandwidth

$$B > 0.5GHz$$



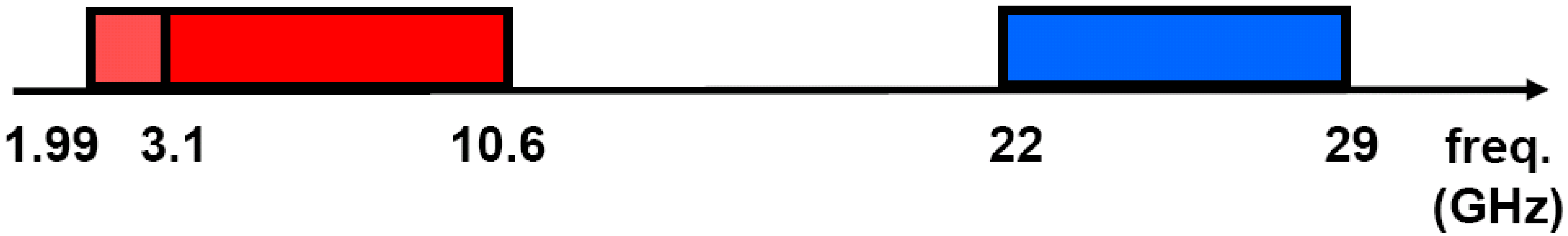
Properties

- Wide bandwidth
- Low average power spectral density
- High temporal resolution
- High information transmission capacity



Definition of UWB Systems

FCC: UWB systems should have a -10dB bandwidth of at least 500MHz or a fractional bandwidth of at least 20% (regardless of fractional bandwidth) at any point in time.



- Ground penetrating radar (GPR), through wall imaging, surveillance
- Medical imaging, indoor communication
- Vehicular radar

Why UWB?

1. UWB Communication
   i. Higher data-rate
   ii. immunity to multi-path fading
   iii. narrowband interferers can be nulled with little performance degradation

$$\boxed{C = BW \cdot \log_2(1 + SNR)}$$

bandwidth

signal-to-noise ratio

channel capacity

representing information in bits

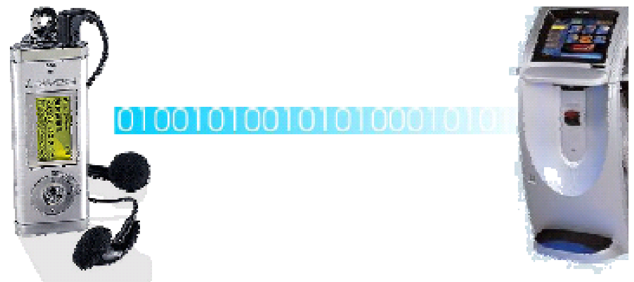
2. UWB Imaging
   i. Higher range resolution
   ii. Higher azimuth beam forming resolution

$$\boxed{\text{Resolution} \propto \frac{1}{BW}}$$

UWB Applications

Applications

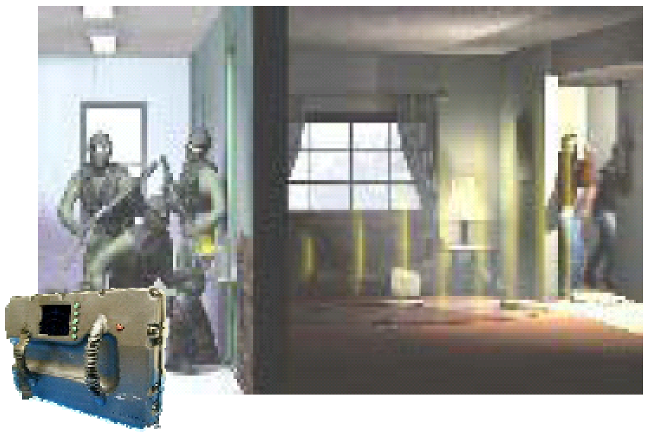
- Communications



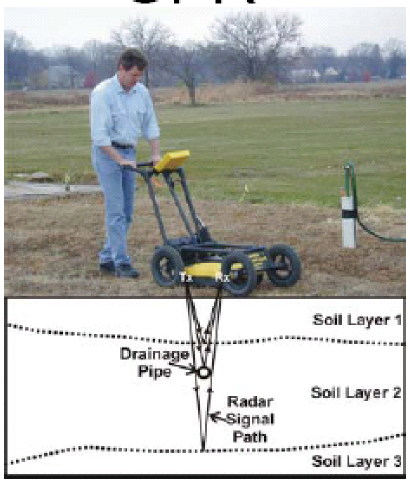
- Localization and Sensing

Material science

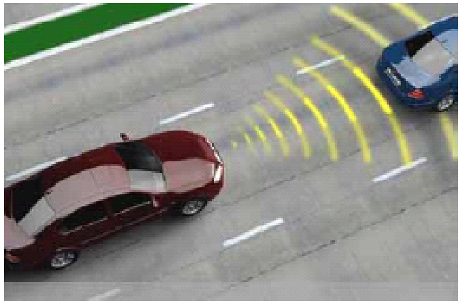
Through wall imaging



GPR



Automotive radar



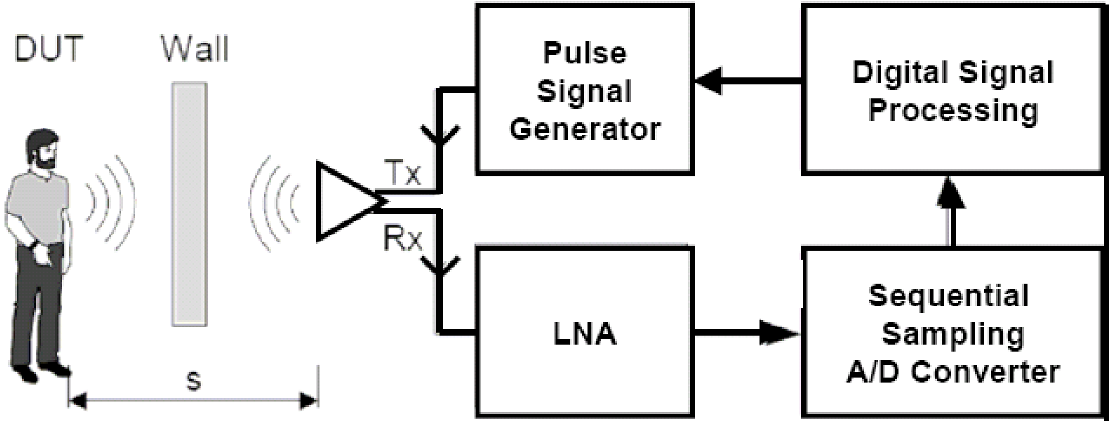
UWB Sensors

Sensors

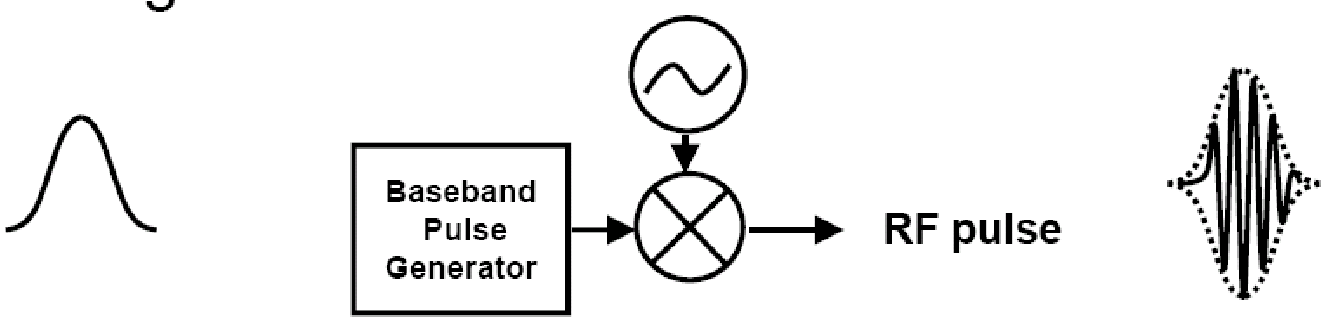
- **Pulse sensors**
  - Sequential sampling sensors
  - Correlating pulse sensors
- **Pseudo random binary sequence sensors**

- Pulse sensors - simple generator architecture
- PRBS sensors - low crest factor of stimulus signal
- Frequency bands: 3.1GHz - 10.6GHz, 22GHz - 29GHz, 60GHz

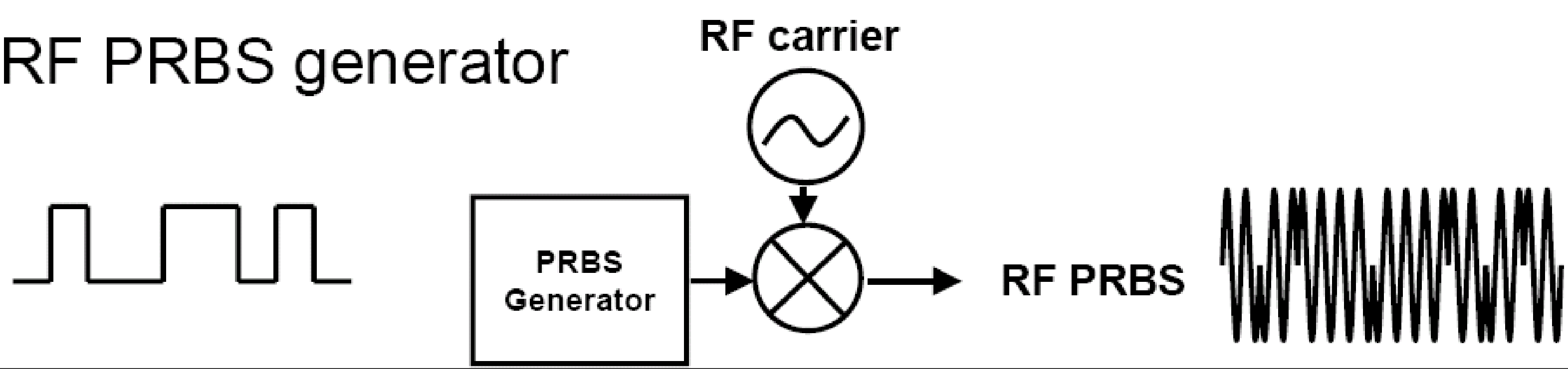
UWB Sensor Architectures



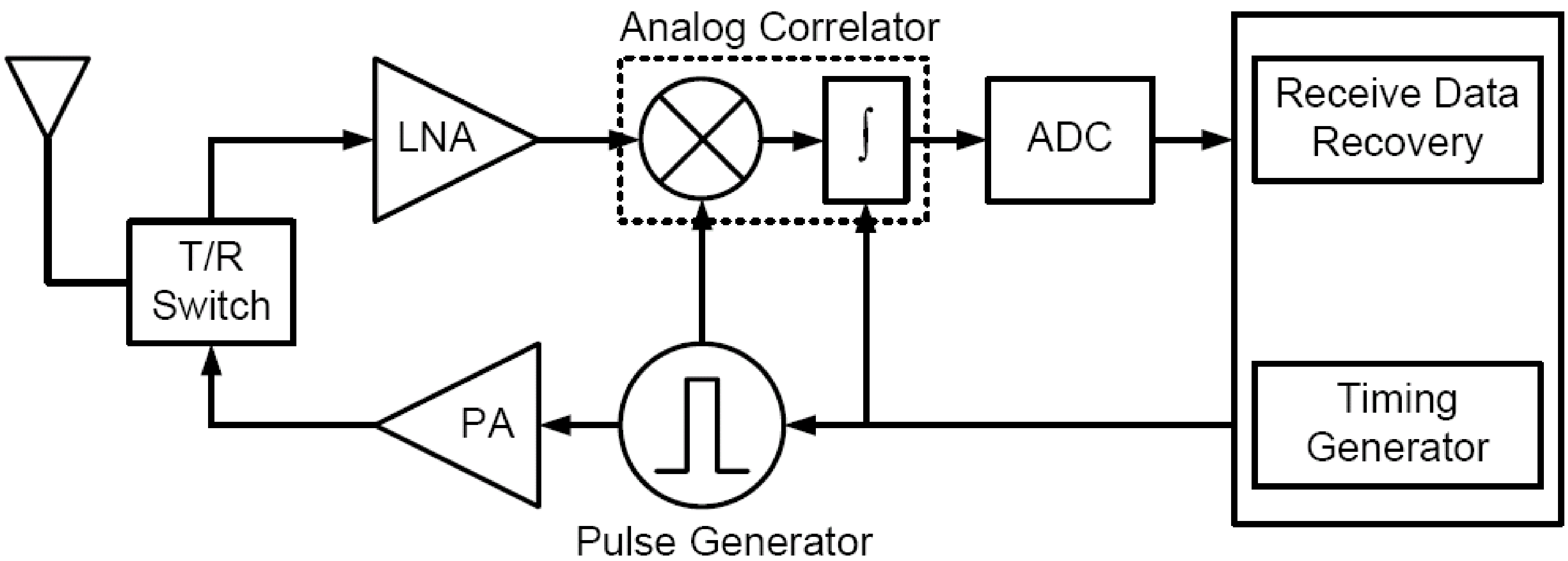
- RF pulse generator



- RF PRBS generator

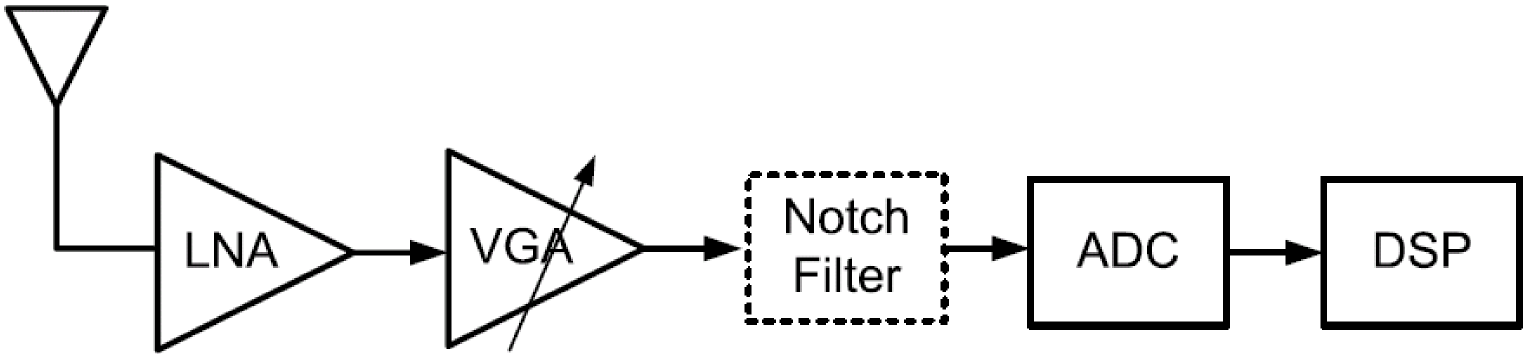


UWB receiver Architecture



- Suitable for communication applications
- Inherently low power architecture
  - no frequency synthesizer
  - ADC after analog correlator
- Challenges: UWB front-end, timing and pulse generators

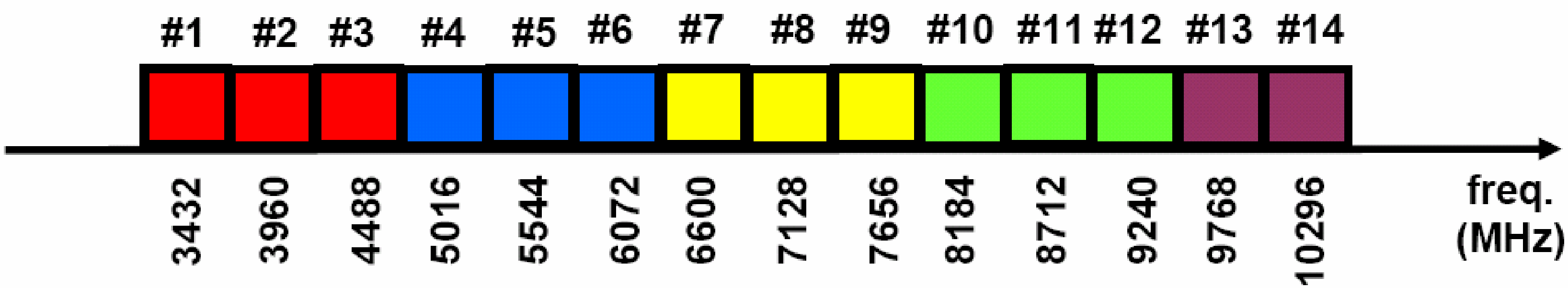
UWB receiver Architecture



- Power consumption of digital signal processing improves with technology scaling => perform all the necessary signal processing (e.g., correlators, RAKE) in DSP
- UWB ADC is the most challenging building block
  - Power consumption almost proportional to BW
  - Dynamic range limited due to narrowband interferer signals
- UWB ADC architectures:
  - time-interleaved (multiple ADCs sampled at successive times)
  - frequency channelized (multiple ADCs, each for a portion of BW)

Multi-band OFDM UWB Architecture

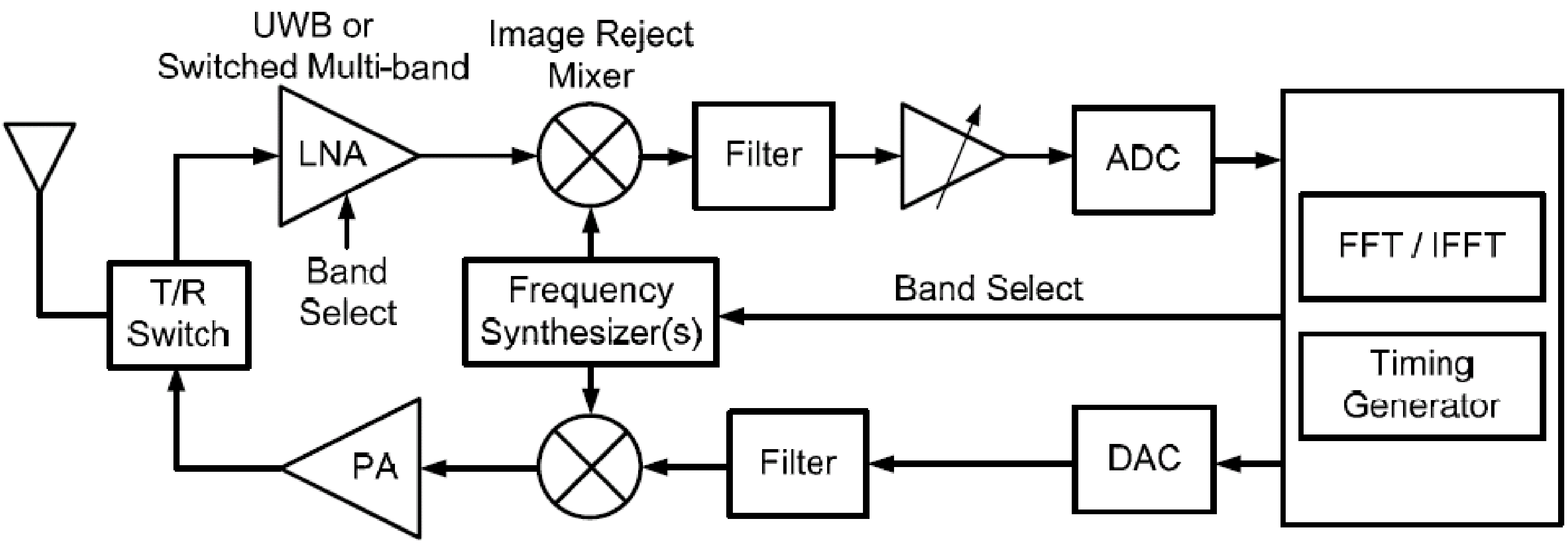
- Communication Applications
  - Orthogonal frequency division multiplexing (OFDM) in each band
  - Carrier hops between bands in less than 9.5ns
  - Fast switching multi-band + digital filter bank (FFT) receiver



128 (sub-carriers per band) x 4.125MHz (sub-carrier spacing) = 528MHz

Band center frequency = 2904 + (528MHz x n_b) MHz, where n_b=1…14

Multi-band OFDM UWB Radio Architecture



Challenges:

- Local oscillator frequency synthesizer
  - <9ns switching time
  - small spurious tones (in-band & out-of-band)
- UWB/multi-band front-end
- Low power FFT/IFFT

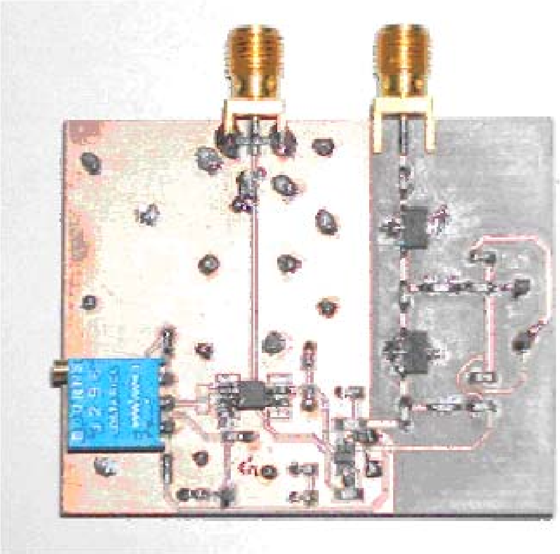
Comparison of MB-OFDM radios

Paper ID	Technology	Power (mW)			Vdd (V)	NF (dB)	Comments
		Rx	Tx	LO			
Tanaka [ISSCC'06]	90nm CMOS	84	177	47	1.1	6.9	All bands using 1 PLL + Dividers + SSB Mixers + MUX
Sander [ISSCC'06]	130nm CMOS	51	97.5	186	1.5	3.6	Bands 1-3 using 1 PLL + Dividers + SSB Mixers + DDS + MUX
Lo* [ISSCC'06]	180nm CMOS	412	397	?(*)	1.8	4.0	Bands 1-3 using 1 PLL + Dividers + SSB Mixers + MUX
Razavi [ISSCC'05]	130nm CMOS	60		45	1.5	6.5	Bands 1-3 using 3 PLLs
Ismail [ISSCC'05]	180nm SiGe BiCMOS	60	N/A	178	2.7	3.3	UWB front-end, Bands 1-7 using 1 PLL + Dividers + SSB Mixer + MUX

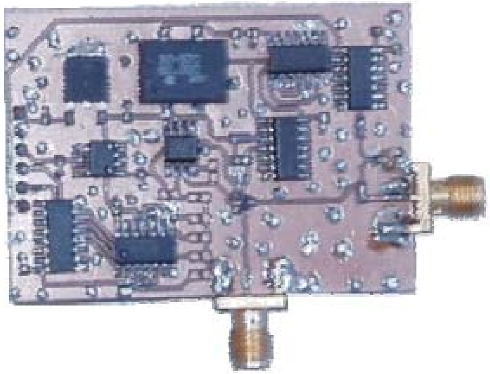
- Significant DC power (up to 75% in Rx) is consumed in the LO generation circuitry.

UWB Components / Subsystems

Step recovery diode based pulse generator for GPR



UWB Rx prototype



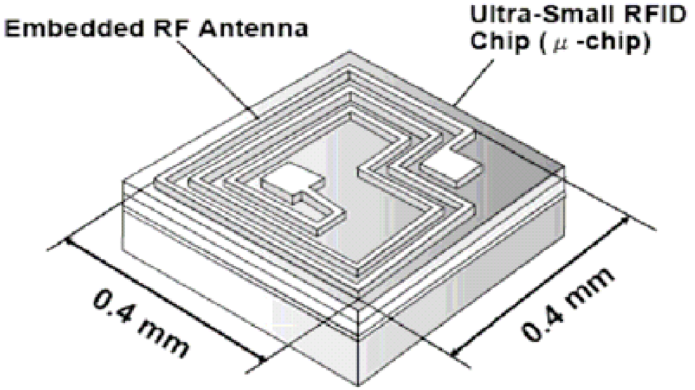
UWB pulse transmitter prototype

Source: Center of Competence in Mechatronics, Linz, Austria

UWB Levels of Integration

Antennas

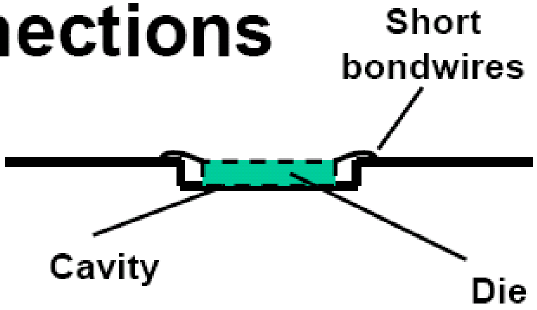
- Monopole antenna for 3-10GHz range
- 30 mm length (lambda/2 @ 5 GHz)
- Integration not feasible



Source: Mitsuo Usami "An Ultra-Small RFID Chip: u-chip", Proc. 2004 IEEE AP-ASIC Conference

- Embedded antennas @ mm-wave frequencies

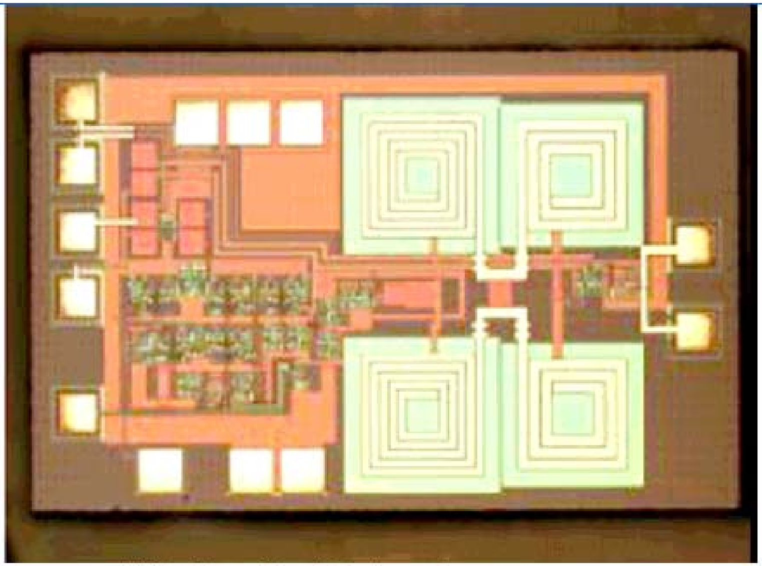
Chip-PCB connections



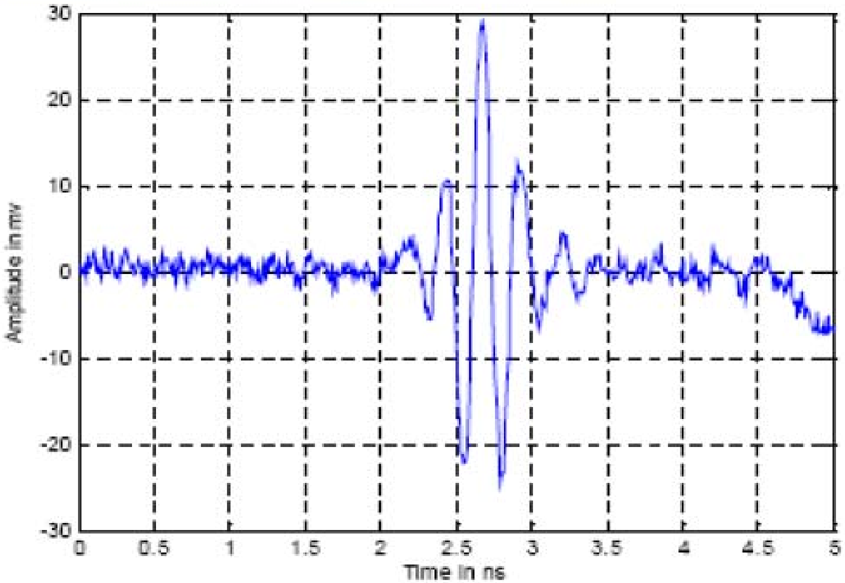
Power amplifiers

- Is integration possible?

UWB Basic Building Blocks (Pulse Generator)



Source: IHP, Frankfurt Order, Germany



- Gaussian baseband pulse
  + frequency shift
- Pulse shaping with passive LC filter
- Trigger pulses derived from VCO signal
- BPSK phase modulation

- 3.1GHz - 5.1 GHz range
- 0.25um SiGe:C BiCMOS technology
- 60mW @ 2.5V

Challenges in UWB IC Design

Components

- Improvement of broadband matching and amplification properties of PA and LNA blocks
- Integration of passive elements (couplers, baluns)
- Jitter performance improvement in sequential sampling sensors
- High-resolution ADCs for Nyquist sampling sensors

Challenges in UWB IC Design

Power consumption

- Low power consumption generators/synthesizers/PAs
- Low power DACs and ADCs
- Use of high speed BiCMOS technologies beneficial

Other

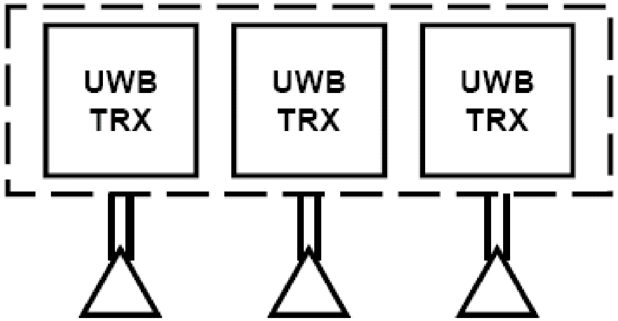
- Sensor chip area
- Crosstalk
- Full CMOS implementations

Future Trends

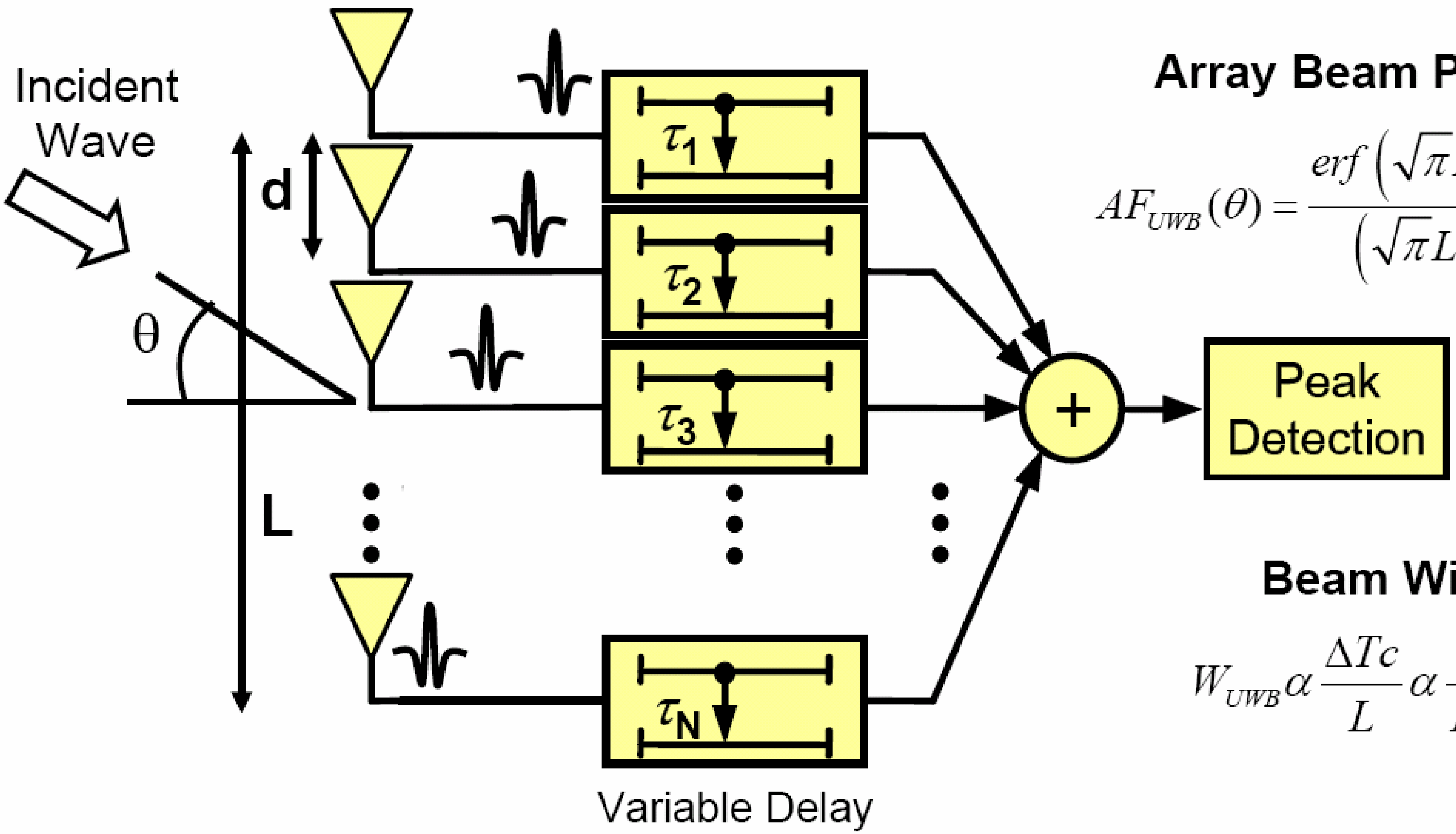
Mm-wave UWB sensors

- Development of UWB radar sensors for 77-81 GHz
- UWB sensors in 122 GHz ISM band

Integrated UWB sensor arrays



Future Trends; UWB Beam forming



Array Beam Pattern

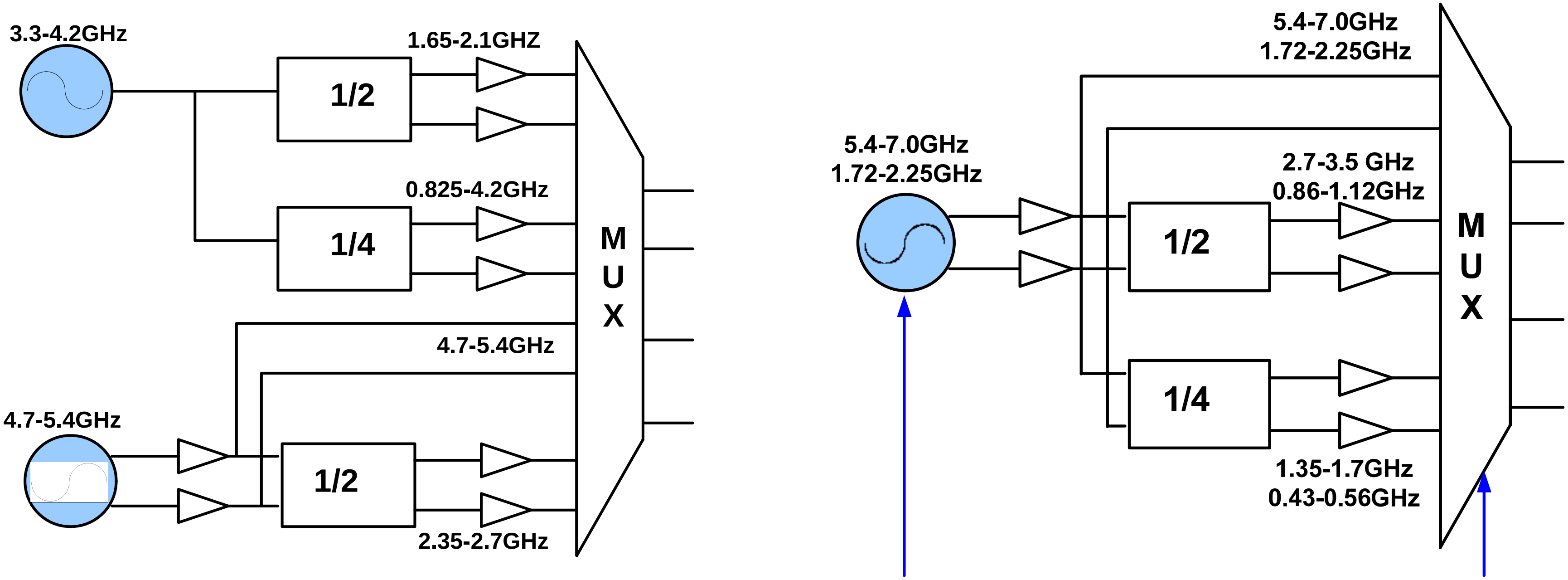
$$AF_{UWB}(\theta) = \frac{erf\left(\sqrt{\pi}L\theta / 2\Delta Tc\right)}{\left(\sqrt{\pi}L\theta / \Delta Tc\right)}$$

Beam Width

$$W_{UWB} \alpha \frac{\Delta Tc}{L} \alpha \frac{c}{BW \times L}$$

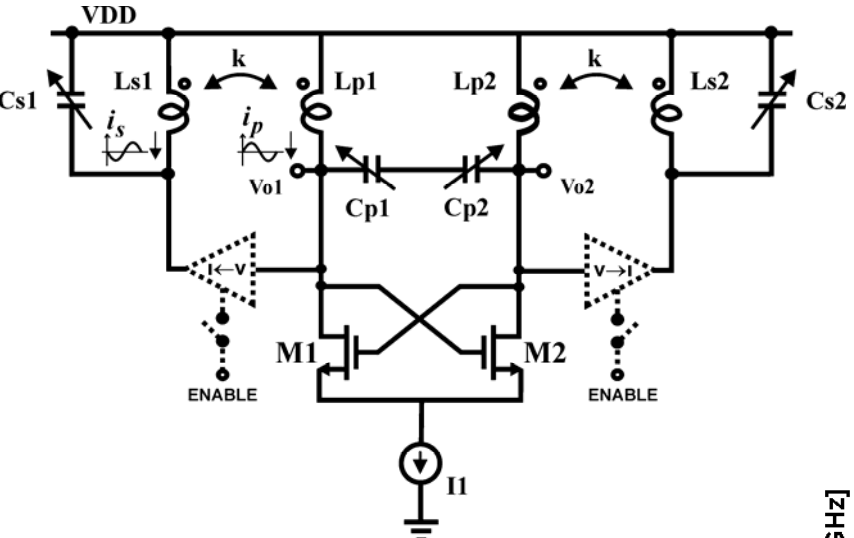
Variable true time delay is required in UWB beam forming.

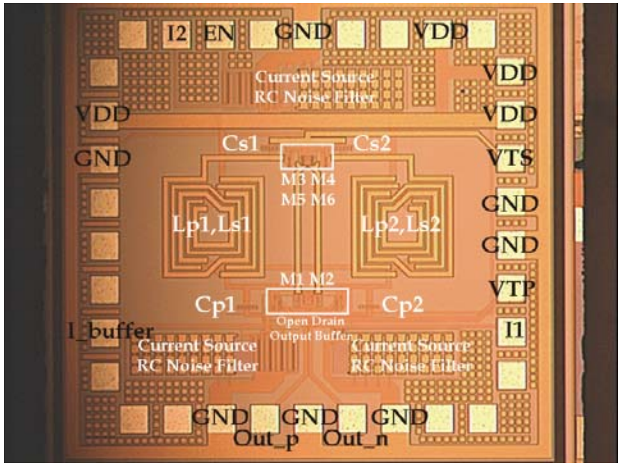
Multi-band VCO



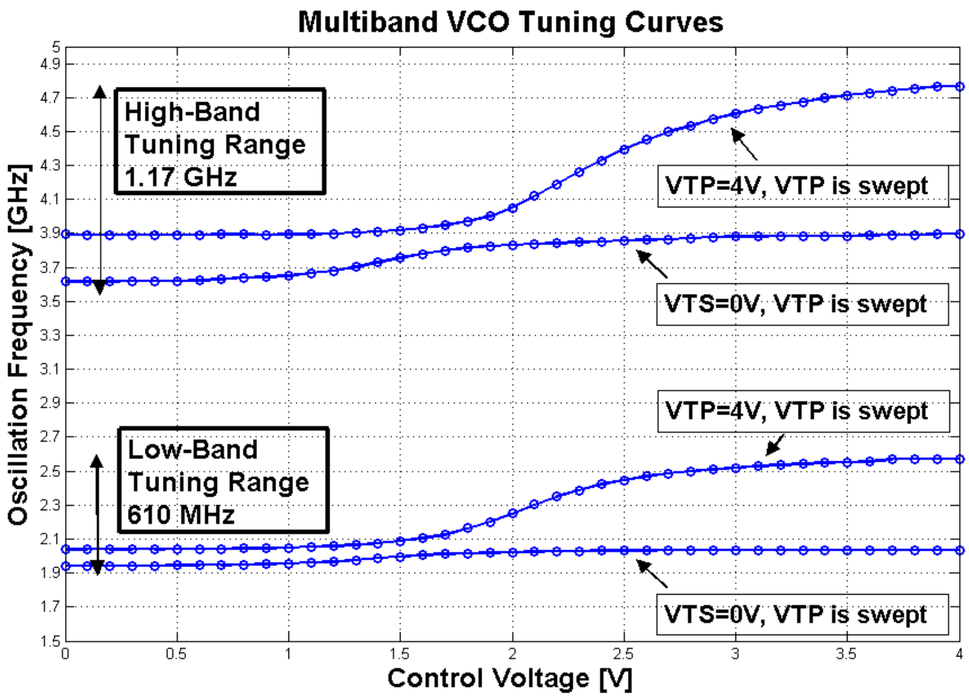
- **Existing Multiband VCOs/Frequency References are based on:**
  - **Switched inductor and/or capacitor LC tanks (Extra parasitics and resistive loss → degrade both tuning range and phase noise)**
  - **Frequency dividers (higher phase noise and power consumption)**
  - **MEMS resonators (non-standard process, extra processing steps, higher fabrication cost)**

Multi-Band VCO--Schematic



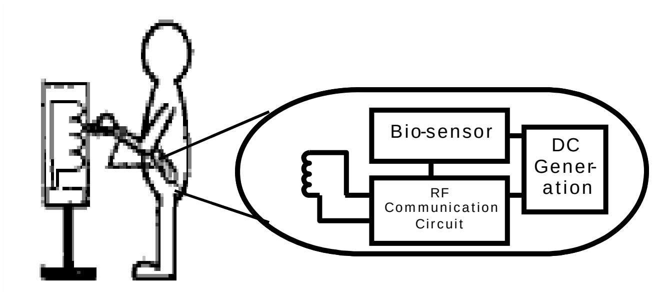


- ❑ **Low-Band and High Band**
- ❑ **Switching between bands:**
  Enable / Disable a buffer
- ❑ **In-Band Tuning:**
  “Primary” and “secondary” varactors



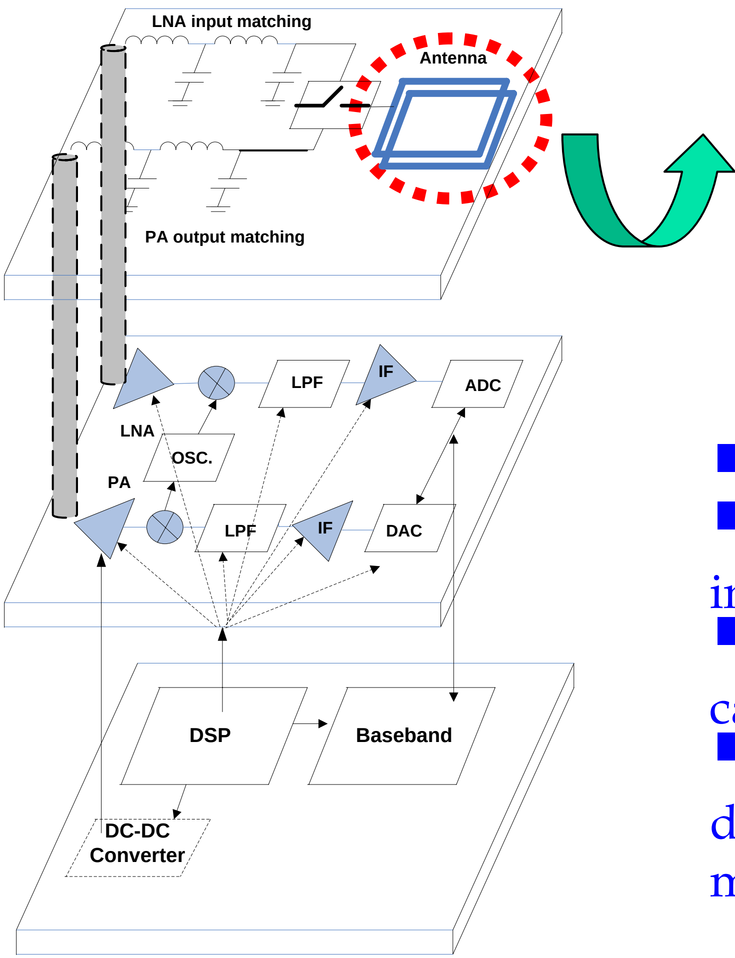
Future Trends

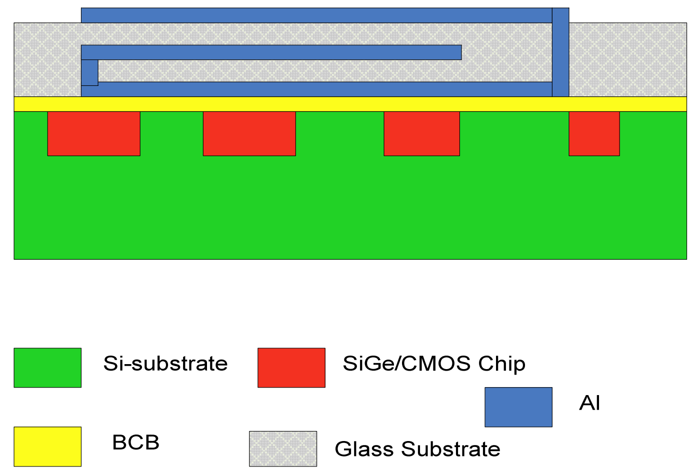
- Wireless Control of machines and devices in the process and automation industry
- Logistic Radio Frequency Identification (RFID), includes transportation, terminals, and warehouses.
- Smart home appliance, remote controls
- Medical monitoring health conditions (wireless body area network WBAN)
- Environmental monitoring, such as smart dust or other ambient intelligence



RF-Powered Wireless Communication Circuits for Bio-Implantable Microsystems

3D RF System Integration





One Possible Antenna Implementation

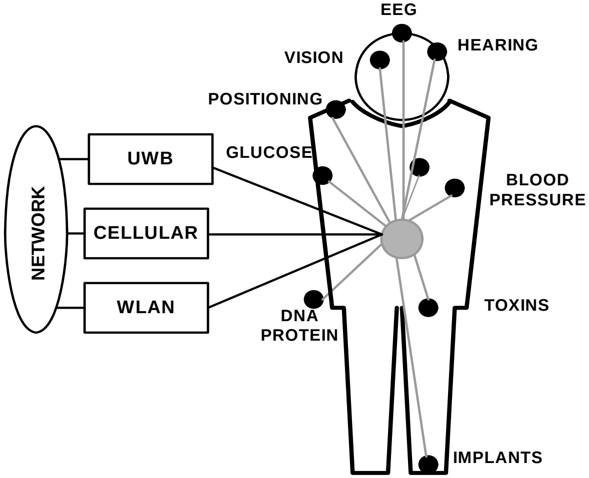
- Integrated Antenna
- High Q inductors (top glass layer or inter-wafer inductors
- Digitally assisted RF/Analog Design (All blocks can be optimized through vertical control signals)
- Power Amplifier linearization→ Digital pre-distortion or dynamic bias through bottom layer monolithic DC-DC Converter

↓

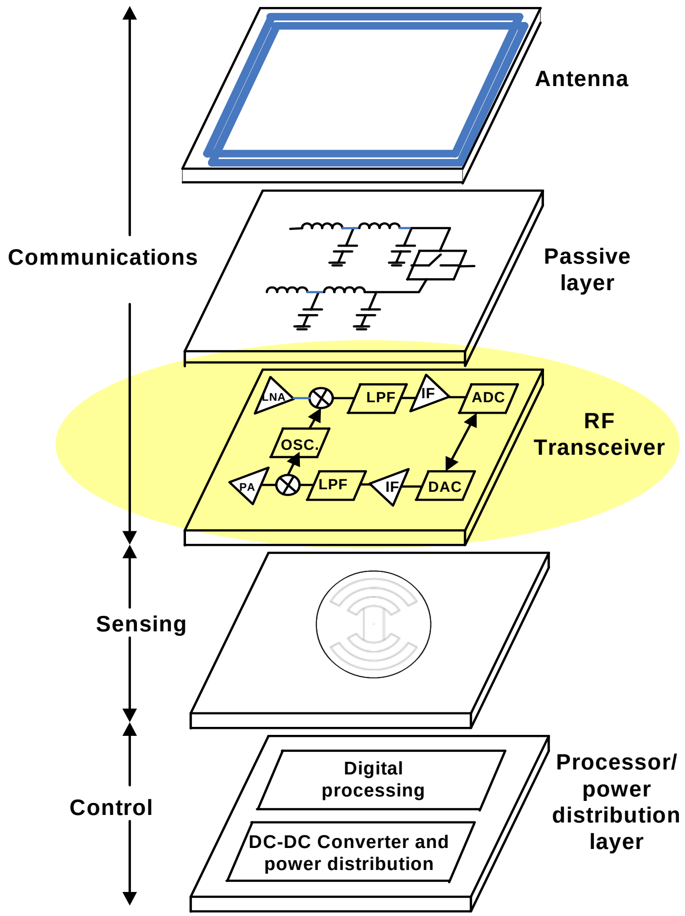
Added functionality/versatility

3D Micro-Power Portable/Implantable RF Wireless

Wireless Body Area Network (WBAN)



(a)



(b)