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

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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
Where we are in terms of technology?

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.*

*Source: International roadmap for semiconductors ITRS 2005

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)
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.

Maximum Amplitudes

<table>
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<th>Heavy Use</th>
<th>Heavy Use</th>
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<td></td>
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<tr>
<td>Sparse Use</td>
<td>Medium Use</td>
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</table>

Power

Frequency

Spectrum in Use

Dynamic Spectrum Access

“Spectrum Hole”

Time
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
- Sense the spectral environment over a wide bandwidth
- detect presence/absence of primary users
- Transmit in a primary user band only if detected as unused
- Adapt power levels and transmission bandwidths to avoid interference to any primary user
**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.

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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

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RF/Analog Front-end

Digital Baseband

MAC Layer

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RF Front-End Challenges

- Wideband down-converter
- Wideband LNA
- Agile LO
- Agile LO
- Program- mable Filter
- Program- mable Filter
- Wideband or multiband antenna
- Wideband power amplifier

**End User Equipment**

- Digital Processor
  - A/D Switch
  - D/A Switch
  - Wideband LNA
  - Agile LO
  - Program- mable Filter

**Digital Processor**

- • Baseband switch
- • Crypto
- • Modem

**Program- mable Filter**

**Wideband or multiband antenna**

**Wideband power amplifier**
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

![Graph showing signal strength vs. frequency with TV bands and PCS labels]
System Challenges

Receiver

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

Transmitter

- Wideband transmission
- Adaptation
- Interference with primary user
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

Fractional bandwidth

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

or

Absolute bandwidth

\[ B > 0.5\text{GHz} \]

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

\[ C = BW \cdot \log_2(1 + SNR) \]

- Bandwidth
- Signal-to-noise ratio
- Channel capacity representing information in bits

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

\[ \text{Resolution} \propto \frac{1}{BW} \]
UWB Applications

Applications

- Communications
- Localization and Sensing

- Material science
- Through wall imaging
- GPR
- Automotive radar

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UWB 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

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- 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 pulse transmitter prototype

UWB Rx 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

Chip-PCB connections

- Embedded antennas @ mm-wave frequencies

Power amplifiers

- Is integration possible?
UWB Basic Building Blocks (Pulse Generator)

- 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

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

Peak Detection

Beam Width

\[ W_{UWB} \propto \frac{\Delta Tc}{L} \alpha \frac{c}{BW \times L} \]

Variable true time delay is required in UWB beam forming.
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

Multiband VCO Tuning Curves

High-Band Tuning Range 1.17 GHz
- VTP=4V, VTP is swept
- VTS=0V, VTP is swept

Low-Band Tuning Range 610 MHz
- VTP=4V, VTP is swept
- VTS=0V, VTP is swept
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
### 3D RF System Integration

- **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 predistortion or dynamic bias through bottom layer monolithic DC-DC Converter

**Added functionality/versatility**
Wireless Body Area Network (WBAN)