Automated Receiver Design and Optimization for 4G Wireless Communication Systems

Delia Rodríguez de Llera González, Ana Rusu, Mohammed Ismail

Electronic, Computer and Software Systems (ECS)
School of Information and Communication Technology (ICT)
Royal Institute of Technology (KTH)
Sweden

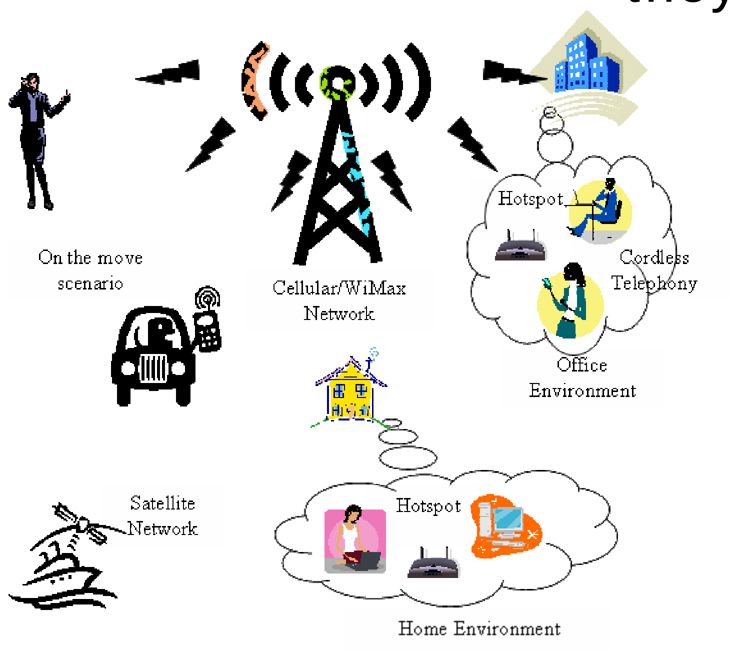
Funded by SSF

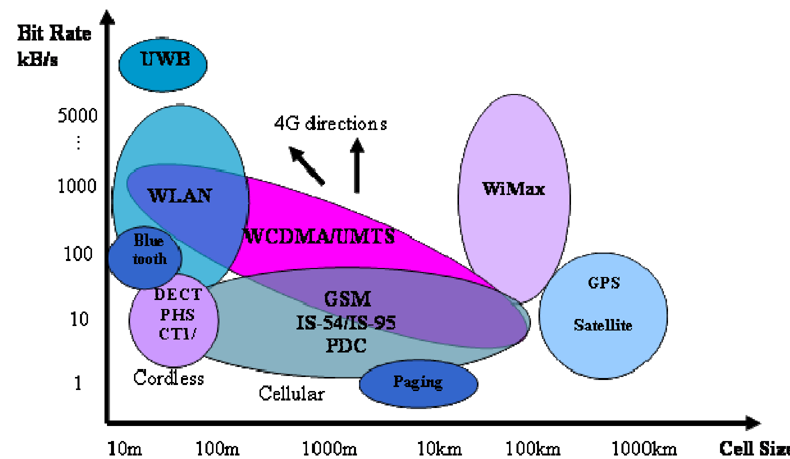
Outline

- Multi-standard receivers, do we need them?
- Basic design considerations and trade-offs.
- The receiver budget problem and the traditional approach.
- TACT overview.
- Algorithm description.
- Example: WCDMA/WLAN multi-standard receiver.
- Conclusions and future work.

Why multi-standard transceivers?

Different wireless scenarios and the connectivity options they provide.





Why multi-standard transceivers?

Scenario:

Coexistence of different wireless systems of different generations.

User point of view:

Need of portable terminals able to use different wireless standards without the user having to bother:

- Finding the available services
- Carrying different kinds of terminals

Why multi-standard transceivers?

Engineering point of view:

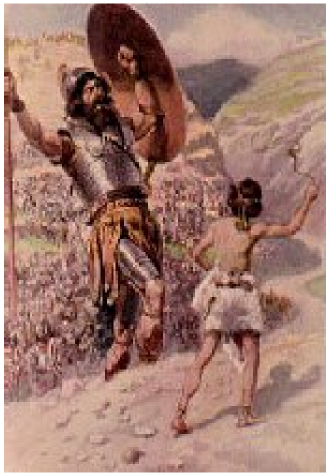
Programmable hardware that reuses blocks in order to save area and power $\Rightarrow$ Multi-standard capability and portability.

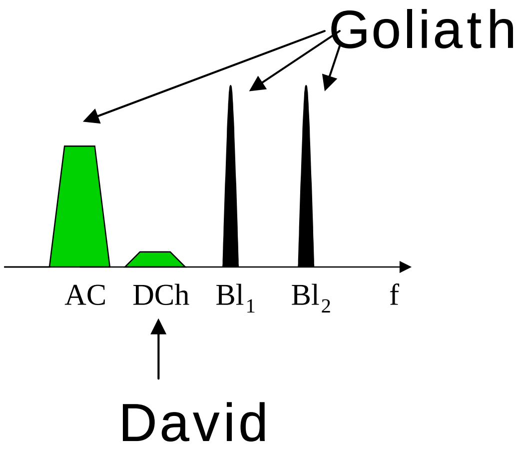
Why is it challenging?

Because all these standards have been conceived independently $\Rightarrow$ The hardware architectures that suit them best are very different.

Why Rx are tougher than Tx?

- David vs. Goliath type of situation:
- The desired channel may be a weak signal in a hostile environment.
- David figured it out… will we?





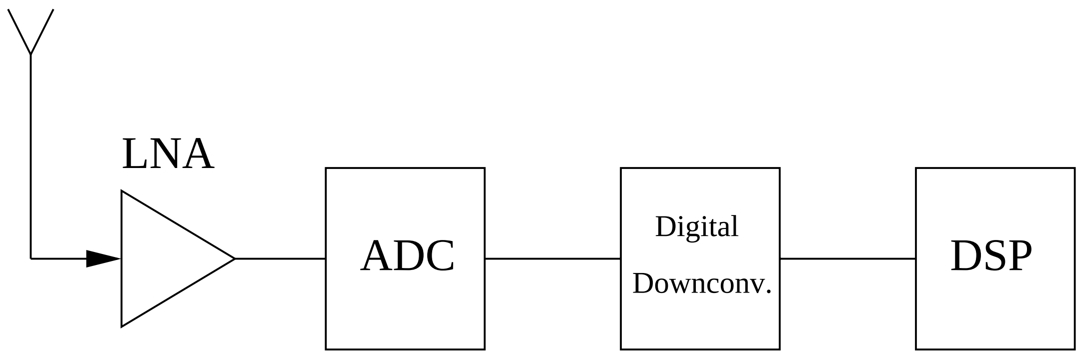
To bear in mind...

- Sensitivity: Minimum detectable signal.
- Maximum input signal.
- Selectivity: ability to select a (possible) weak desired signal channel in the (possible) presence of much stronger adjacent interferers (blockers, adjacent channels, etc.).
- The standards define a set of test procedures the Rx has to pass to get certified (intermodulation tests, etc.)

To bear in mind… (cont.)

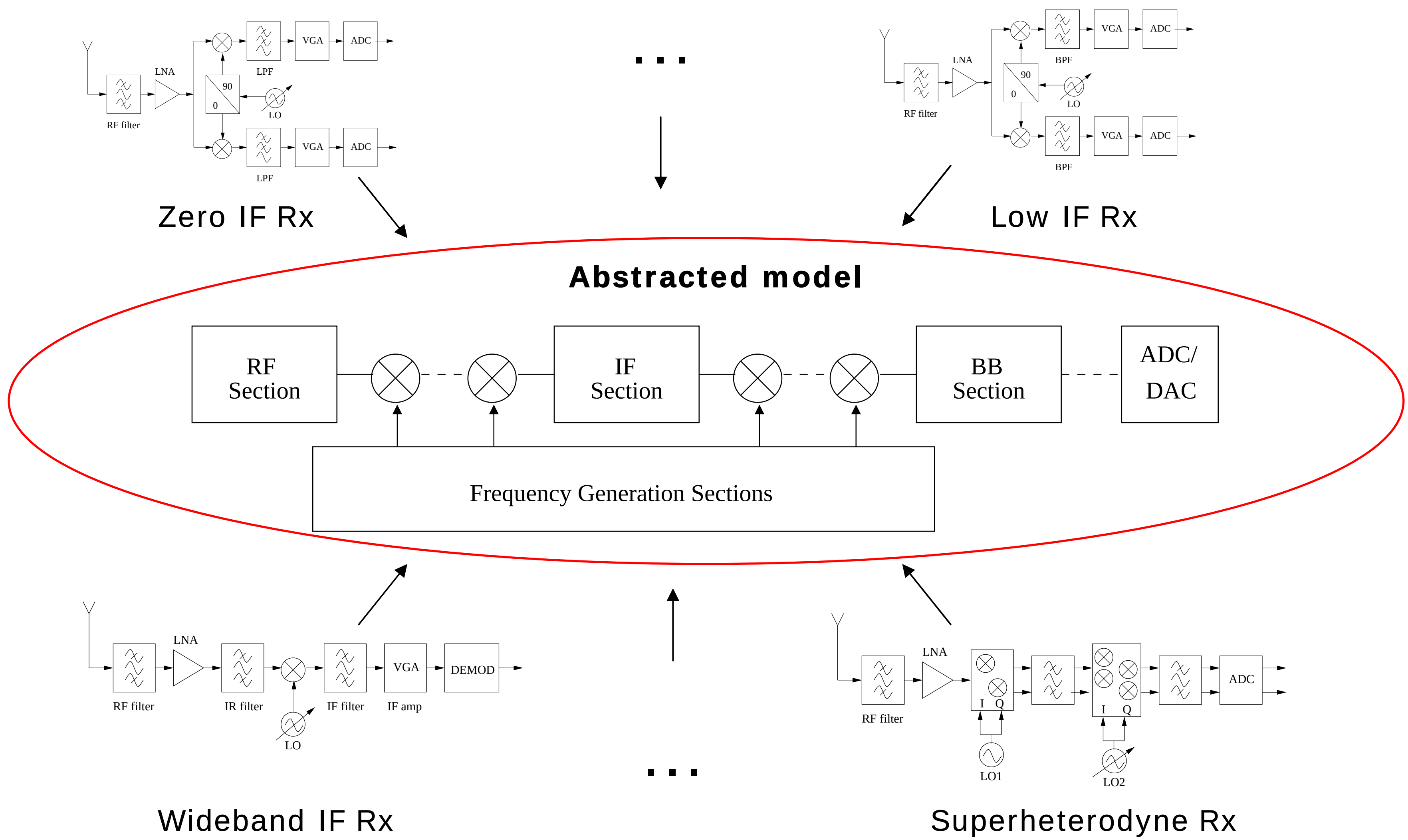
- Input signal(s):
  - Signals belonging to the standard:
    - Desired channel
    - Adjacent channels (ACs)
  - Interferers
- And their characteristics (if known):
  - Amplitude range
  - Bandwidth (BW)
  - Modulation type
- Noise
- Linearity
- …

Trend



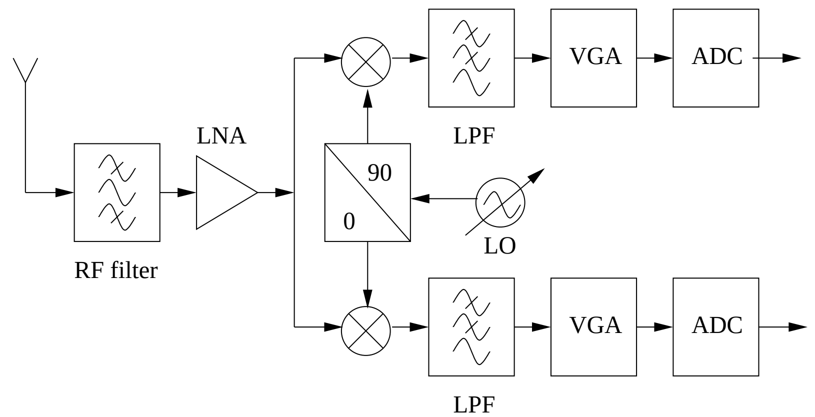
- Get as close as possible to the Software Radio (SR) paradigm.
- Move to higher and higher IF Rx.
- Digitize at higher frequencies and move as much processing as possible to the digital domain.
- Is this really advantageous?

Still...



RF filter
LNA
LPF
VGA
ADC
LO
90
0
Zero IF Rx
...
BPF
Low IF Rx
Abstracted model
RF Section
IF Section
BB Section
ADC/ DAC
Frequency Generation Sections
IR filter
IF filter
IF amp
DEMOD
Wideband IF Rx
I Q
LO1
LO2
Superheterodyne Rx

The Rx Budget Problem

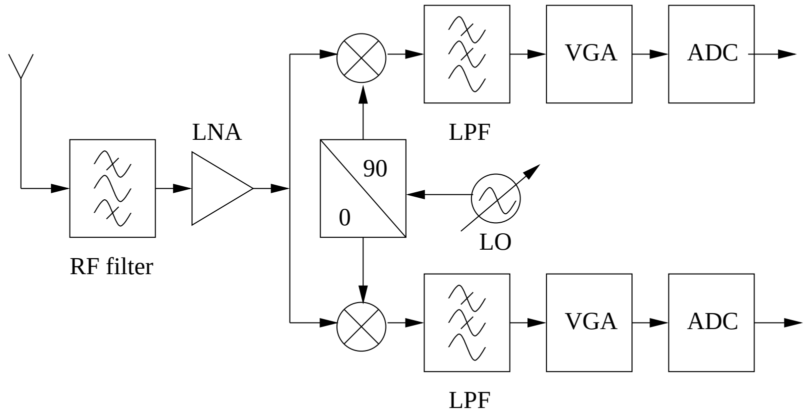


- Classical (single-standard) Rx budget problem:
  - How to distribute the requirements among the different blocks of the Rx so that standard specs are met?
  - How to deal with the parameter interdependencies?
  - What Rx architecture suits best the target cost functions?

- Complicated by the Multi-standard case:
  - What blocks should be programmable and what blocks should be duplicated?
  - Is there any standard that should have an independent signal path?

The Rx Budget Problem

Or... What if I change A_{LNA}?



- Imagine you are designing a zero-IF Rx with the traditional method, i.e. spreadsheets.
- Everything is set.
- Now you want to tweak the budget.
- This is what happens...

The traditional approach

- Usually based on Excel sheets.
- The advantage:
  - They give you a good feeling of the parameter inter-dependencies.
- Other than that:
  - Cumbersome.
  - Error prone.
  - Not very flexible.
  - First order approximation.
  - Limited number of solutions that can be explored in a short time.

Spreadsheet Approach

Radio & Mixed Signal Innovations

Power and noise figure budget for a WCDMA receiver. 3.84 Mcps TDD Option							
Gain Budget	(Voltage)						
	Switch	RF Filter	LNA	Mixer	LPF	VGA	ADC
Minimum/Nominal Voltage Gain (dB)	-0,5	-3	10	8	-3	6	0
Maximum Voltage Gain (dB)	-0,5	-3	25	8	-3	45	0
Cumulative Minimum/Nominal Voltage Gain (dB)	-0,5	-3,5	6,5	14,5	11,5	17,5	**17,5**
Cumulative Maximum Voltage Gain (dB)	-0,5	-3,5	21,5	29,5	26,5	71,5	**71,5**
Minimum/Nominal Linear Voltage Gain	0,944060876	0,7079458	3,1622777	2,511886	0,707946	1,995262	1
Maximum Linear Voltage Gain	0,944060876	0,7079458	17,782794	2,511886	0,707946	177,8279	1
Cumulative Minimum/Nominal Linear Voltage Ga	0,944060876	0,6683439	2,113489	5,308844	3,758374	7,498942	7,498942
Cumulative Maximum Linear Voltage Gain	0,944060876	0,6683439	11,885022	29,85383	21,13489	3758,374	3758,374
Minimum/Nominal Linear Power Gain	0,891250938	0,5011872	10	6,309573	0,501187	3,981072	1
Maximum Linear Power Gain	0,891250938	0,5011872	316,22777	6,309573	0,501187	31622,78	1
Noise Budget	(Power)						
	Switch	RF Filter	LNA	Mixer	LPF	VGA	ADC
Noise Figure (dB) for Min Gain	0,5	0,5	3	18	25	30	30
Noise Figure (dB) for Max Gain	0,5	0,5	1,5	18	25	15	30
Input Referred NF (dB) Min/Nom Gain	**20,68416095**	20,184161	17,22036	27,06138	34,48734	30,97236	30
Input Referred NF (dB) Max Gain	**4,835022867**	4,3350229	2,5467953	20,89021	25,76792	15,00434	30
Noise Factor f for Min Gain	1,122018454	1,1220185	1,9952623	63,09573	316,2278	1000	1000
Noise Factor f for Max Gain	1,122018454	1,1220185	1,4125375	63,09573	316,2278	31,62278	1000
Input Referred Noise Factor for Min/Nom Gain	117,0620419	104,33165	52,727352	508,3209	2810,181	1250,937	1000
Input Referred Noise Factor for Max Gain	3,04440402	2,7133279	1,797544	122,7497	377,3913	31,65437	1000

Spreadsheet Approach

Radio & Mixed Signal Innovations

Power and noise figure budget for a WCDMA receiver. 3.84 Mcps TDD Option							
Gain Budget	**(Voltage)**						
	Switch	**RF Filter**	**LNA**	**Mixer**	**LPF**	**VGA**	**ADC**
Minimum/Nominal Voltage Gain (dB)	-0,5	-3	10	8	-3	6	0
Maximum Voltage Gain (dB)	-0,5	-3	20	8	-3	45	0
Cumulative Minimum/Nominal Voltage Gain (dB)	-0,5	-3,5	6,5	14,5	11,5	17,5	**17,5**
Cumulative Maximum Voltage Gain (dB)	-0,5	-3,5	16,5	24,5	21,5	66,5	**66,5**
Minimum/Nominal Linear Voltage Gain	0,944060876	0,7079458	3,1622777	2,511886	0,707946	1,995262	1
Maximum Linear Voltage Gain	0,944060876	0,7079458	10	2,511886	0,707946	177,8279	1
Cumulative Minimum/Nominal Linear Voltage Ga	0,944060876	0,6683439	2,113489	5,308844	3,758374	7,498942	7,498942
Cumulative Maximum Linear Voltage Gain	0,944060876	0,6683439	6,6834392	16,78804	11,88502	2113,489	2113,489
Minimum/Nominal Linear Power Gain	0,891250938	0,5011872	10	6,309573	0,501187	3,981072	1
Maximum Linear Power Gain	0,891250938	0,5011872	100	6,309573	0,501187	31622,78	1
Noise Budget	**(Power)**						
	Switch	**RF Filter**	**LNA**	**Mixer**	**LPF**	**VGA**	**ADC**
Noise Figure (dB) for Min Gain	0,5	0,5	3	18	25	30	30
Noise Figure (dB) for Max Gain	0,5	0,5	1,5	18	25	15	30
Input Referred NF (dB) Min/Nom Gain	**20,68416095**	20,184161	17,22036	27,06138	34,48734	30,97[illegible]36	30
Input Referred NF (dB) Max Gain	**6,909150743**	6,4091507	4,199615	20,89021	25,76792	15,00434	30
Noise Factor f for Min Gain	1,122018454	1,1220185	1,9952623	63,09573	316,2278	1000	1000
Noise Factor f for Max Gain	1,122018454	1,1220185	1,4125375	63,09573	316,2278	31,62278	1000
Input Referred Noise Factor for Min/Nom Gain	117,0620419	104,33165	52,727352	508,3209	2810,181	1250,937	1000
Input Referred Noise Factor for Max Gain	4,908118891	4,3743656	2,6300349	122,7497	377,3913	31,65437	1000

Ayayay...!

Noise figure

The noise figure measures how much the SNR degrades as the signal passes through a system.

The noise factor of each block can be defined as:

$$nf = \frac{(SNR)_i}{(SNR)_o}$$

Which expressed in dB turns into the noise figure:

$$NF = 10 \cdot \log(nf)$$

Noise figure of cascaded stages

- Friis equation[1] defines the noise factor of cascaded stages as:

$$nf = 1 + (nf_1 - 1) + \frac{nf_2 - 1}{A_{p_1}} + \cdots + \frac{nf_m - 1}{A_{p1} \cdots A_{p_{m-1}}}$$

- A high front-end gain is desirable from the noise figure standpoint.

[1]Friis equation is a first order approximation. It is incomplete for cascaded stages where frequency translation is performed (it doesn't consider the noise of the image band).

Lineary of cascaded stages

- For cascaded stages, the overall linearity is:

$$\frac{1}{IIPk^2} = \frac{1}{IIPk_1{}^2} + \frac{A_1}{IIPk_2{}^2} + \ldots + \frac{A_1 \cdots A_{m-1}}{IIPk_m{}^2}$$

- A low front-end gain is desirable from the linearity standpoint.

ADC Dynamic Range

- The dynamic range of the ADC will be:

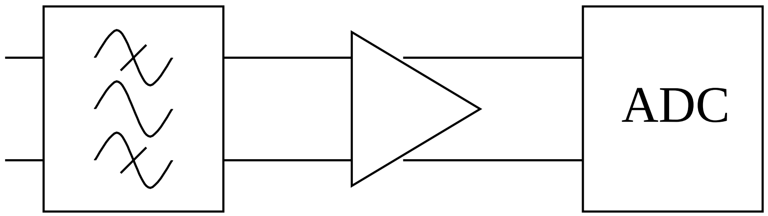
$$DR_{ADC} = P_{\max} - P_{noise} + M$$

- It is related to the effective number of bits as:

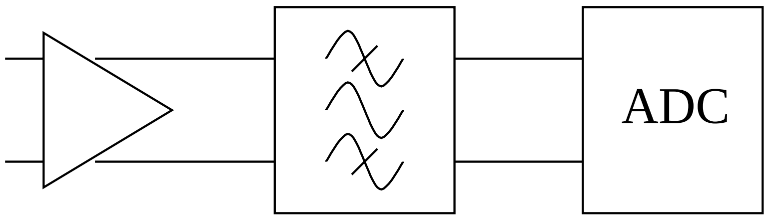
$$ENOB_{ADC} = \frac{DR_{ADC} - 1.76}{6.02}$$

The block order is not conmutative

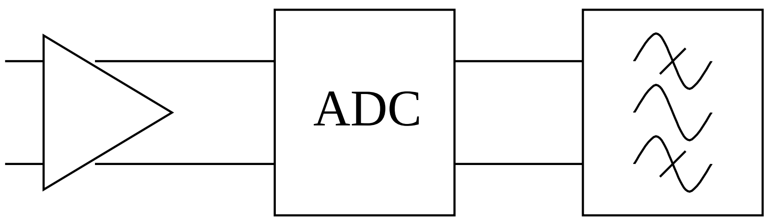
1. Relaxed amplifier linearity, moderate ADC DR, tough on the noise performance.



2. Relaxed filter noise performance, moderate ADC DR, tough on the amplifier linearity.



3. Tough amplifier linearity, tough ADC DR and linearity, digital filtering.



Some trade offs

- Noise and linearity performace impose opposite conditions in the gain distribution!!!
- The order in which amplification, filtering and A/D conversion are carried out has an enormous impact on:
  - The specs of the individual Rx blocks
  - The overall Rx performance.
- Analog-digital partitioning: where do we make the cut?
- How much filtering in the analog domain?

(Semi) Automated approaches

- There is a number of tools that provide some automation in the Trx budget evaluation.
- Most of them focus on analysis[1] $\Rightarrow$ The engineer still has to “design” the budget.
- The ones that help in the design process[2] address only the single-standard case.

1 ADS, Systemvue, WhatIF, SPECTRASYS, Ansoft, etc.
2. ORCA

Objective of our Budget Tool

Finding a multi-standard receiver budget that meets or exceeds the specs of the addressed wireless standards while keeping the requirements of each of the receiver blocks as relaxed as possible.

TACT

What is TACT?

TACT is a multi-standard RF transceiver architecture comparison tool. It allows for a fast system level design of chipsets suitable for multi-standard 4G wireless systems.

Why a tool like TACT?

Evaluating and comparing the feasibility and performance of different Trx implementations at an early design stage is key in obtaining an optimal design with a fast time-to-market.

TACT description

- TACT is an open, user friendly MATLAB/Simulink based tool.
- It automates the process of design space exploration and comparison of different Trx blocks and architectures.
- The performance metrics of the tool are based on a set of cost functions:
  - Area
  - Power consumption
  - Noise Figure
  - Local Oscillators Phase Noise
  - Linearity
  - Dynamic range
  - Availability of already designed/tested IP blocks

General Considerations & Applications

General Considerations:

- TACT tools are organized in a hierarchical way.
- They can be used separately or following TACT's design flow.
- To take advantage of this hierarchical approach, the search space should be larger in the first steps of the design.

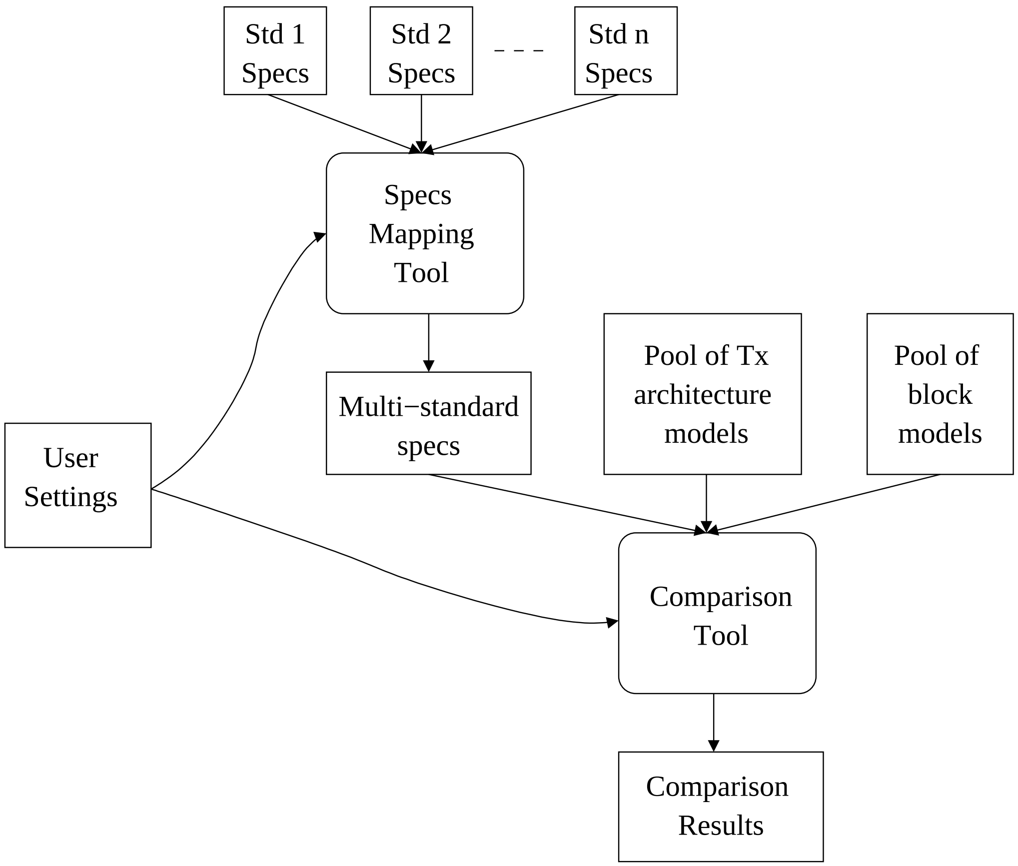
Applications

- Help engineers design, optimize and understand the budget design of multi-standard transceiver in:
  - Education.
  - Industry.
  - Research.

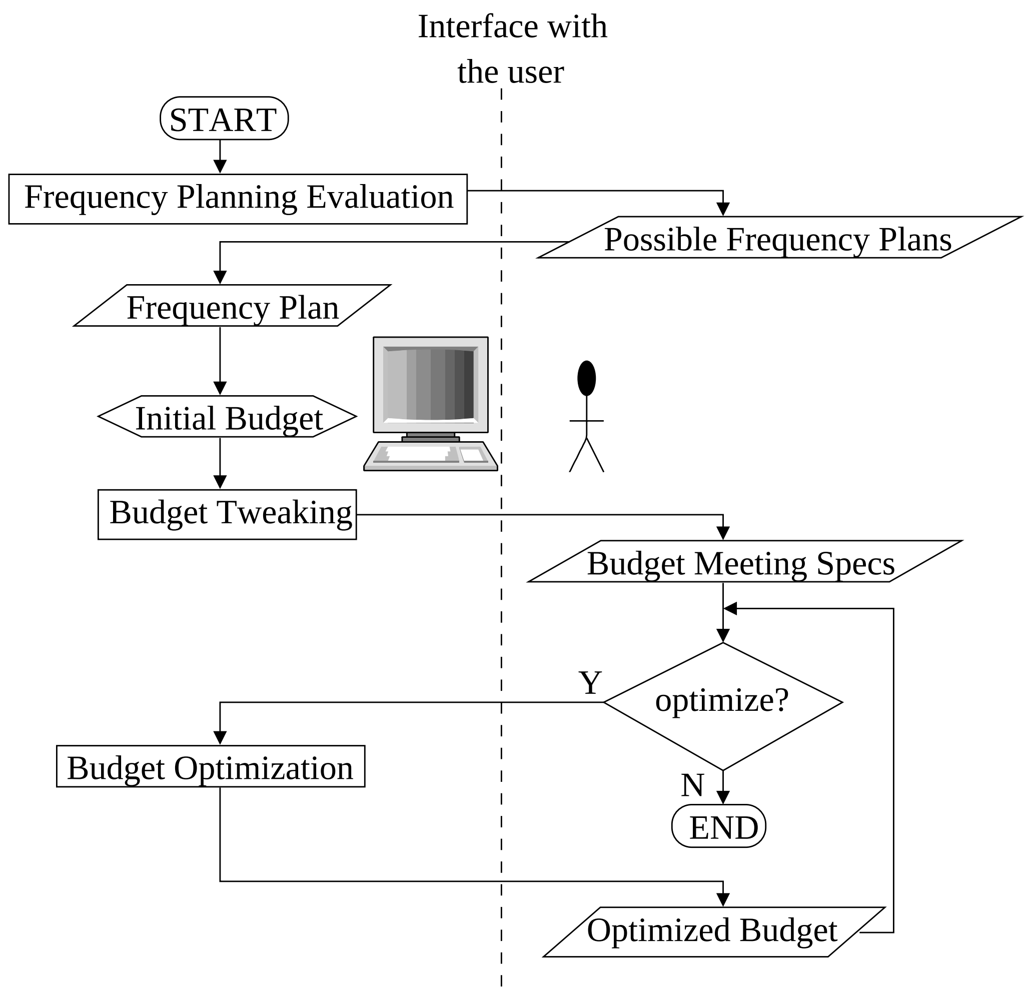
Our approach

- TACT is a very high level tool.
- Our approach is to:
  - Use TACT to design the multi-band multi-standard transceiver at high level.
  - Instantiate already available tools to refine the design.

TACT Components



The Comparison Tool



Summary of the Algorithm

```
while specs_met == false
    if gain_redistrib_needed == true
      redistribute_gain;
    else % gain redistribution not needed
     if rand ¡ p % change it anyway sometimes
        redistribute_gain;
     else
       redistribute_params_not_meeting_specs;
     end;
    end;
    cost = check_specs;
    if cost ¡ specs
     specs_met = true;
    end;
    if cost ¡ best_cost
     best_budget = this_budget;
    end;
end;
```

Impact Oriented Parameter Distribution: NF

Current overall NF
Desired NF increment

Nf margin
Gain Setting
Current NF

$$\Delta = \Delta_1 + \frac{\Delta_2}{A_1} + \cdots + \frac{\Delta_m}{A_1 \cdots A_{(m-1)}}$$

Parameter	RF filter	LNA	Mixer	IF filter	VGA
nf max	10	[illegible]	[illegible]	[illegible]	1000
nf min	1.26	[illegible]	[illegible]	[illegible]	3.16
Ai	0.36	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	6.38	2.26	[illegible]
[illegible]			4.17		
[illegible]			0.23		
δi	0.29	0.29	3.21	0.26	33.12
χ_i	0.29	0.79	0.13	0.002	0.83
χ'_i	0.14	0.38	0.06	9.7e-4	0.4
Δi	0.032	0.032	0.35	0.03	3.69
new nf	1.517	1.517	6.02	2.23	32.6
new ov. nf	3.94				

Impact Oriented Parameter Distribution: NF

$$nf = 1 + (nf_1 - 1) + \frac{nf_2 - 1}{A_1} + \cdots + \frac{nf_m - 1}{A_1 \cdots A_{(m-1)}}$$

$$\chi_i = \begin{cases} \delta_1 & \text{if } i = 1 \\ \frac{\delta_i}{A_1 \cdots A_{i-1}} & \text{if } i \neq 1 \end{cases}$$

$$\chi'_i = \frac{\chi_i}{\sum_i \chi_i}$$

$$\Delta_i = \begin{cases} \Delta \cdot \chi'_1 & \text{if } i = 1 \\ \Delta \cdot \chi'_i \cdot A_1 \cdots A_{i-1} & \text{if } i \neq 1 \end{cases}$$

Margin for change = current NF – NF min

Impact of the cha

Relative impact o

Increment of NF_i

Parameter	RF filter				
		1.26	3.16	1.99	3.16
		65.8	5.5	0.3	5e+5
		1.5	6.38	2.26	36.3
χ_i	0.29				
χ'_i	0.14				
Δi	0.032	0.032	0.35	0.03	3.69
new nf	1.517	1.517	6.02	2.23	32.6
new ov. nf	3.94				

Impact Oriented Parameter Distribution: NF

$$nf = 1 + (nf_1 - 1) + \frac{nf_2 - 1}{A_1} + \cdots + \frac{nf_m - 1}{A_1 \cdots A_{(m-1)}}$$

Parameter	RF filter	LNA	Mixer	IF filter	VGA
nf max	10	10	100	10	1000
n[illegible]	[illegible]	[illegible]	[illegible]	1.99	3.16
A_i	[illegible]	[illegible]	[illegible]	0.3	5e+5
current nf	1.55	1.5	6.38	2.26	36.3
overall nf			4.17		
Δ			0.23		
δi	[illegible]	0.2[illegible]	[illegible]	[illegible]	[illegible]
χ_i	0.29	0.7[illegible]	[illegible]	[illegible]	[illegible]
χ'_i	0.14	0.38	0.06	9.7e-4	0.4
Δi	0.032	0.032	0.35	[illegible]	[illegible]
new nf	1.517	1.517	6.02	2.25	32.6
new ov. nf			3.94		

Randomized

New NF_i = Old NF_i - Δ_i

New NF = Old NF - Δ

Impact Oriented Parameter Distribution: Linearity

- Similar method for the linearity distribution:

$$IP_{3new} = \mu IP_3$$

$$\frac{1}{IP_3^2} - \frac{1}{IP_{3new}^2} = \frac{1}{IP_3^2} - \frac{1}{\mu^2 IP_3^2} = \frac{\mu^2 - 1}{\mu^2 IP_3^2} =$$

$$\frac{\mu_1^2 - 1}{\mu_1^2 IP_{3,1}^2} + A_1 \frac{\mu_2^2 - 1}{\mu_2^2 IP_{3,2}^2} + \cdots + A_1 \cdots A_{n-1} \frac{\mu_n^2 - 1}{\mu_n^2 IP_{3,n}^2}$$

Which can be rewritten as:

$$\frac{1}{\eta} = \frac{1}{\eta_1} + \frac{A_1}{\eta_2} + \cdots + \frac{A_1 \cdots A_{n-1}}{\eta_n}$$

where

$$\frac{1}{\eta_i} = \frac{\mu_i^2 - 1}{\mu_i^2 IP_{3,i}^2}$$

Gain, DR_{ADC} and Filtering

- The ADC requirements are set by the characteristics of the signals at its input.
- These are closely related with the gain distribution and the filtering profile of the receiver.
- Depending on
  - the absolute signal levels
  - the signals determining the dynamic range of the ADC

  there will be changes on:
  - The gain profile and Automatic Gain Control (AGC) ranges.
  - The filtering profile
  - Both

Radio & Mixed Signal Innovations

Example: WCDMA/WLAN Multi-standard Receiver

RF Specs

Radio & Mixed Signal Innovations

Summary of the WCDMA (TDD) and WLAN (802.11b) RF specifications.

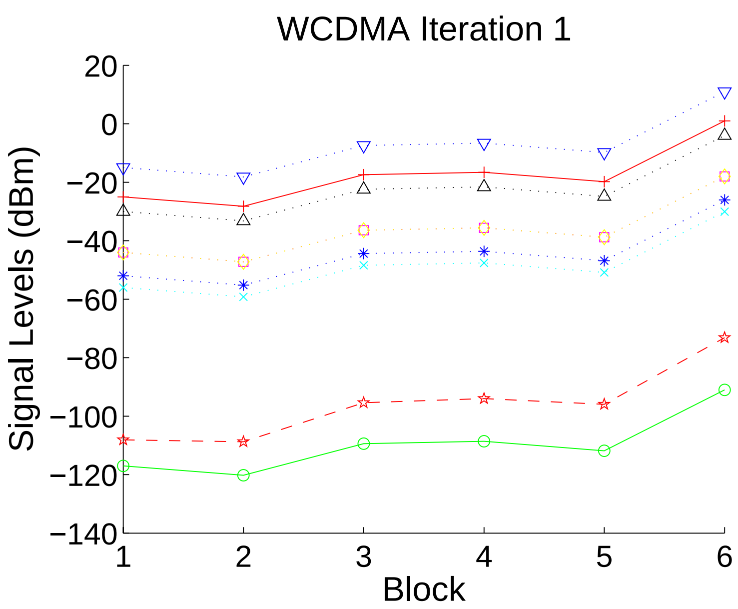
Parameter	**WCDMA**	**WLAN**
RF Frequency Band	2010-2025 MHz 1900-1910 MHz	2400-2485 MHz
RF Channel Bandwidth	3.84 MHz	20 MHz
Channel Separation	5 MHz	5/25 MHz
Sensitivity	-117 dBm	-76 dBm
Max Power Level	-25 dBm	-10 dBm
Adjacent Ch. Selectivity	33 dB	35 dB

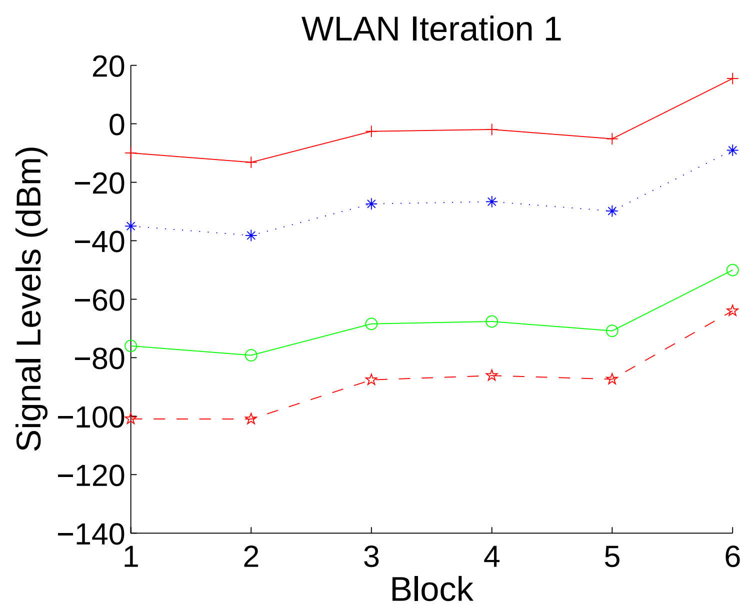
Receiver Specs

Summary of the receiver specs for WCDMA (TDD) and WLAN (802.11b).

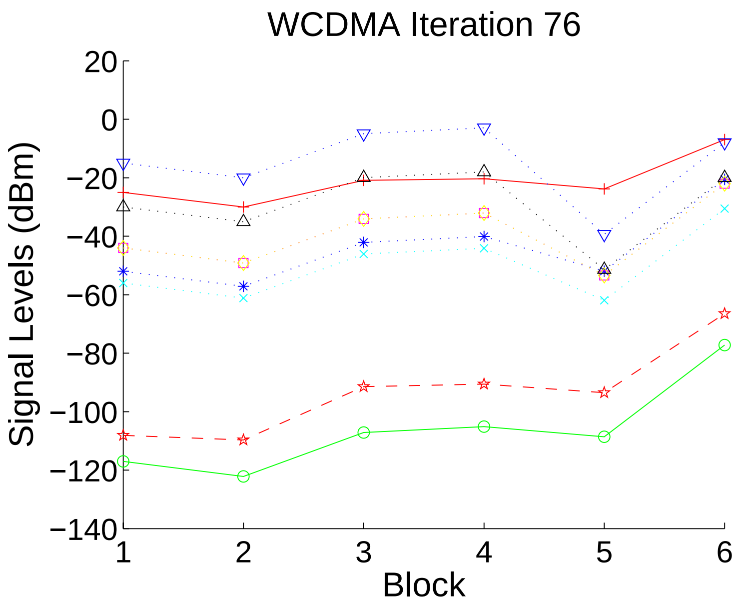
Parameter	WCDMA		WLAN	
NF	9	dB	11	dB
IIP3	-17	dBm	-5	dBm
IIP2	14	dBm	23	dBm
Phase Noise	-120 -126 -139 -136	dBc/Hz@5MHz dBc/Hz@10MHz dBc/Hz@15MHz dBc/Hz@20MHz	-123	dBc/Hz@5MHz

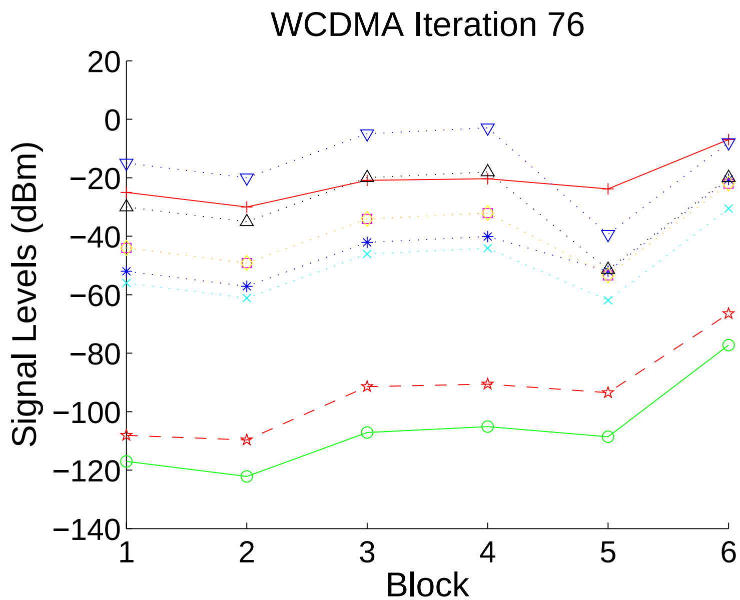
Evolution of the Budget



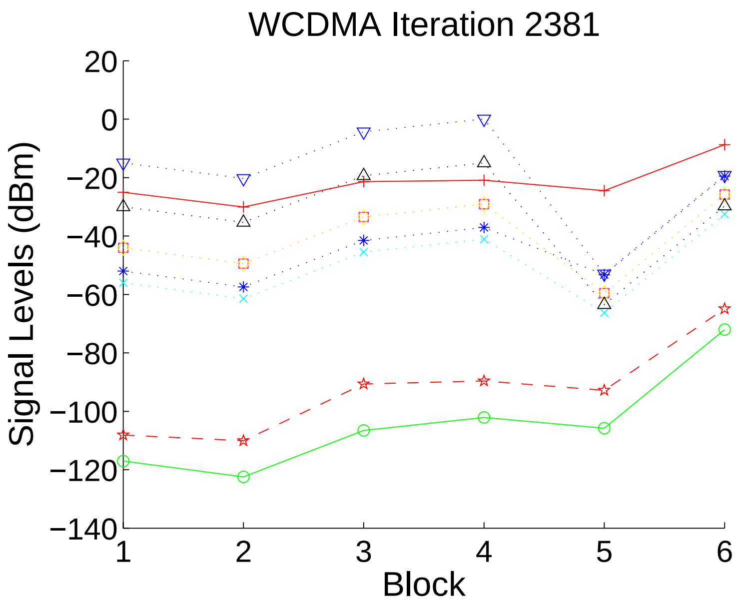


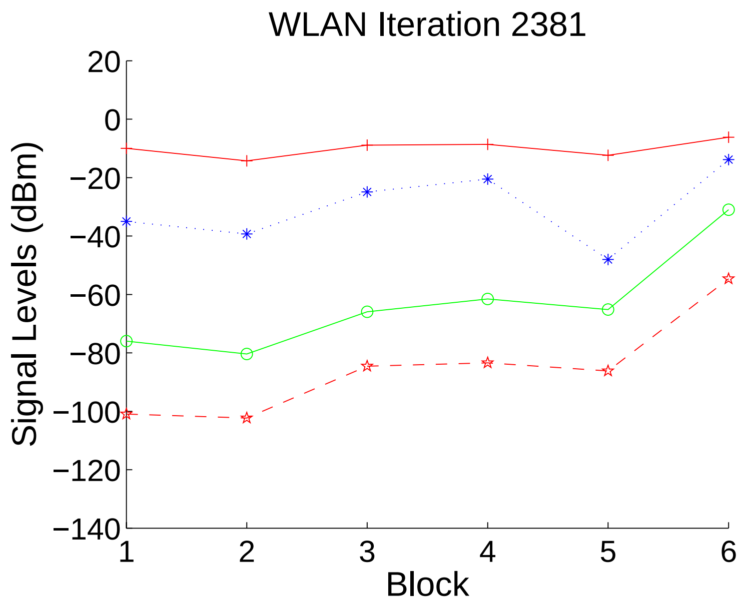
Evolution of the Budget



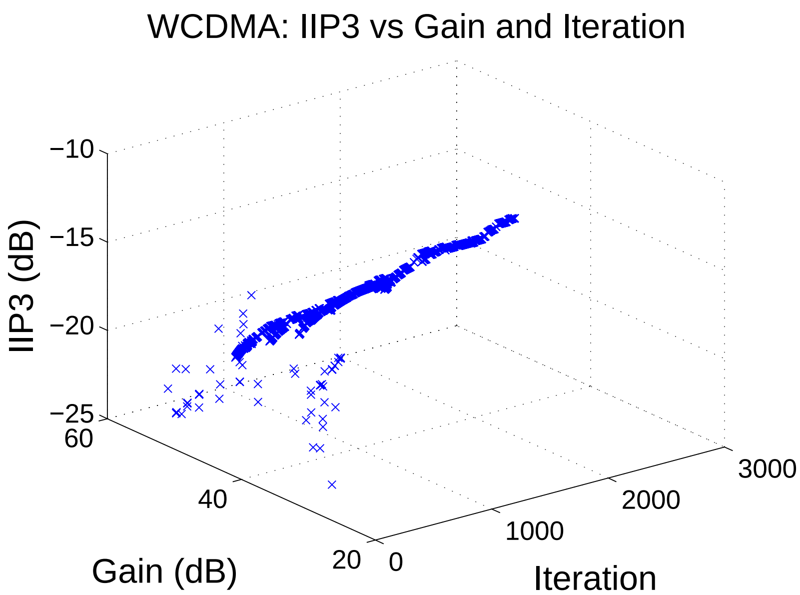


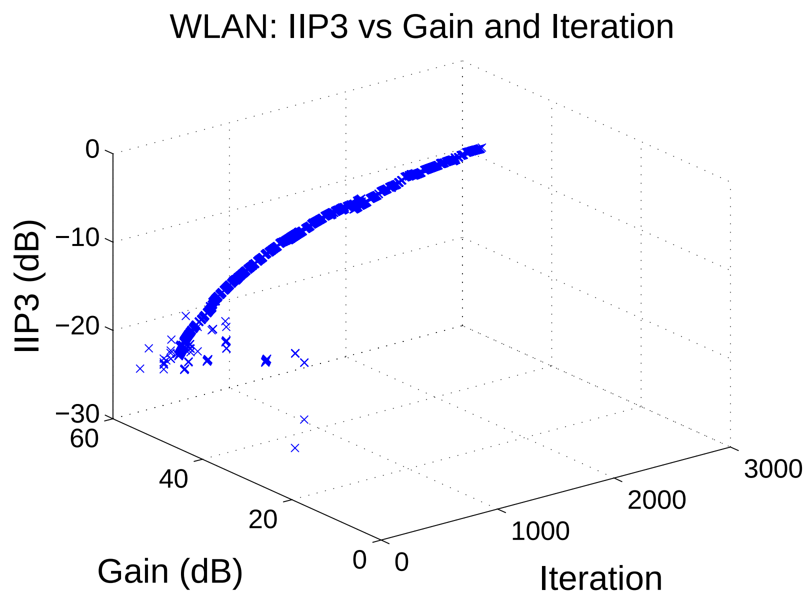
Evolution of the Budget





Evolution of the Budget





Performance Summary

Summary of the performance of the proposed WCDMA (TDD) / WLAN (802.11b) receiver.

	WCDMA		**WLAN**	
Parameter	Specs	Sim. Result	Specs	Sim. Result
Gain	-	48.38 dB	-	53.12 dB
DR_{ADC}	60 dB	58.65 dB (9.45 bits)	40 dB	39.11 dB (6.2 bits)
NF	9 dB	5.98 dB	11 dB	6.1 dB
IIP3	-17 dBm	-0.33 dBm	-5 dBm	-2.68
IIP2	14 dBm	29.9 dBm	23 dBm	27.44

Performance Summary

Radio & Mixed Signal Innovations

WCDMA					
Parameter	RF Filter	LNA	Mixer	BB Filter	VGA
Gain	-2.2	16	0.5	-2.3	36
NF	1.4	1.4	6.7	12.4	12
IIP3	34	9.4	14	34	24
IIP2	93	53.93	43	93	53
WLAN					
Parameter	RF Filter	LNA	Mixer	BB Filter	VGA
Gain	-2	18	0.7	-2.2	38
NF	1.8	1.8	7.7	14	15
IIP3	34	9.4	14	34	24
IIP2	93	53	43	93	53

Execution Time

Tmin	Tmax	Tmean	σ
3.07 s	25.45 s	9.69 s	3.73

Conclusions

- Designing a Rx is not an easy task.
- As much automation as possible is needed in order to perform a thorough design space exploration in a short time leading to first pass success and short time-to-market.
- This presentation introduces the budget tool of a multi-standard RF transceiver architecture comparison tool: TACT. The use of TACT eases the design of physical circuits able to be dynamically re-configured.
- Usefulness of TACT as an automated multi-standard receiver design tool shown: WCDMA/WLAN multi-standard receiver designed with TACT presented.

Future Work

- Interfaces with available tools (ADS) are under development and tests with Commercial Off-The-Shelf (COTS) components planned $\Rightarrow$ complete design flow + TACT verification.
- Graphical User Interface (GUI) is under development.
- Implementation of additional optimization algorithms is under study with focus on Genetic Algorithms.

Some References

[1] Ahola, Rami and et al. (2004). ASingle-ChipCMOSTransceiver for 802.11a/b/gWireless LANs. *IEEE Journal of Solid-State Circuits*, 39(12).
[2] Crols, Jan, Donnay, St´ephan, Steyaert, Michiel, and Gielen, Georges (1995). A High-Level Design and Optimization Tool. In *Digest of Technical Papers. IEEE/ACM International Conference on Computer-Aided Design*.
[3] Gielen, Georges G. E. (2002). Modeling and Analysis Techniques for System-Level Architectural Design of Telecom Front-Ends. *IEEE Transactions on Microwave Theory and Techniques*, 50(1).
[4] Hooijmans, Pieter (2006). Architectures for mobile RF convergence and future RF transparency. *RFDESIGN*.
[5] http://www.ansoft.com/. *ANSOFT*.
[6] http://www.eagleware.com/products/genesys/ whatif.html/. *Eagleware Elanix WhatIF*.
[7] http://www.eesof.tm.agilent.com/. *Advance Design System EDA Software (ADS)*.
[8] http://www.nathaniyer.com/. *Cascade*.
[9] Li, Xiaopeng and Ismail, Mohammed (2002). *Multi-standard CMOSWireless Receivers. Analysis and Design*. Kluwer Academic Publishers.
[10] Mattisson, Sven (2006). *Radio Design in Nanometer Technologies*, chapter Cellular RF Requirements and Integration Trends. Springer.
[11] Razavi, Behzad (1998). *RF Microelectronics*. Prentice Hall PTR.
[12] Rodríguez de Llera González, Delia, Rusu, Ana, Ismail, Mohammed, and Tenhunen, Hannu (2005). TACT: A Multi-standard RF Transceiver Architecture Comparison Tool. In *IEEE Midwest Symposium on Circuits and Systems (MWSCAS)*.
[13] Sierra Pérez, Manuel, Galocha Irangüen, Belén, Fernández Jambrina, José Luis, and Sierra Castañer, Manuel (2003). *Electrónica de Comunicaciones*. Pearson, Prentice Hall.
[14] Svensson, Christer and Andersson, Stefan (2006). *Radio Design in Nanometer Technologies*, chapter Software Defined Radio - Visions, Challenges and Solutions. Springer.

Thank you for your attention!