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The challenge of an RF frontend for software defined radio

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Outline

The software defined radio
Radio hardware architecture
Real world constraints
Possible architectures
Conclusions

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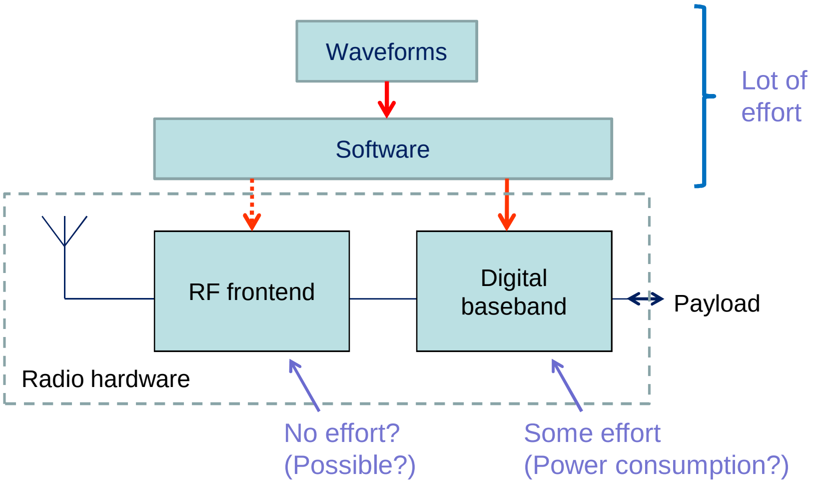
Software defined radio



Waveforms

Software

RF frontend

Digital baseband

Payload

Radio hardware

Lot of effort

No effort? (Possible?)

Some effort (Power consumption?)

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Software defined radio

Waveforms and software need a hardware platform!

Digital part, need GPP+DSP+FPGA – very expensive in power
Solution: application specific DSP

Analog part, many frequency bands, strong disturbers, sensitivity
No complete solution in sight

Worrying view of SDR forum:
“signals are sampled after suitable band selection filter”
What about *suitable band selection filter*?! (Fred Harris 2008)

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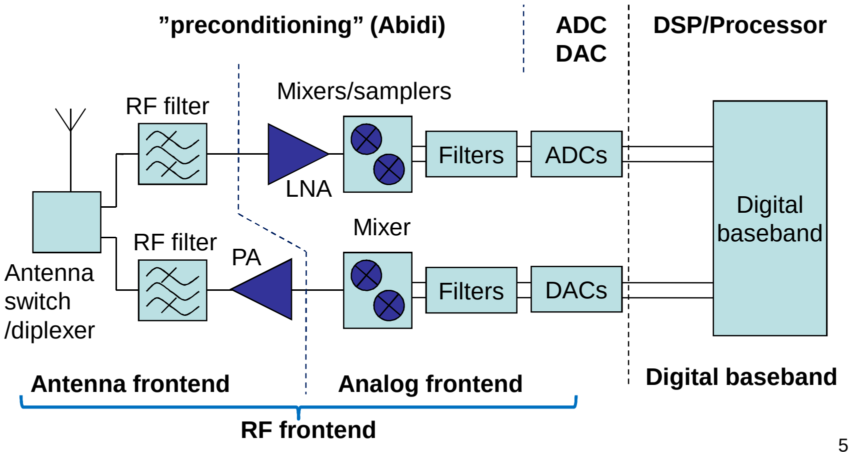
Radio hardware architecture



”preconditioning” (Abidi)

ADC
DAC

DSP/Processor

RF filter

Mixers/samplers

LNA

Filters

ADCs

Digital baseband

Antenna switch /diplexer

RF filter

PA

Mixer

Filters

DACs

Antenna frontend

Analog frontend

Digital baseband

RF frontend

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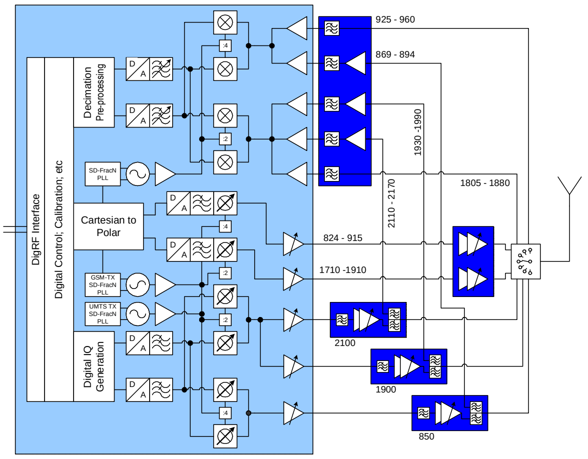
Radio hardware architecture



Example:
A contemporary mobile phone

3 external LNAs
5 external PAs
8 external passive filters
3 external duplex filters

External filters are SAW (mechanical resonators)

Note – just 5 narrow bands

Radio hardware architecture

We will start to discuss receiver

Antenna frontend

Depends on passive filters – No flexible technique available!

Analog frontend

Flexible technique available - also at high performance/ low power
But several problems to be managed

Digital baseband

Flexible technique available – also at high performance/ low power
Very recent developments – application specific DSP

Real world constraints

Unfortunately, we must adapt to reality

We need to receive a ***weak signal*** in presence of a ***strong one***

Best sensitivity – adapt to thermal noise background

Unintentional disturber (broadcast, nearby client, …)
Our own transmitter
Intentional disturber (jammer)

Real world constraints

A disturber transmitting power P_D at distance R with antenna gain G_D give a received (blocker) power in receiver with antenna gain G_r:

$$P_B = \frac{\lambda^2}{16\pi R^2} G_D G_r P_D$$

Where λ is the wavelength ($\lambda = c/f_c$).

A blocker of power P_B gives a peak-to-peak voltage over $R_0 = 50\Omega$ of

$$V_{p-p} = \sqrt{8 P_B R_0}$$

Real world constraints

Best sensitivity – environmental noise at ambient temperature:

Noise spectral density: $S_N = kT$

With a channel bandwidth of B, we require a dynamic range of:

$$DR = \frac{P_B}{S_N B}$$

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Real world constraints

This can be expressed as a ADC requirement of (quantization noise = thermal noise; f_s sampling rate, n bits):

$$f_s 2^{2n} = \frac{4}{3}\frac{P_B}{kT}$$

Theory of ADC power consumption estimates ADC power to about $30P_S$, where P_S is the power needed to sample the signal:

$$P_S = 24kTf_s 2^{2n}$$

(So power is proportional to requirement above!)

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Real world constraints

Unintentional disturbers

TV transmitter, 10kW 400MHz, 300m (mast height), P_B=3.2mW

Nearby transmitter, say 30W, 100MHz, 3m distance, P_B=1600mW

Own transmitter (FDD)

Example 3G mobile, 300mW, if same antenna P_B=300mW

Jammer

100W, 100MHz, 1km, antenna gain G_D=20dB, P_B=2.9mW

(Assumed antenna gains 2dB (λ/2 dipole))

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Real world constraints

Some examples

Blocker	Voltage p-p	ADC power
10µW (-20dBm)	60mV	9.6mW
1mW (0dBm)	0.6V	0.96W
300mW (25dBm)	11V	290W

We can hardly accept more than ~1mW at ADC (ADC power)
(10µW preferred)

We can hardly manage ~300mW by receiver electronics (voltage)

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Real world constraints

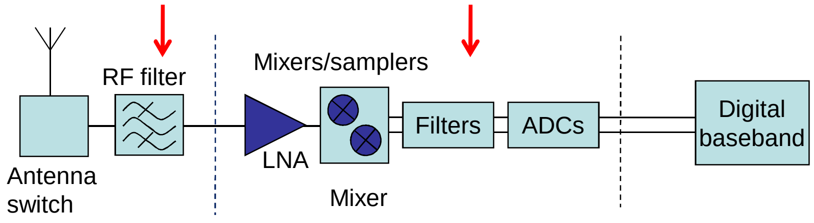
Consequences

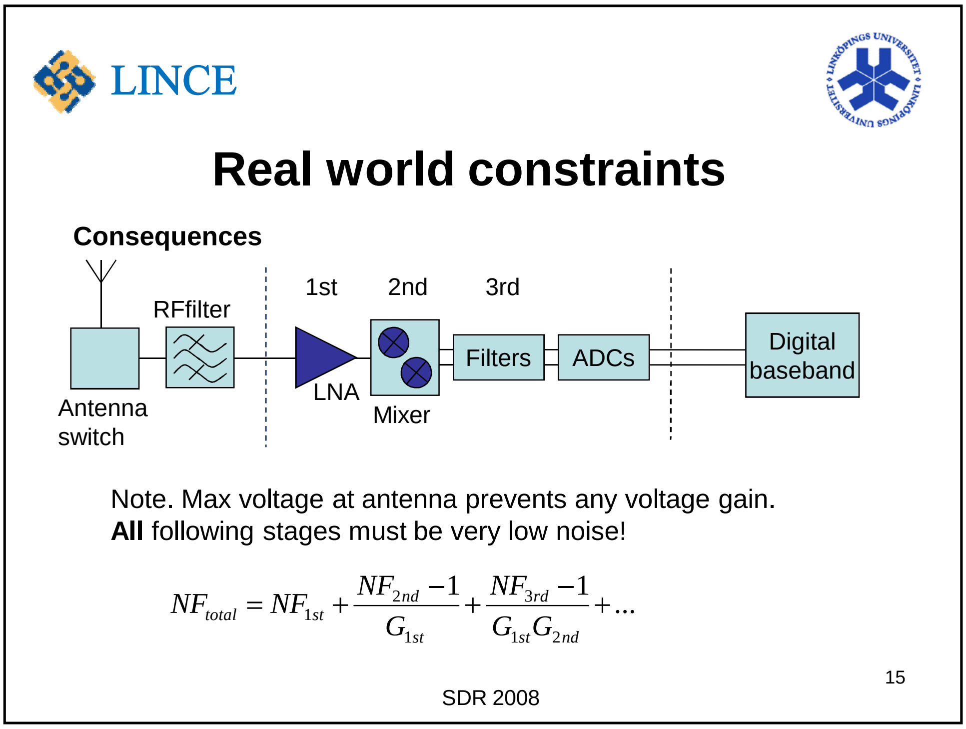
Blockers > 1mW
MUST be stopped here

BUT passive RF filter *unflexible*

Blockers ~1mW
preferably stopped here

(Baseband filter may be fixed)



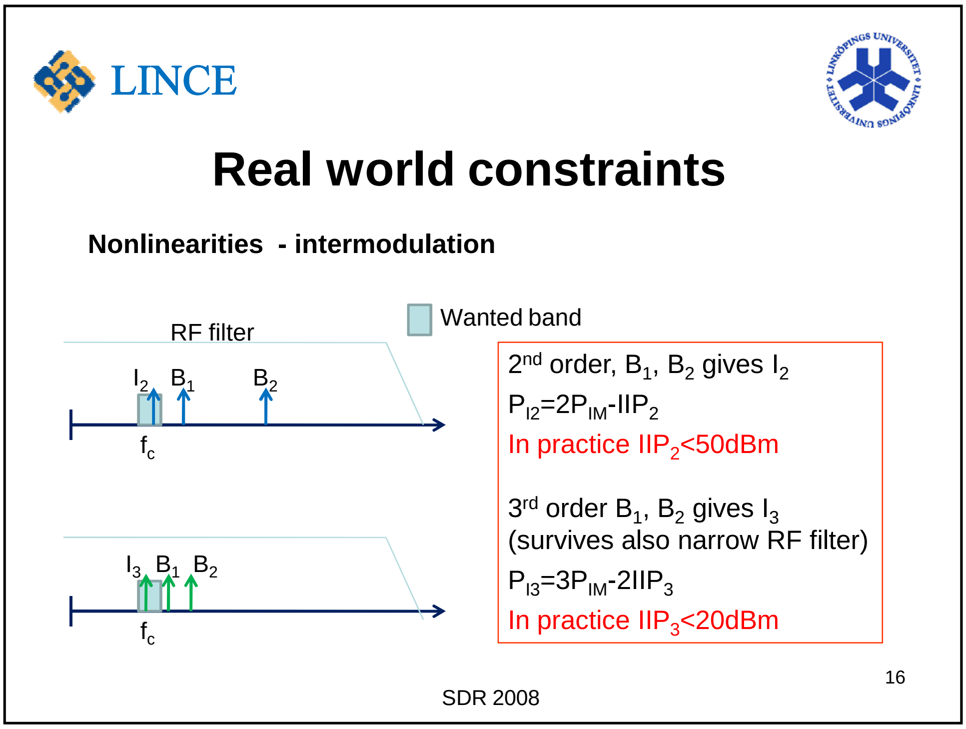


Real world constraints

Consequences

Note. Max voltage at antenna prevents any voltage gain.
All following stages must be very low noise!

$$NF_{total} = NF_{1st} + \frac{NF_{2nd} - 1}{G_{1st}} + \frac{NF_{3rd} - 1}{G_{1st} G_{2nd}} + \dots$$



Real world constraints

Nonlinearities - intermodulation

2^{nd} order, B_1, B_2 gives I_2

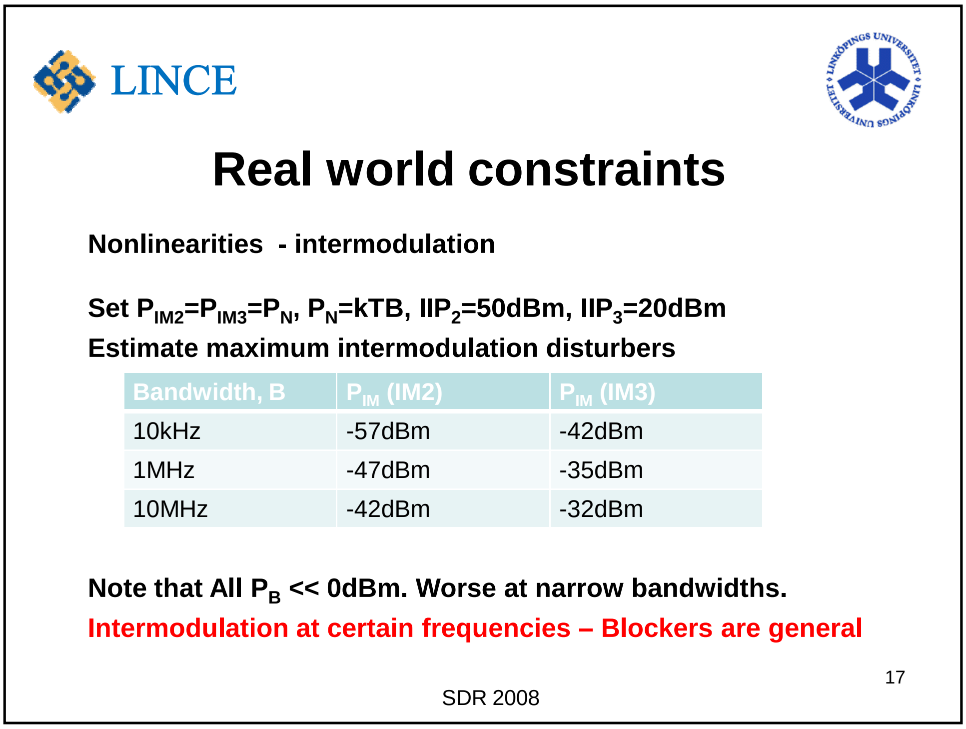
$P_{I2}=2P_{IM}-IIP_2$

In practice $IIP_2<50$dBm

3^{rd} order B_1, B_2 gives I_3
(survives also narrow RF filter)

$P_{I3}=3P_{IM}-2IIP_3$

In practice $IIP_3<20$dBm



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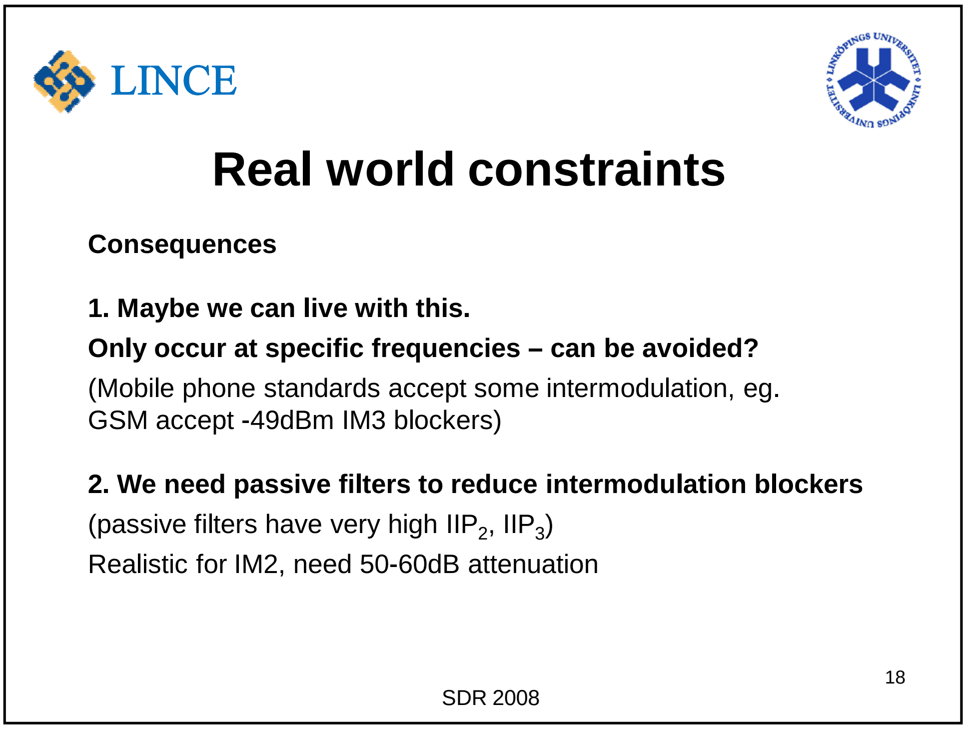
Real world constraints

Nonlinearities - intermodulation

Set $P_{IM2}=P_{IM3}=P_N$, $P_N=kTB$, $IIP_2=50dBm$, $IIP_3=20dBm$
Estimate maximum intermodulation disturbers

Bandwidth, B	P_{IM} (IM2)	P_{IM} (IM3)
10kHz	-57dBm	-42dBm
1MHz	-47dBm	-35dBm
10MHz	-42dBm	-32dBm

Note that All P_B << 0dBm. Worse at narrow bandwidths.
Intermodulation at certain frequencies – Blockers are general



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Real world constraints

Consequences

1. Maybe we can live with this.
Only occur at specific frequencies – can be avoided?
(Mobile phone standards accept some intermodulation, eg.
GSM accept -49dBm IM3 blockers)

2. We need passive filters to reduce intermodulation blockers
(passive filters have very high IIP_2, IIP_3)
Realistic for IM2, need 50-60dB attenuation

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Real world constraints

Conclusions

Application without nearby transmitters or FDD
(example GSM mobile phone, soldier transceiver)

Fully electronic solution possible (needs high linearity)

Application with nearby transmitters or FDD
(examples, 3G mobile phone, military platform transceiver)

Must utilize tunable passive RF filters

Important to specify Blocker, IM2 and IM3 requirements

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Possible architectures

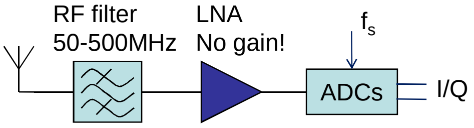
As an example,
we use UHF 50-500MHz

4 cases

1. Blockers <0dBm – direct ADC
2. Blockers <0dBm – upconvering superheterodyne
3. Blockers <0dBm – homodyne / low IF
4. Blockers >0dBm – tunable passive RF filters

Possible architectures 1

Blockers <0dBm – fully flexible.
Fixed RF filter, Nyquist sampling at $f_s>2f_{cmax}$



RF filter
50-500MHz

LNA
No gain!

f_s

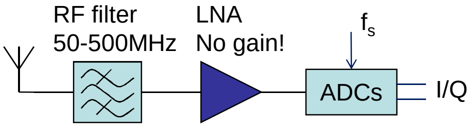
ADCs

I/Q

For f_c=500MHz
we need f_s~2GHz

$f_s 2^{2n}=3.2 \cdot 10^{17}$, with f_s=2GHz we have n=14b

Possible architectures 1



RF filter
50-500MHz

LNA
No gain!

f_s

ADCs

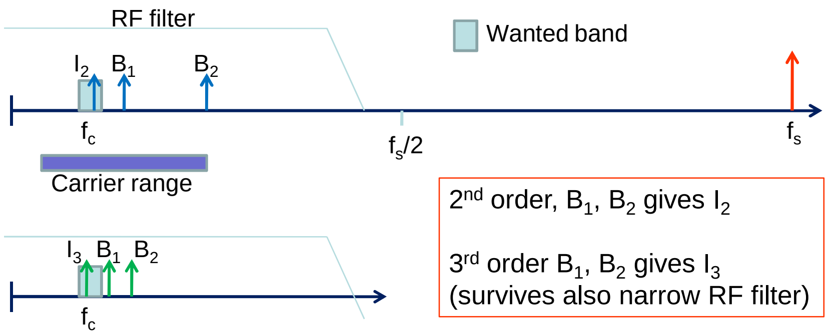
I/Q

Straight-forward ADC: 2GS/s n=14b, not available today, but possible (similar solution proven for 150-160MHz)

Bandpass ΣΔ-ADC possible, 1st order, B=1MHz need 2GS/s n=5b (similar solution demonstrated for f_c=100MHz)

Possible architectures 1

Very high linearity constraints - Intermodulation

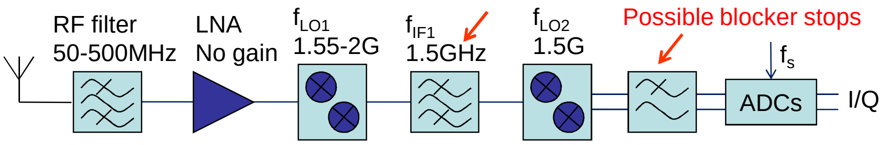


2nd order, B_1, B_2 gives I_2

3rd order B_1, B_2 gives I_3
(survives also narrow RF filter)

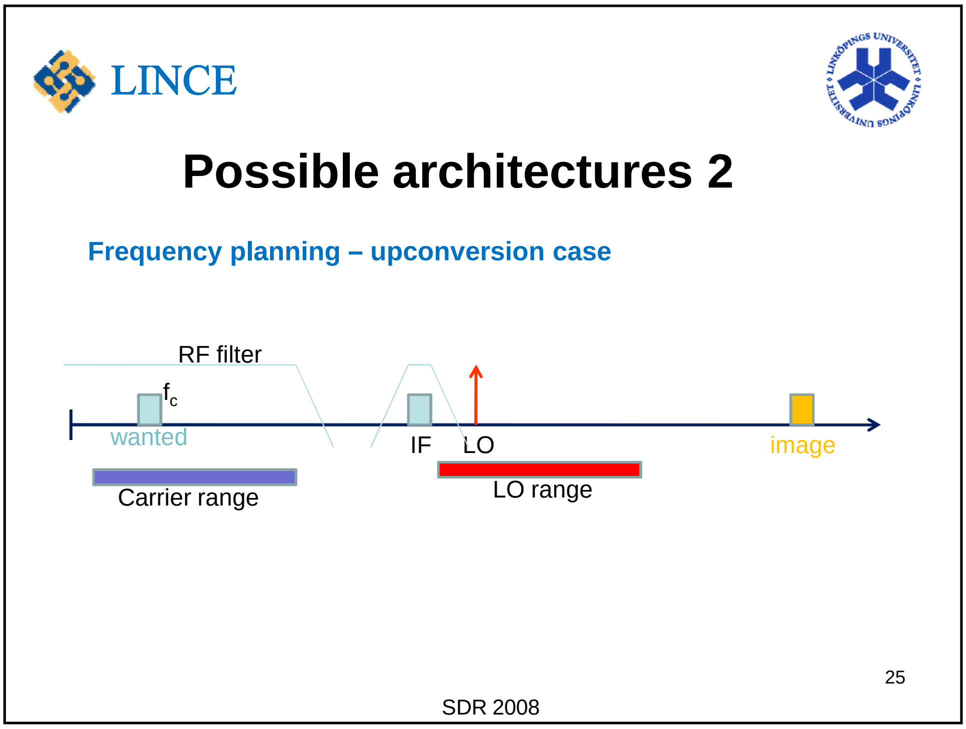
Possible architectures 2

Blockers <0dBm – fully flexible
Fixed RF filter, upconverting superheterodyne ($f_{IF1}>f_{cmax}$)



$f_s 2^{2n}=3.2 \cdot 10^{17}$ as before. We can choose f_s=100MHz gives n=16 (commercially available, eg. 160MS/s 16b 1.45W).
Narrow IF and baseband may remove blockers; much relaxed ADC

Similar solutions are available as TV receivers
50-900MHz, single chip complete receiver, ~1W (but P_{IM}=-10dBm)



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Possible architectures 2

Frequency planning – upconversion case

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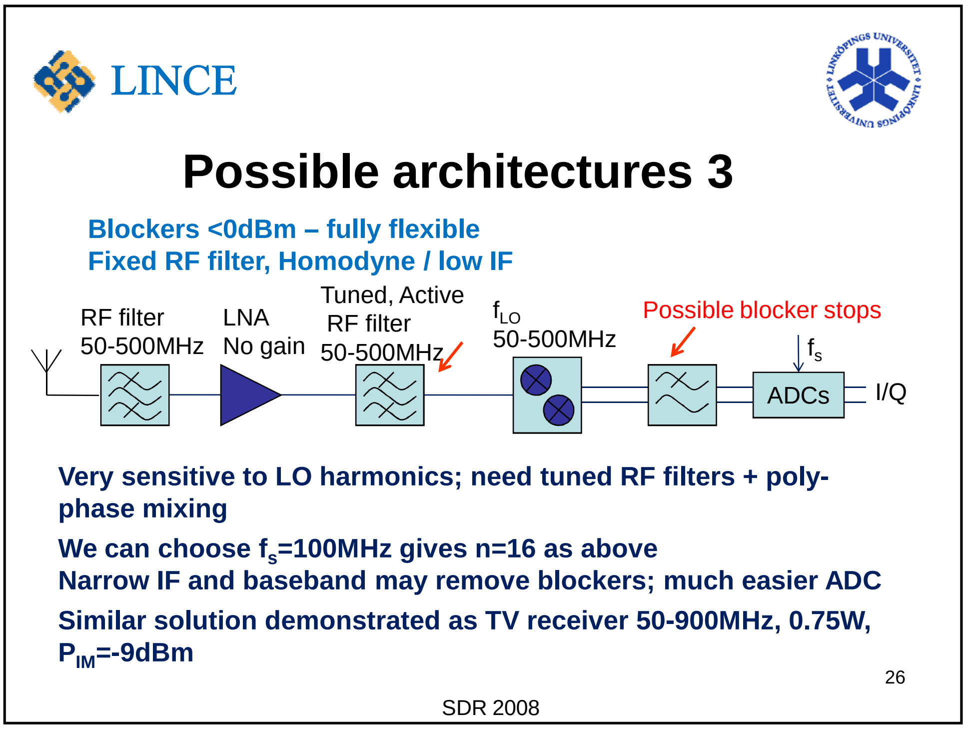

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Possible architectures 3

Blockers <0dBm – fully flexible
Fixed RF filter, Homodyne / low IF

Very sensitive to LO harmonics; need tuned RF filters + poly-phase mixing

We can choose f_s=100MHz gives n=16 as above
Narrow IF and baseband may remove blockers; much easier ADC

Similar solution demonstrated as TV receiver 50-900MHz, 0.75W, P_{IM}=-9dBm

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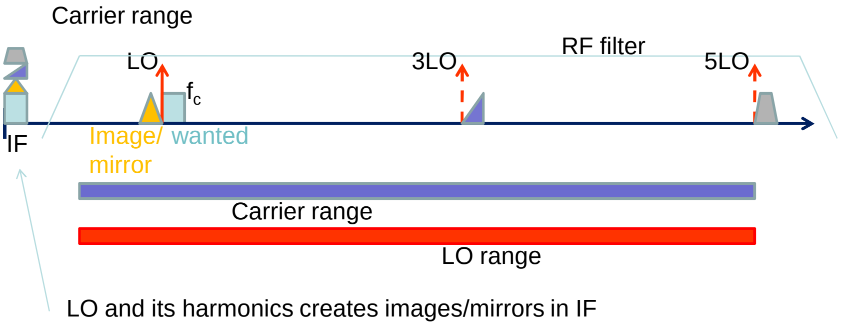
Possible architectures 3

Frequency planning – homodyne/low IF case



LO and its harmonics creates images/mirrors in IF

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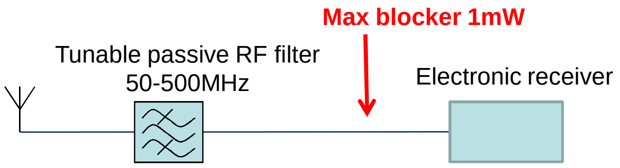
Possible architectures 4

Blockers >0dBm – tunable passive RF filters



Tunable passive filter (only passive technique can manage >1V)

1) **Filter bank with switches (large, switch attenuation)**
   (50-500MHz may need 7 half octave filters)
2) **Electronically tunable (need large control voltages; not available)**

Possible architectures 4

Tunable passive RF filters – possible technologies

Filter bank with switches

Fixed filters based on mechanical resonators, SAW, BAW, MEMS
Fixed filters based on lumped elements, stripline or waveguide resonators
Switches based on transistors or diodes
Switches based on MEMS

Electronically tunable filters

MEMS variable capacitors
Electromechanically tuned resonators

Radio hardware architecture

Transmitters

Antenna frontend and power amplifier (PA)

Depends on passive filters – No flexible technique available!

Analog frontend

Flexible technique available - also at high performance/ low power

Digital baseband

Flexible technique available – also at high performance/ low power
Application specific DSP

Possible architecures

Transmitter constraints:

High power, 300mW – 30W, requires voltages of 11-110V @50Ω
May require special technology (except possibly 300mW – soldier radio)

Low spurious content

High efficiency
Particularly tough at advanced modulation
(including non-constant envelope)

Possible architecures

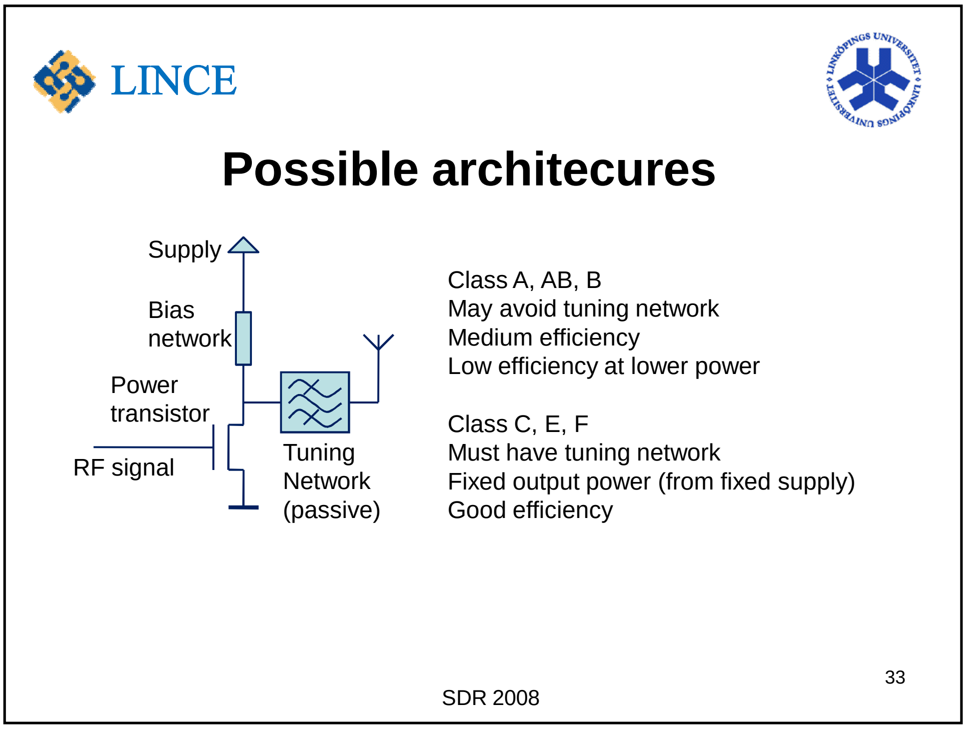
Class A, AB, B
Limited efficiency, normally utilize passive filters

Class C
Good efficiency, requires passive filter, constant envelope

Class D
Very good efficiency possible, normally utilize passive filter, constant envelope

Class E, F
Very good efficiency, require passive filters, constant envelope

Class C, D, E, F combined with outphasing or polar architecture
Good efficiency also with non-constant envelope



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Possible architecures

Supply

Bias
network

Power
transistor

RF signal

Tuning
Network
(passive)

Class A, AB, B
May avoid tuning network
Medium efficiency
Low efficiency at lower power

Class C, E, F
Must have tuning network
Fixed output power (from fixed supply)
Good efficiency

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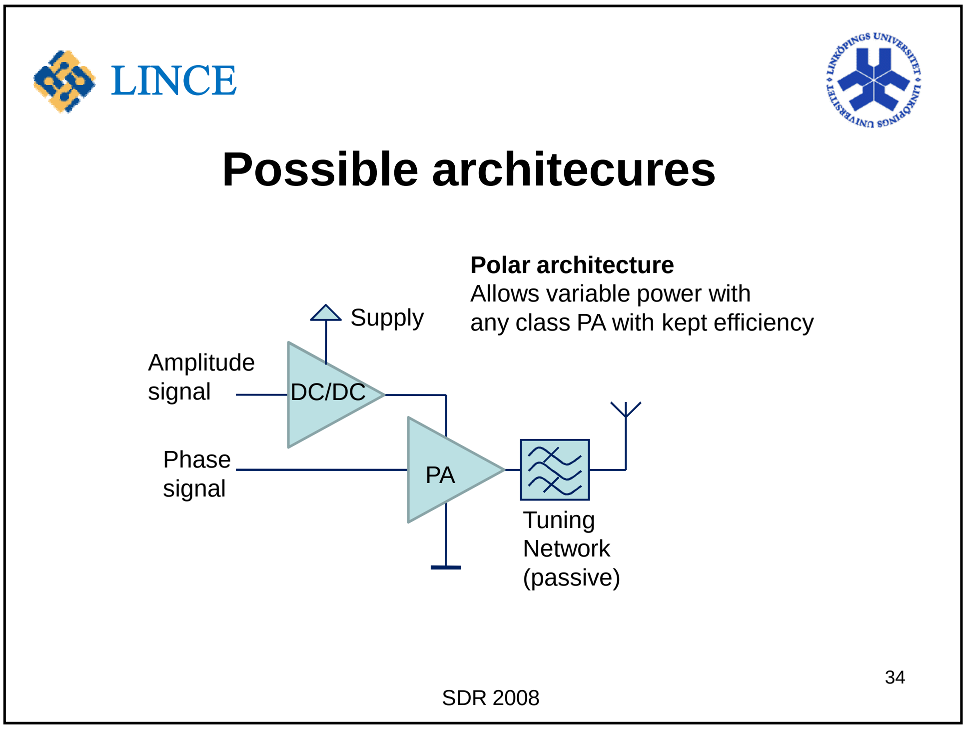

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Possible architecures

Polar architecture
Allows variable power with
any class PA with kept efficiency

Supply

Amplitude
signal

DC/DC

Phase
signal

PA

Tuning
Network
(passive)

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Possible architectures

Conclusions

All known PAs utilize narrow passive filters.
For SDR these needs to be tuneable, but no technology available
Possible solution: MEMS capacitors

Class A, AB may manage without narrow filters – limited efficiency

Class D may manage without narrow filters – good efficiency

Conclusions

RF frontends are the most challenging part for SDR

Problems related to radio basics – not to waveforms

No technology available today for the most demanding requirements

>0dBm disturbers

Need tunable passive filters or switched passive filter banks

A “soldier radio” may be designed using available technology

≤ 0dBm disturbers

Challenges: appropriate receiver architecture (learn from TV tuners)
receiver dynamic range and linearity
low power digital baseband (application specific DSP)
appropriate PA technology