INF5490 RF MEMS

L16: Wireless systems using RF MEMS

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INF5490: topics

- ”RF MEMS”
  - → 2 parts: **RF** and **MEMS**
  - Description and modeling of MEMS components in focus

- This lecture:
  - **MEMS components used in RF systems**

Today’s lecture

- Wireless communication
- Different principles for RF transmission

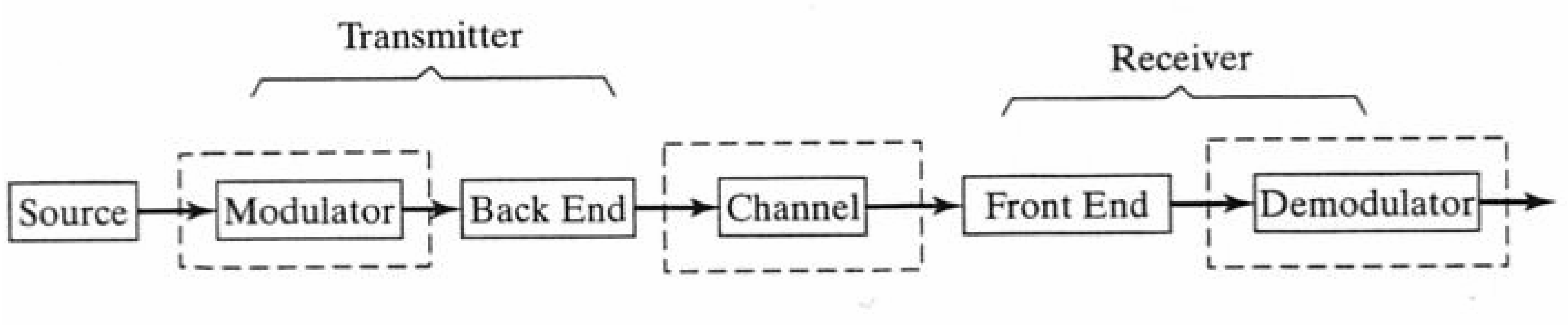
- Technology and components used today

- Transceiver with RF MEMS
  - ”RF **receiver** front-end” architecture
  - **Transmitter** architecture
- Relevant research topics

RF-systems

- RF is essential for wireless communication
  - Radio waves used for transmitting/receiving
    - Electromagnetic waves (Maxwell´s equations)
- Radio **”transceiver”** is a basic component
  - Transmitter + Receiver
- RF systems must
  - Transfer **power** at a specific **frequency**
  - Use a limited **bandwidth**
- **Filtering** needed to separate channels

General communication system



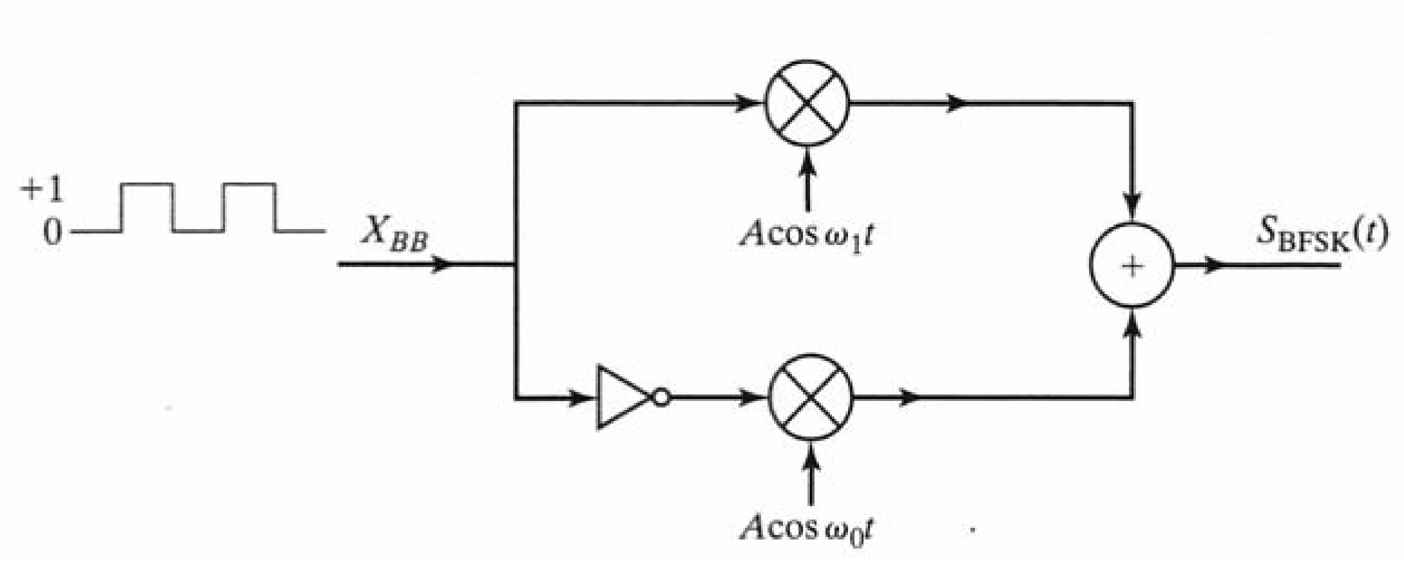
Bit streams are modulated (coded) onto a **carrier**

Radio channel introduces noise, interference, disturbances

Receiver shapes the signal for demodulation

Different coding principles

- Many different modulation schemes exist
  - F.ex. **BFSK, Binary Frequency Shift Keying**
  - Transfering digital data
  - Coding bits to 2 different frequencies (Tb is bit-duration)

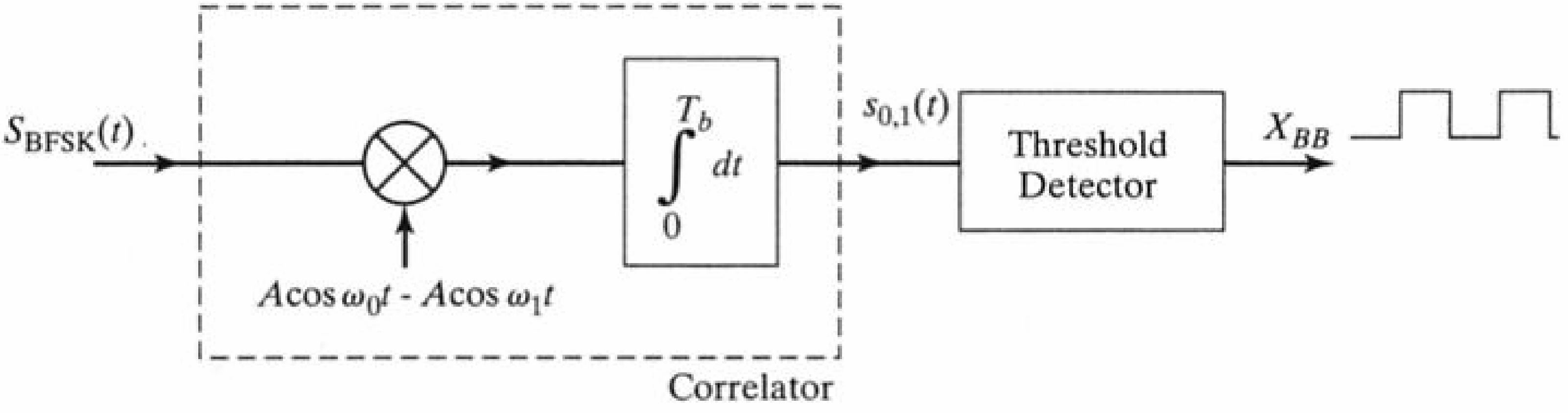


Demodulation BFSK

- Coherent demodulator

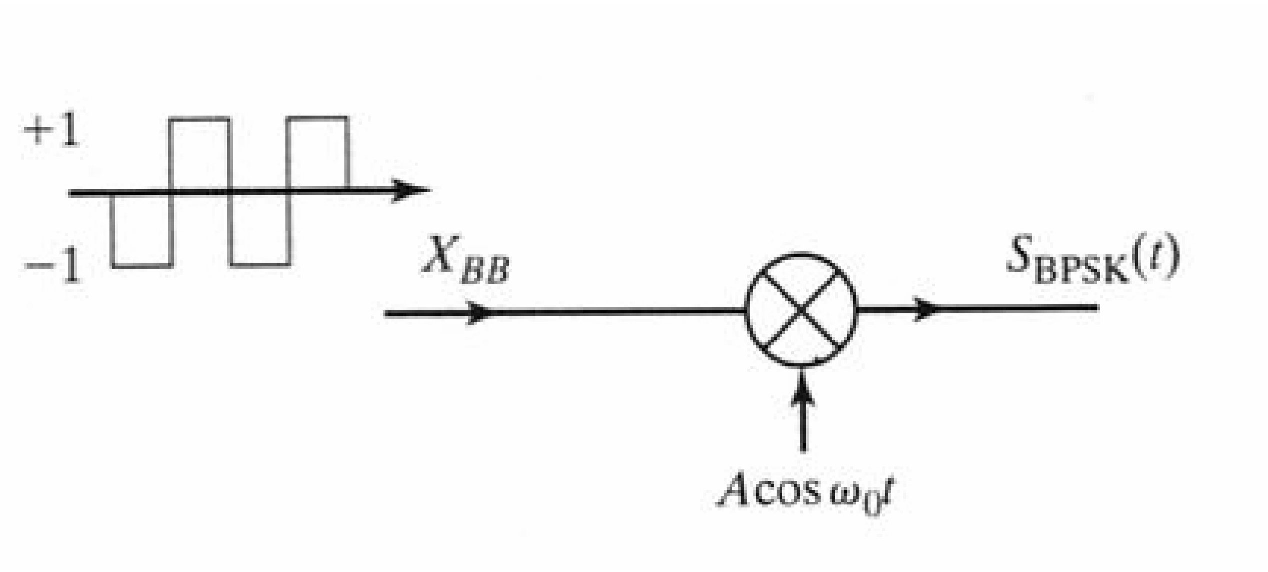
$$\text{logic 0:} \quad s_0(t) = \int_0^{T_b} (A\cos\omega_0 t)(A\cos\omega_0 t - A\cos\omega_1 t)\,dt = \frac{A^2 T_b}{2}; \qquad (1.1)$$

$$\text{logic 1:} \quad s_1(t) = \int_0^{T_b} (A\cos\omega_1 t)(A\cos\omega_0 t - A\cos\omega_1 t)\,dt = -\frac{A^2 T_b}{2}. \qquad (1.2)$$



BPSK

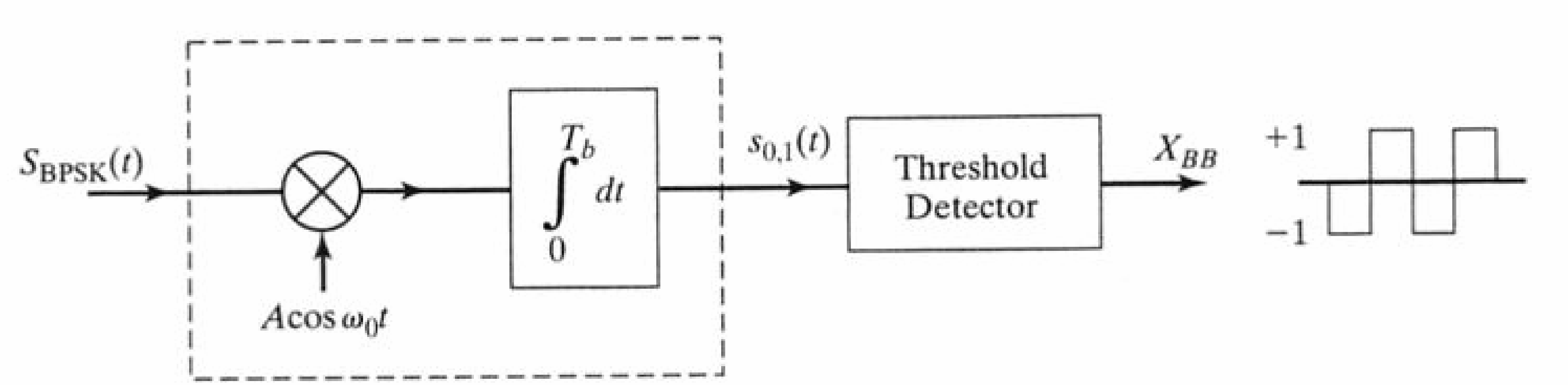
- **Binary Phase-Shift Keying**
- Modulate phase onto carrier
  - Phase changes 180 degrees from 0 to 1 (+ π)



Demodulation BPSK

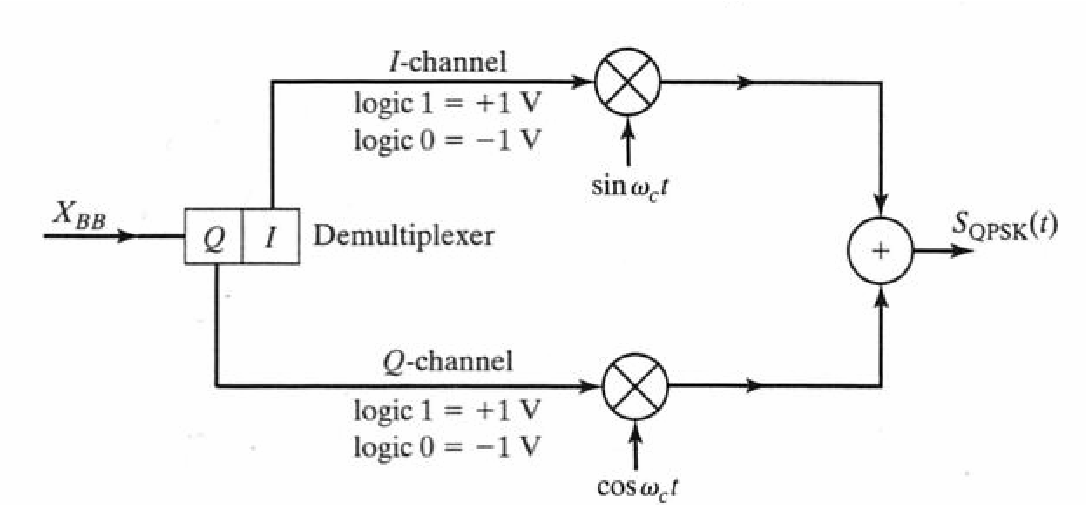
$$\text{logic 1:}\quad s_1(t) = \int_0^{T_b} (-A\cos\omega_0 t)(A\cos\omega_0 t)\,dt = -\frac{A^2T_b}{2};$$

$$\text{logic 0:}\quad s_0(t) = \int_0^{T_b} (A\cos\omega_0 t)(A\cos\omega_0 t)\,dt = \frac{A^2T_b}{2}.$$



QPSK

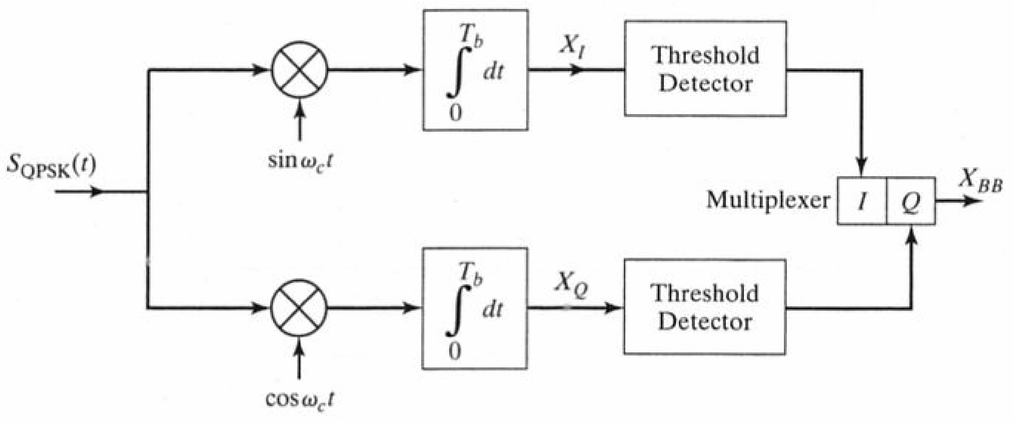
- **Quadrature Phase-Shift Keying**
- Having more than 2 representations of input data
  - Input is combined into bit-groups 00,01,10,11
- Half bit rate in each channel
- Demultiplexer sends every second bit up or down
- I and Q-channels are 90 degrees out of phase
  - **In-phase** component and **quadrature** component



$$s_{\mathrm{QPSK}}(t) = \pm A \cos \omega_c t \pm A \sin \omega_c t.$$

QPSK, contd.

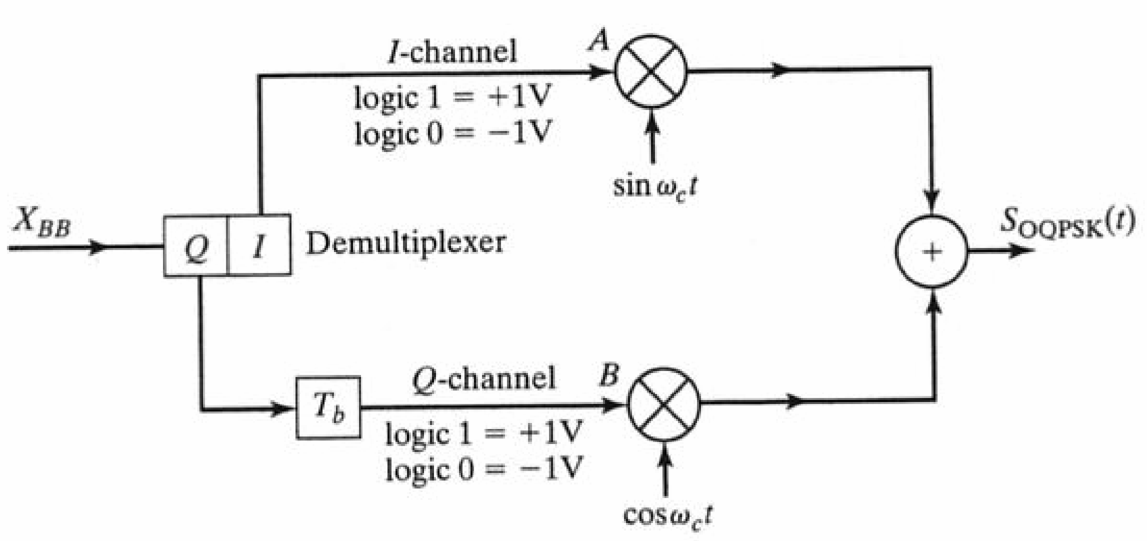
- QPSK demodulation
  - Sin and cos-signals are orthogonal
  - Each channel is demodulated independently as for BPSK



- QPSK is an ex. of **quadrature modulation** where the bit flow is split into pairs of bits (dibits)
  - Each dibit is mapped into four levels before modulation

Offset QPSK: modulator

- Each transmitting channel is non-ideal, having **finite bandwidth**:
  - → **Offset QPSK** can be used
  - Time delay Tb introduced in Q-channel
    - Offset = half the symbol period (2 Tb = period)
    - Hinders simultaneous signal transitions at A and B
    - Smaller phase shift. Lower requirements to channel bandwidth

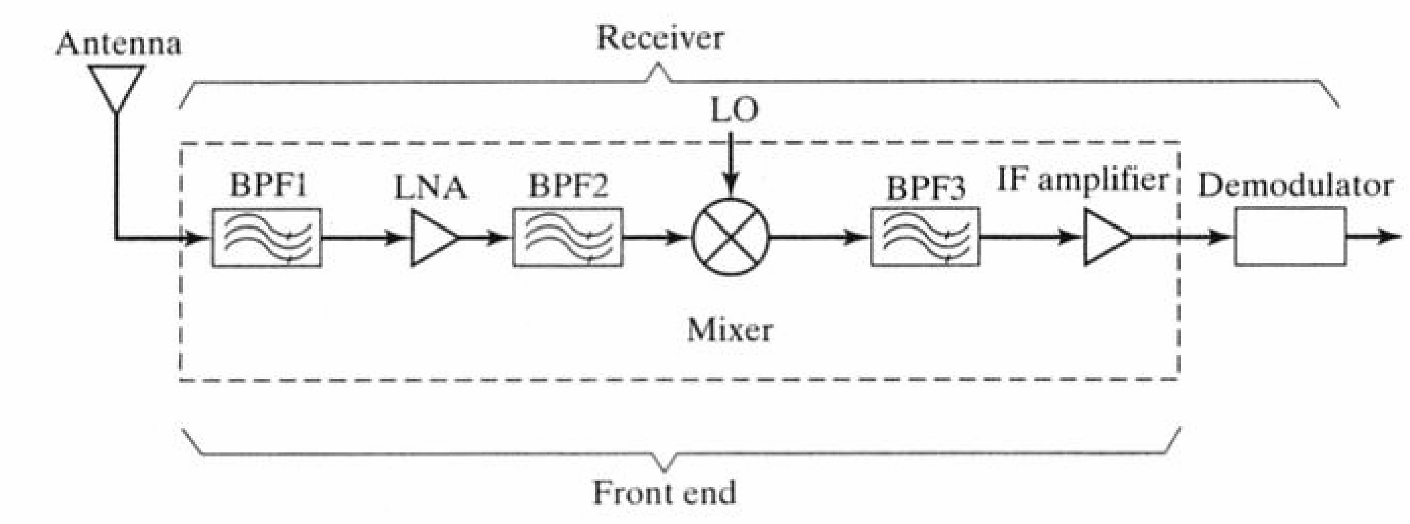


Minimum Shift Keying

- Avoid large phase shifts at the end of each symbol!
  - Large, fast changes in phase mean large symbol bandwidth
  - Solution: Multiply channel signals with **half sine pulses** instead of rectangular pulses
- This is an example of **MSK, Minimum Shift Keying**
  - Continuous phase shift: not abrupt change of phase and no fast signal change
- MSK has a larger decrease in its spectrum than QPSK
  - Lower sidelobe signal influence

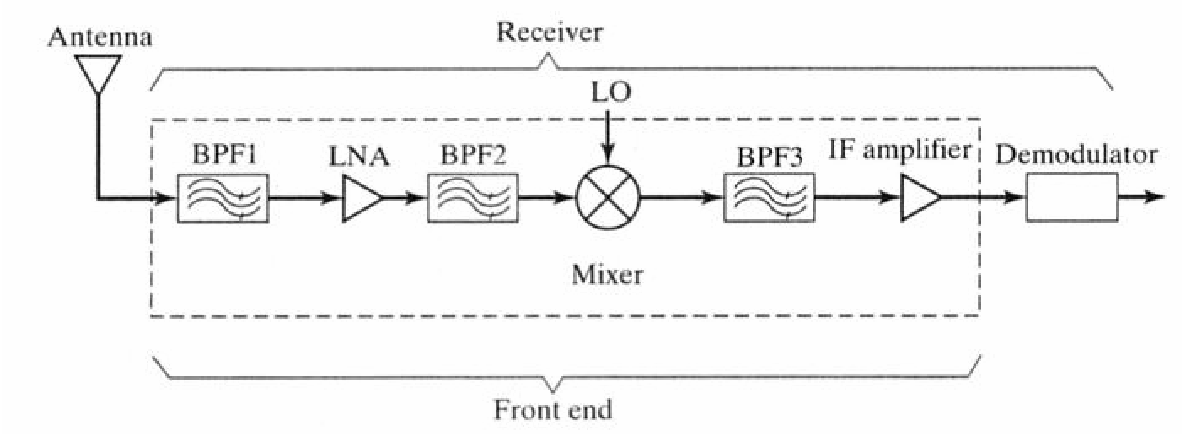
Receiver architecture

- Input filter, BPF1
  - **Band** selection filter
  - Narrow band RF filtering
  - Reduces Gauss noise and interference
  - Compromise, otherwise impractical. Good RF filtering is costly



Receiver, contd.

- **LNA**, RF amplifier **(Low Noise Amplifier)**
  - Requires high gain due to low SNR
  - LNA amplifies also **interference/noise** → Saturation can result
  - High gain means high BPF1 requirements
    - ”Compromise”: the BPF1 must be practical
  - LNA is non-linear, adds also **internal noise**
    - Generates intermodulation products from interference
    - These may have the same frequency as the signal and be destroying



LNA – Low Noise Amplifier

- Amplifier is typical **non-linear**
  - Output may be a 3rd order polynomial of the input signal

$$y(t) = \alpha_1 s(t) + \alpha_2 s^2(t) + \alpha_3 s^3(t)$$

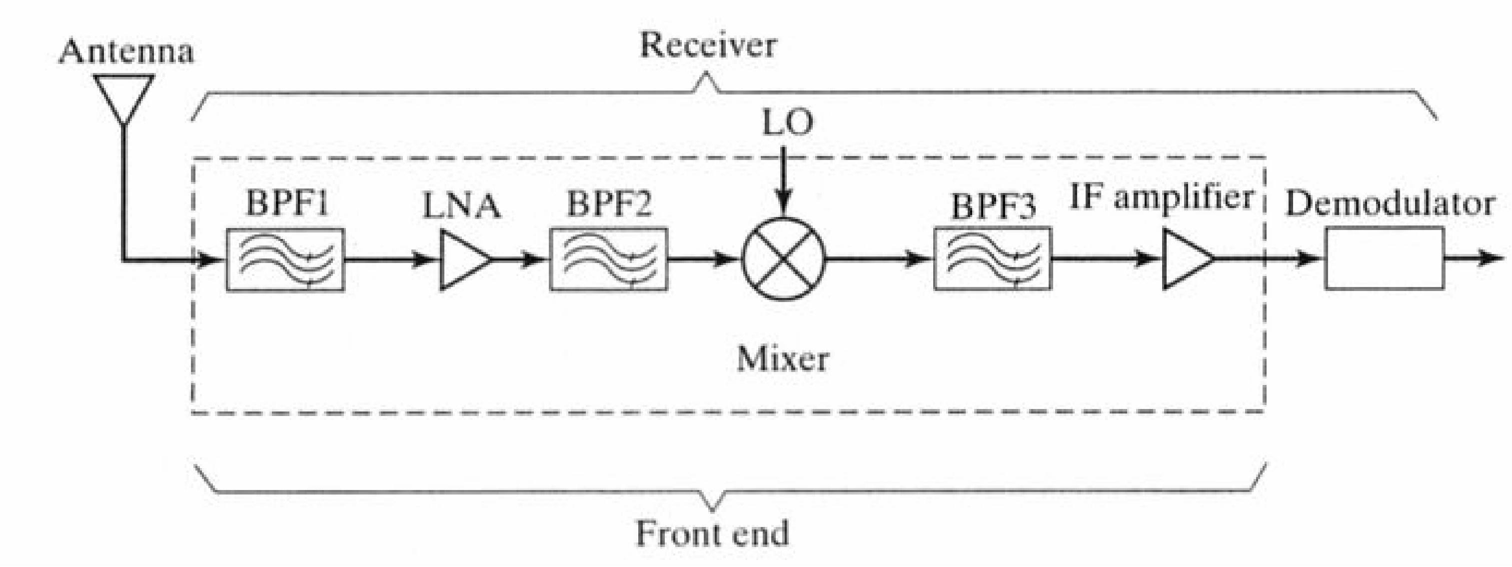
  - For a single frequency input signal, double and triple frequencies are generated

$$y(t) = \alpha_1 A \cos \omega_0 t + \alpha_2 A^2 \cos^2 \omega_0 t + \alpha_3 A^3 \cos^3 \omega_0 t$$
$$= \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right) \cos \omega_0 t + \frac{\alpha_2 A^2}{2} \cos 2\omega_0 t + \frac{\alpha_3 A^3}{4} \cos 3\omega_0 t$$

Harmonics are generated $\mathrm{HD}_3 = \frac{1}{4}\frac{\alpha_3}{\alpha_1} A^2$ (3. harmonic)

Architecture, contd.

- **Anti-image filter** used before mixing, BPF2
- **Mixing**
  - Frequency transformed to **Intermediate Frequency, IF**
  - Variable or fixed local oscillator (LO) -frequency



Mixing

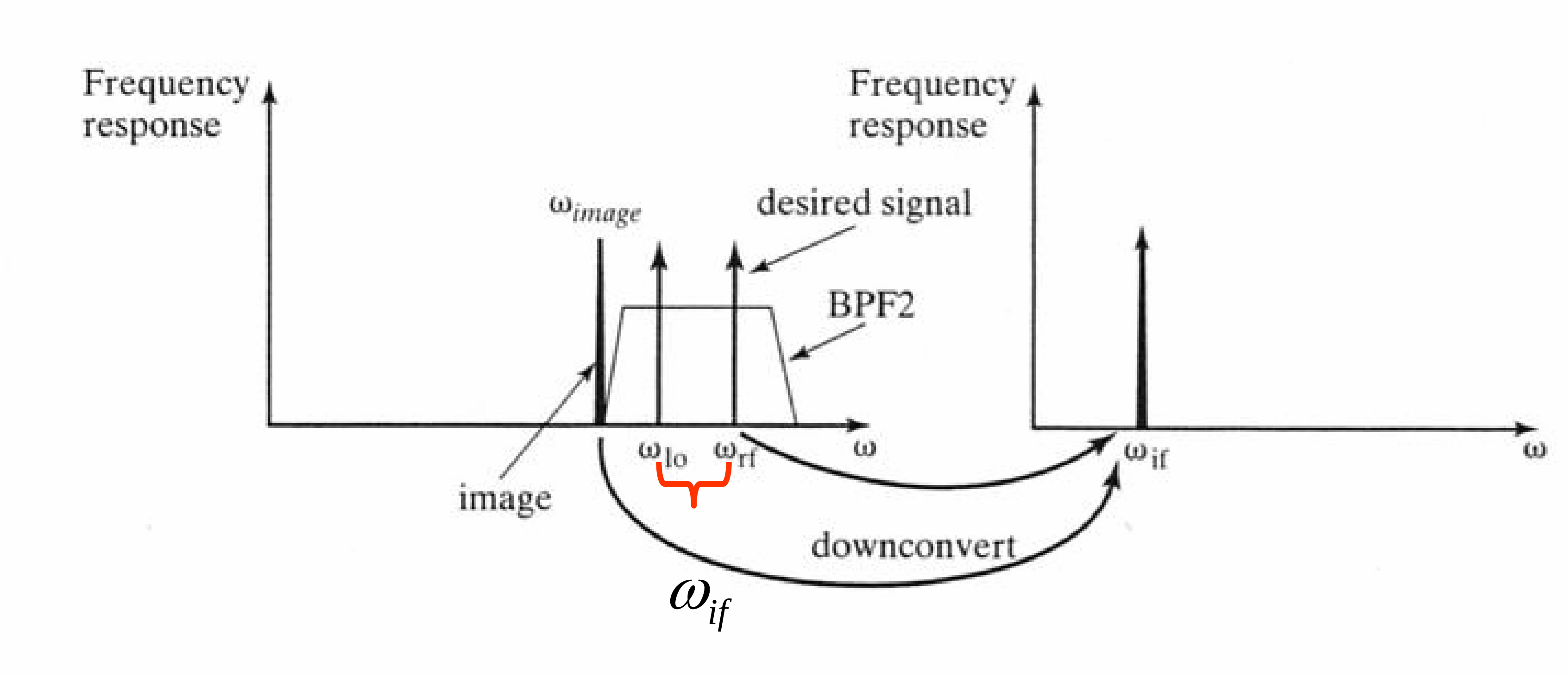
- Mixing is mathematically equivalent to multiplication
- Multiplication of 2 frequencies, ω_{rf} ω_{lo}
  - Intermediate frequency generated ω_{if} which is the difference between ω_{rf} and ω_{lo}

$$V_{\mathrm{if}}(t) = A\cos\omega_{\mathrm{rf}}t \times A\cos\omega_{\mathrm{lo}}t$$

$$V_{\mathrm{if}}(t) = \frac{1}{2}A^2(\cos(\omega_{\mathrm{rf}} + \omega_{\mathrm{lo}})t + \cos(\omega_{\mathrm{rf}} - \omega_{\mathrm{lo}})t)$$

$$= \frac{1}{2}A^2(\cos(\omega_{\mathrm{rf}} + \omega_{\mathrm{lo}})t + \cos\omega_{\mathrm{if}}t)$$

- Suppose a frequency
  - $\omega_{image} = \omega_{rf} - 2 \times \omega_{if}$
  - The frequency is below the oscillator frequency
  - Calculations show that this is mixed to the same IF →



Mixing of image frequency with local oscillator frequency

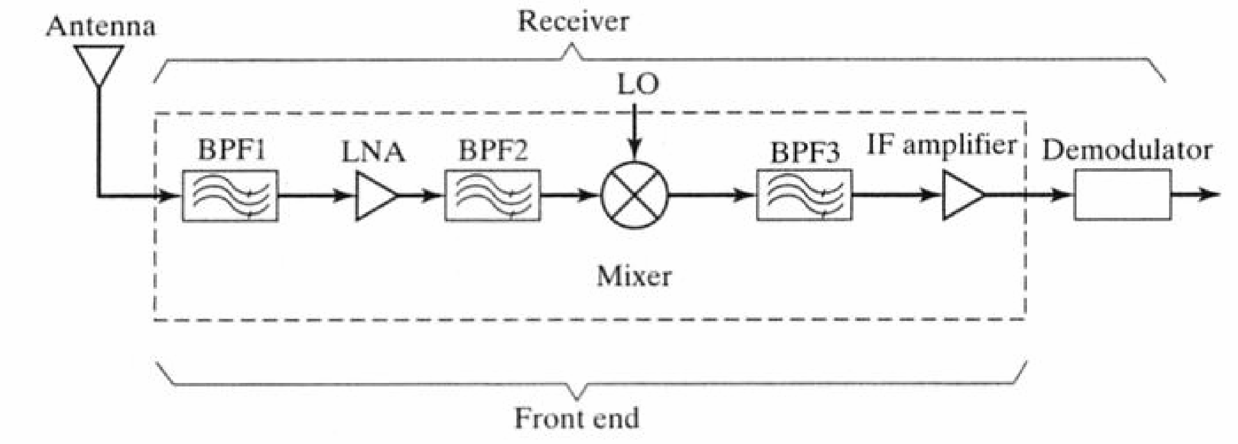
$$\begin{aligned}
&\cos(\omega_{image} - \omega_{lo})t \\
&= \cos(\omega_{rf} - 2\omega_{if} - \omega_{lo}) \\
&= \cos(\omega_{rf} - \omega_{lo} - 2\omega_{if}) \\
&= \cos(\omega_{if} - 2\omega_{if}) \\
&= \cos(-\omega_{if}) \\
&= \cos\omega_{if}
\end{aligned}$$

→ Same intermediate frequency generated!

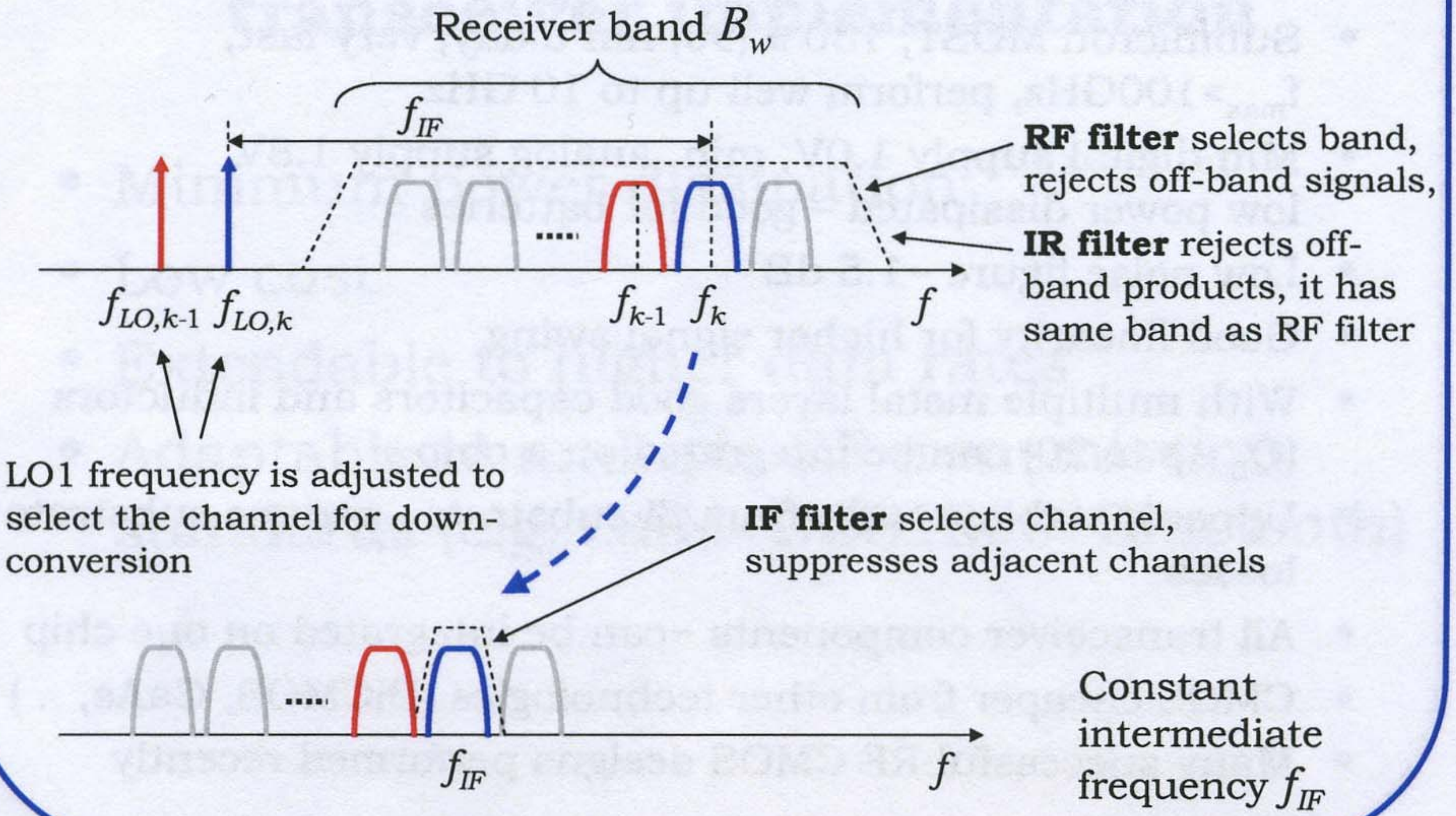
BPF2 Image rejection filter

- Must remove image frequency using a filter, BPF2
  - For low IF, the difference is small, interference may come from **neighboring channels** within the transmission standard
  - For high IF, the difference is large, interference may come from signals following **other standards**

- ”Trade-offs” between the various filters
  - Must select correct channel
  - On the same time remove
    - Image-frequency
    - Other interfering frequencies



Superheterodyne receiver (cont'd)



RF filter selects band, rejects off-band signals,

IR filter rejects off-band products, it has same band as RF filter

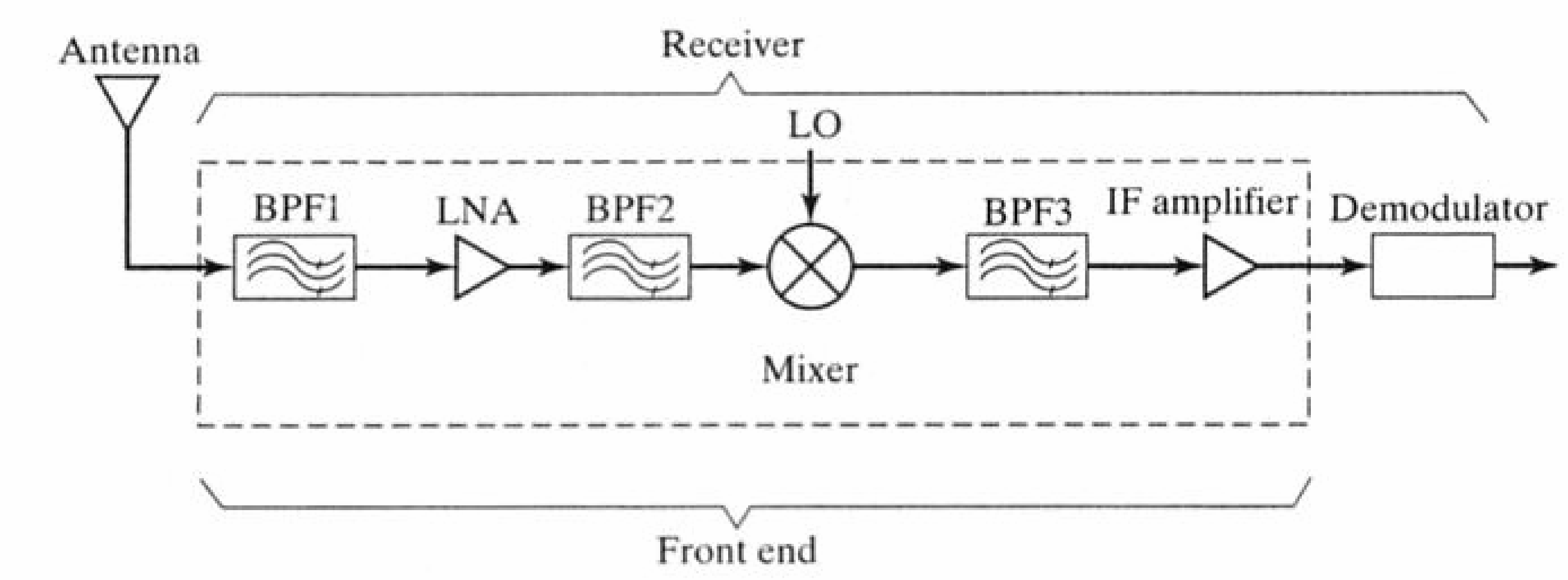
LO1 frequency is adjusted to select the channel for down-conversion

IF filter selects channel, suppresses adjacent channels

Constant intermediate frequency f_{IF}

Architecture, contd.

- Following band-pass filter, BPF3
  - Operates at **intermediate frequency**, IF
  - Not so high Q-factor requirement, - more practical to implement
- Amplifier at IF



Transition to RF results in

- Increased frequency:
  - → Shorter wavelength
    - in vacuum: $\lambda \cdot f = c$
  - → Signals vary over short distances
    - voltage V, current I
  - → Smaller component dimensions required
    - High precision fabrication required
    - → **micro machining**

Present technology

- Technology and components used today
  - **Discrete**, **passive** components with good properties
    - R, C, L
    - Ex. crystals, inductors
  - Such components needed due to **high performance and precision requirements**
  - **Off-chip solutions** are the result
    - PCB assembly
    - Systems take a lot of space
    - Integrated solutions not possible

  - **Active** components
    - Amplifiers, switches
    - GaAs, bipolar Si, CMOS Si, PIN-diodes

Present RF technology has limitations

- The discrete components have **limited performance**
  - Conventional PIN-diodes are inefficient for high frequencies
  - RF filters are especially difficult to implement
    - high Q-factor is difficult to achieve
    - costly
- Systems may not be fully integrated
  - PCB implementations
  - Efficient integration is import for cost, volume and reliability

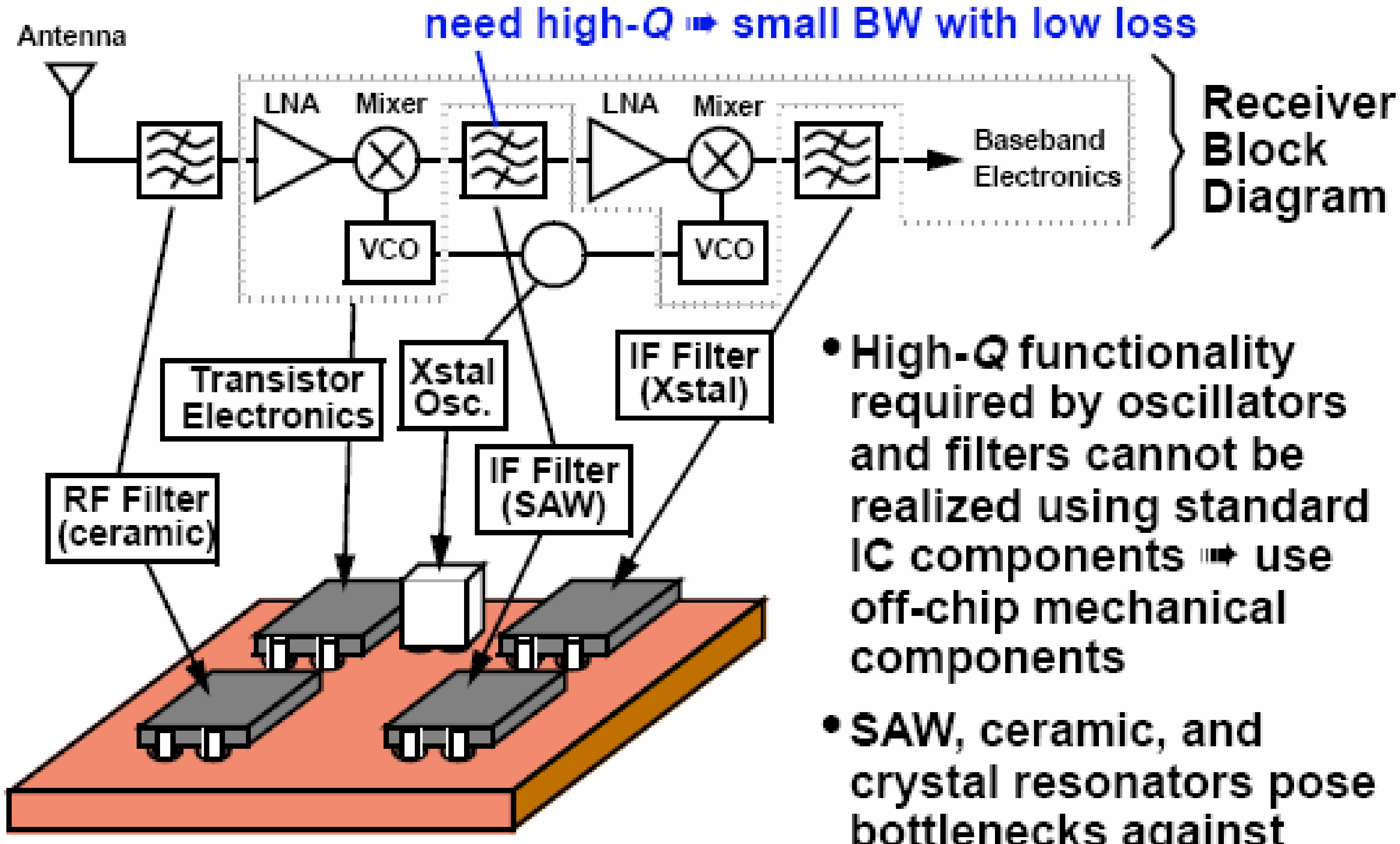
Transceivers using RF MEMS

- How micromechanical circuits can be used in **communication systems**

- Ex.: **”RF receiver front-end”-architecture**
  - A. **Direct substitution** of off-chip passive components
  - B. Special **RF MEMS blocks**
  - C. RF front-end with **only mechanical** components

- Architectures are somewhat ”speculative”
  - We are not there yet
  - **Give motivation for further progress!**

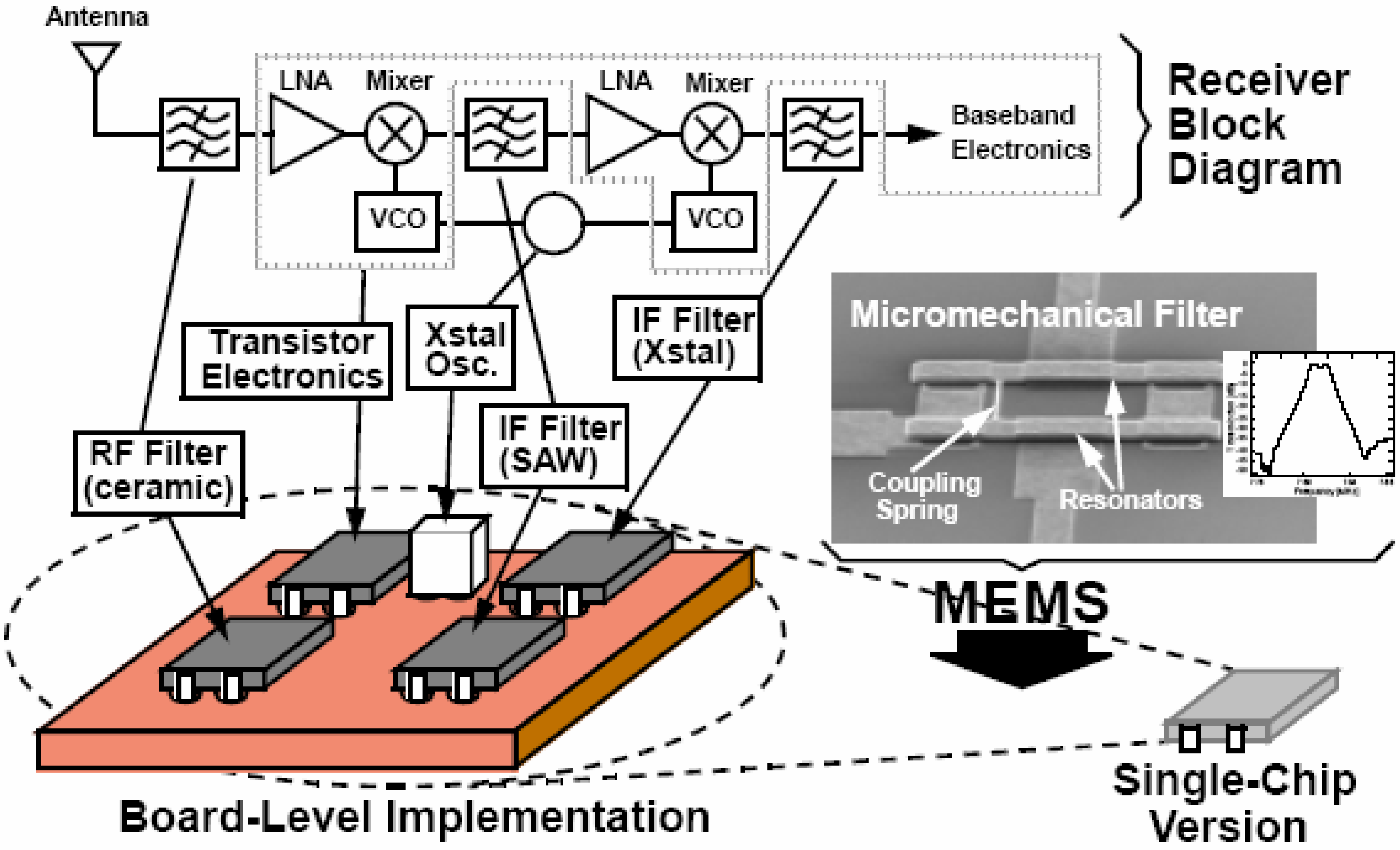
Miniaturization of Transceivers



Board-Level Implementation

- High-Q functionality required by oscillators and filters cannot be realized using standard IC components ➠ use off-chip mechanical components
- SAW, ceramic, and crystal resonators pose bottlenecks against ultimate miniaturization

Target Application: Integrated Transceivers



Antenna

LNA

Mixer

VCO

LNA

Mixer

VCO

Baseband Electronics

Receiver Block Diagram

Micromechanical Filter

Coupling Spring

Resonators

Transistor Electronics

Xstal Osc.

IF Filter (Xstal)

RF Filter (ceramic)

IF Filter (SAW)

MEMS

Single-Chip Version

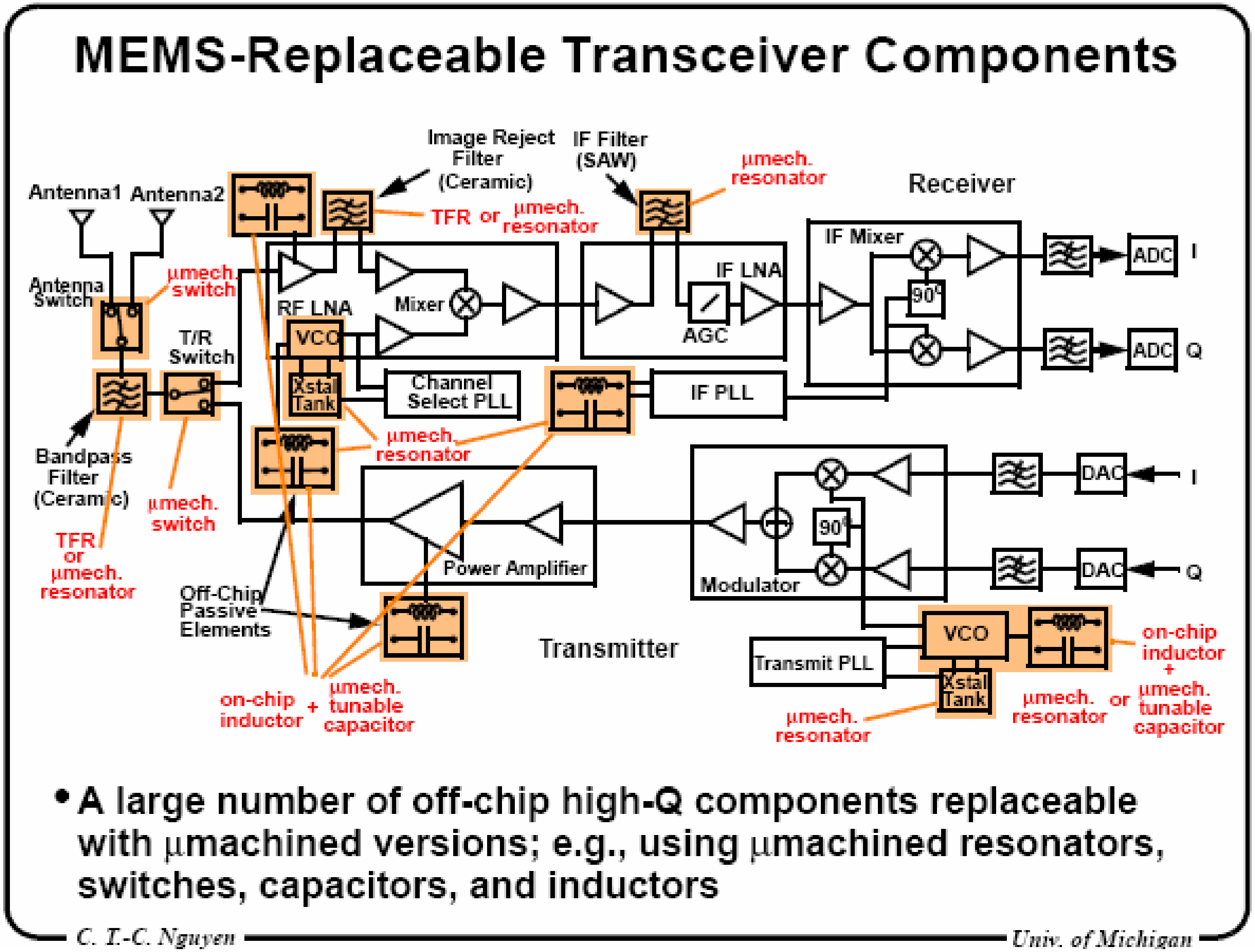
Board-Level Implementation

- Off-chip high-*Q* mechanical components present bottlenecks to miniaturization ➠ replace them with μmechanical versions

A. Direct substitution

- Different types of MEMS-based components
  - Inductors with medium Q-value
  - Tunable capacitors
    - Used in VCO and matching networks
  - Low loss MEMS switches (~0.1 dB)
    - Increases flexibility of antenna
  - Resonators

- Used for
  - RF-filters (ceramic)
    - ”preselect filter”, ”image-reject filter”
  - IF-filter (SAW)
    - ”channel-select filter”
  - Crystal reference oscillator



MEMS-Replaceable Transceiver Components

- A large number of off-chip high-Q components replaceable with µmachined versions; e.g., using µmachined resonators, switches, capacitors, and inductors

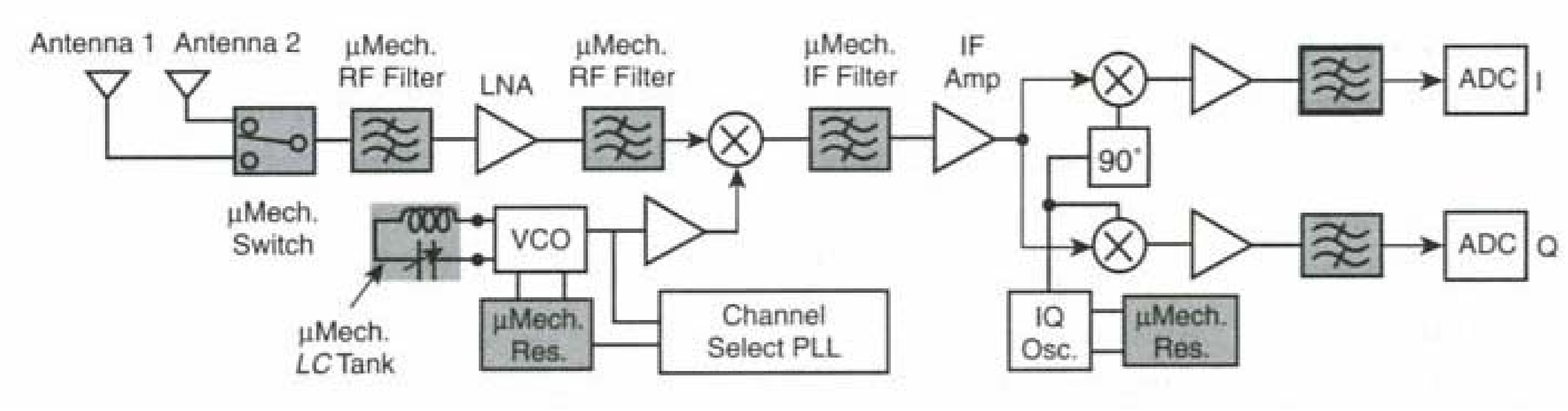
C. T.-C. Nguyen   *Univ. of Michigan*

Itoh et al, fig 12.1

Benefits of MEMS substitutes

- Reduction of **dimensions**
- Possible **integration**
  - Multi-chip
  - Monolithic
- **Power reduction**
- More flexibility for **impedance matching** of MEMS filters

- **Termination impedance** matched to the following LNA (Low Noise Amplifier)
  - ”Higher” (than 50 Ω) LNA input impedance can be used → power reduction and reduced noise



B. Special RF MEMS blocks

- Figure shows 3 basic blocks that are substituted by RF MEMS
  - **B1.** Switchable RF **channel-select filter bank**
  - **B2.** Switchable micromechanical **frequency synthesizer**
  - **B3.** Micromechanical **mixer-filter** block

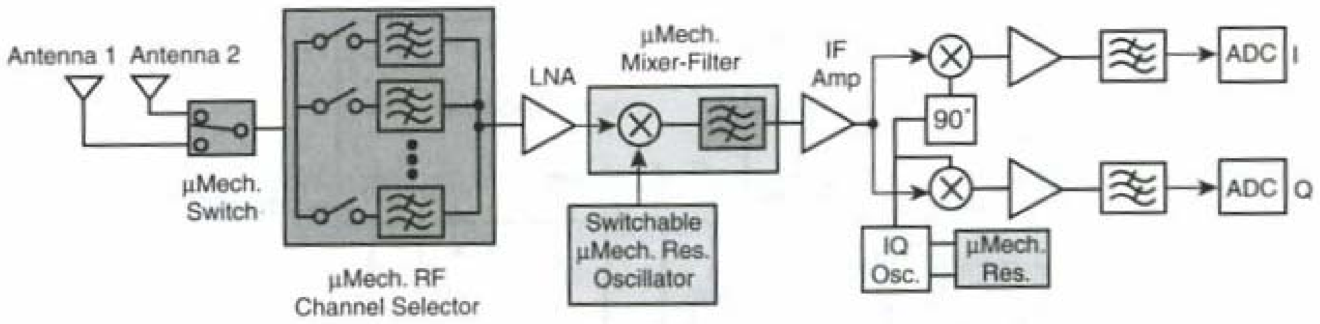
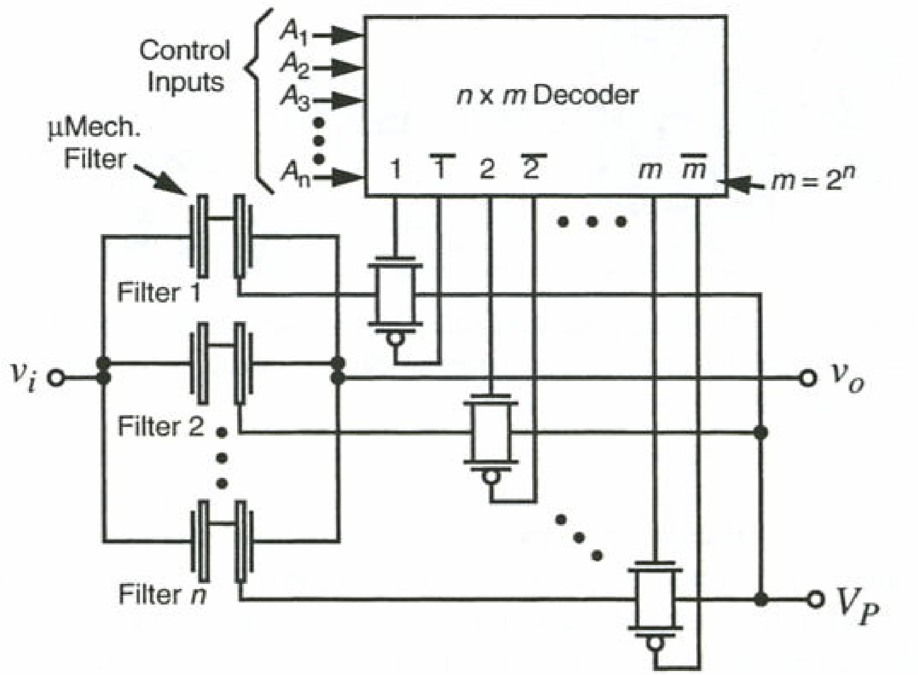


Figure 12.21. System block diagram for an RF channel-select receiver architecture utilizing large numbers of micromechanical resonators in banks to trade *Q* for power consumption. (On-chip μmechanics are shaded.)

B1. Switchable RF channel-select filter bank

- Idea
  - Use **many, simple,** non-tunable filters with high Q
  - One for each channel, -switched on command
  - A communication standard needs 100 – 1000 of filters



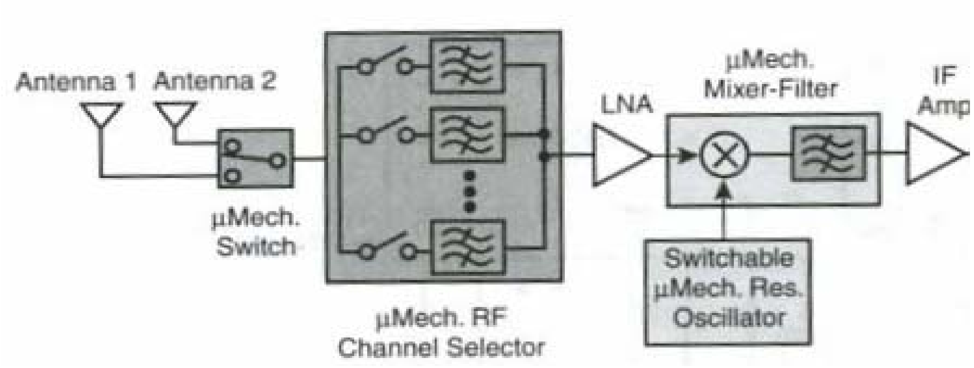
- Block diagram
  - Common input and output
  - Controlled by Vp from decoder
    - With no Vp the outputs are effectively ”open-circuited”

Use of RF filter bank

- **Narrow RF channel** can be selected directly
  - A succeeding electronic block can be **simplified!**
  - Signal will not be influenced by adjacent channels
- LNA can be simplified
  - Dynamic range can be reduced, meaning reduced power consumption
  - Less stringent requirements to IIP3 gives an order of magnitude reduction in LNA **power consumption**:
    - Ex. **CDMA** cell phone, test results:
    - Single tone signal 900 kHz outside of centre frequency
    - LNA IIP3 > + 7.6 dBm by conventional implementation **(intermodulation!)**
    - By using a filter bank the tone is damped 40 dB → IIP3 < -29.3 dBm
  - Requirements of LNA **linearity** is reduced
    - Then LNA gain can be increased → improving SNR for the following blocks
  - Reduced phase noise requirements for LO
    - → also power reduction
    - On-chip realization of LO might be possible

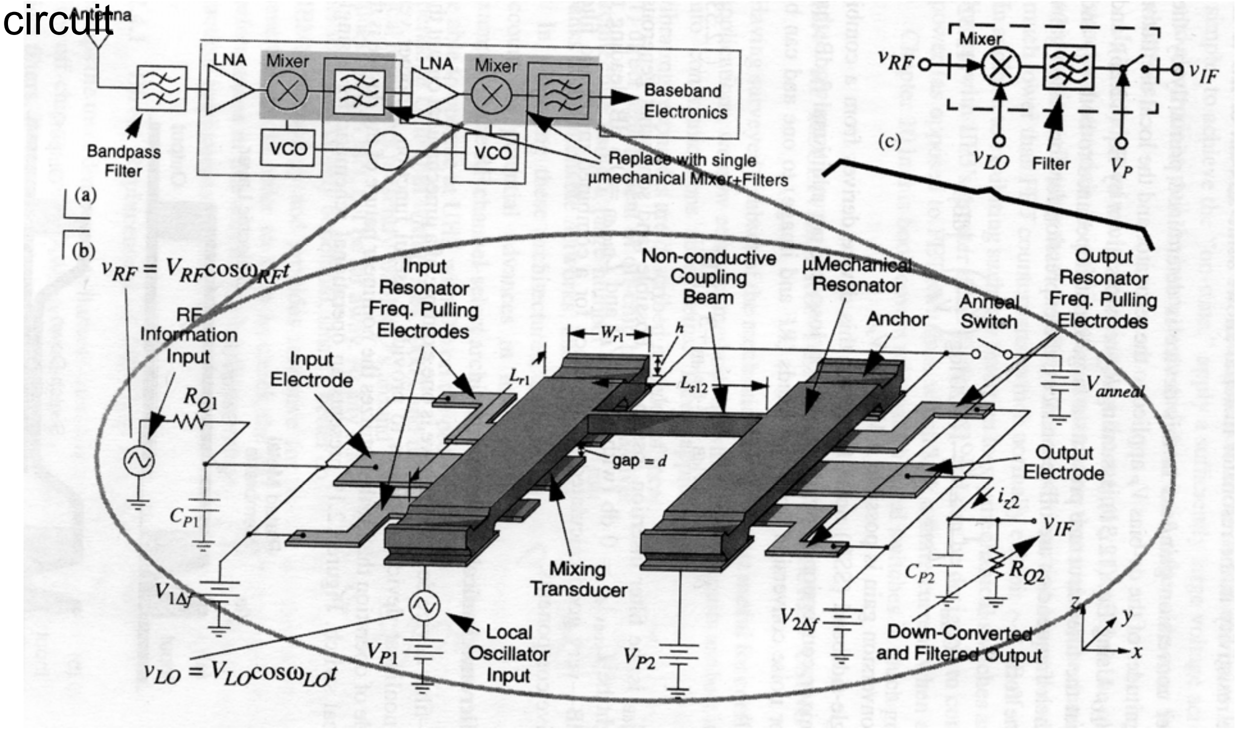
B2. Switchable MEMS frequency synthesizer

- Implementing VCO with MEMS resonators
  - Oscillator can be implemented using a **switchable resonator bank**
  - Resonators oscillate with the frequencies needed for the given standard
  - Resonators must have high Q and should be thermally stabilized (mechanically or by electronic compensation)
    - Might allow the VCO to operate without crystal reference
    - → significant power reduction, f.ex. 90 nW versus 1-4 mW



B3. Micromechanical mixer-filter

- Use of a micro-machined mixer-filter eliminates the DC power consumption compared to what present commercial mixers need
- Two input ports used in the mixer-filter: one for RF, one for LO
  - RF-input port can be made capacitive
  - Output port can be tailored to a specific **impedance**
  - → LNA can be simplified and does not need a separate impedance matching circuit



C. RF front-end with RF MEMS only

- Do we need LNA for RF?
  - Use of relatively broadbanded **”image-reject”** MEMS RF filter followed by a narrowband **IF-mixer-filter**
    - The only active RF-component are then the LO
    - → This gives low power consumption

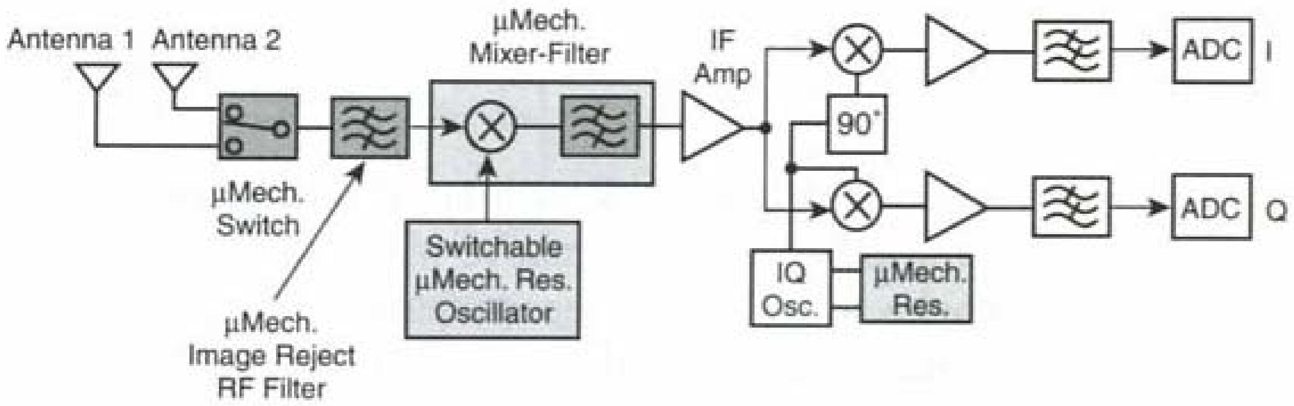


Figure 12.23. System block diagram for an all-MEMS RF front-end receiver architecture. (On-chip µmechanics are shaded.)

Benefits of using RF MEMS only

- System is power efficient
  - Power consumption of LNA and mixer eliminated
  - Can increase standby-time for cell phones significantly!
- Some of the actual components have already been demonstrated
  - Filter and mixer circuits
  - Ex. an image-reject filter at UHF with 3 dB insertion loss has been demonstrated
- A promising implementation technology is to use high Q **f-f- beams**
  - Higher frequencies than c-c beam

RF MEMS transmitter architecture

- Little done in using RF MEMS in transmitters
  - Due to lack of high power capability
    - Transmitting power is a significant parameter
- Active research on this matter

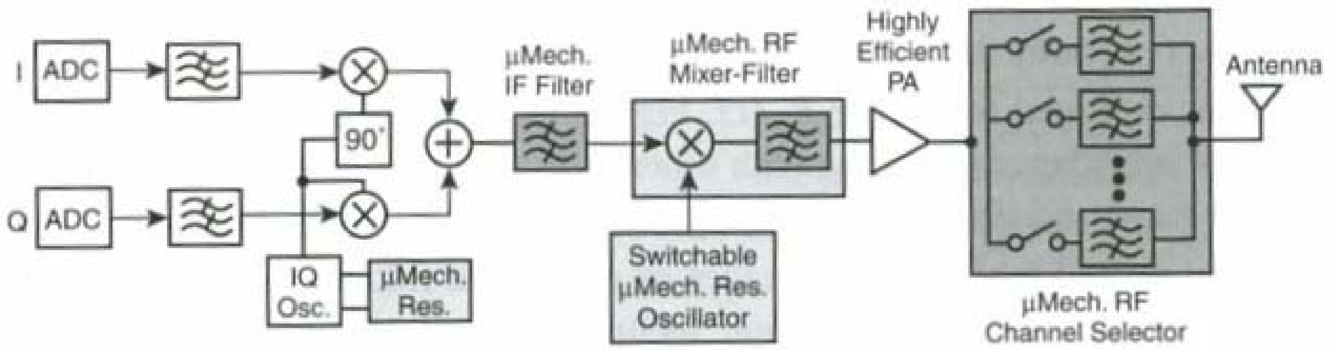
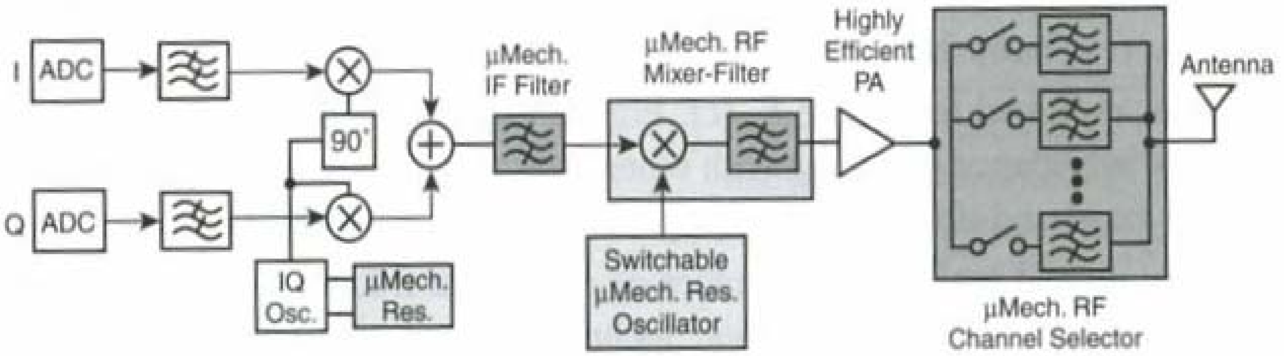


Figure 12.24. RF channel-select transmitter architecture, possible only if high-power µmechanical resonators can be achieved. Here, on-chip µmechanical blocks are shaded, and the PA is not necessarily implemented on-chip.

RF MEMS transmitter architecture

- RF MEMS **channel selector** can be placed **after PA** (”power amplifier”)
  - Use MEMS filter bank
  - MEMS resonators should sustain high power, have high Q and low ”insertion loss” (<1 dB)
  - ”Pure signals” are sent out
  - **+ PA requirements may be reduced**, since all spectral noise due to non-linearity is filtered out after the PA!
- Architecture may give significant reduction of power consumption
- ”Up-converter” can be realized using MEMS mixer-filter structure



Relevant research topics

- The architectures shown are to some extent based on resonators with performance not yet achieved

- Research topics
  - **1.** Obtain required **high Q at UHF**
  - **2.** Set specific **impedance levels**
  - **3.** Good enough **linearity** and capability to sustain **power**
  - **4.** Efficient **integration methods**

1. Frequency and Q-value

- **Frequency**
  - What frequency range can be covered?
  - Structures/ geometry are critical issues
    - Research shows that 10 MHz – 2.5 GHz can be achieved by using realistic element dimensions
    - Today components exist that have Q ~ 1000 at 3 GHz
  - Absolute value and tolerances in resonance frequency
    - Depends on fabrication, trimming and tuning
  - Stability of resonator frequency
    - Wrt. temperature variations and aging
- Competing resonator types for high frequency and Q
  - ”Thin-film bulk acoustic resonators”
    - High frequencies (UHF and over), Q > 1000
  - Use of piezolectric materials

Frequency and Q-value, contd.

- **Q-factor**
  - Energy loss in material influences Q value
    - Q-factor depends on material type
  - Q-factor dependence of fabrication
    - Surface cleanness
    - Doping: diffusion and implantation give different properties
  - Loss via anchors reduce Q
    - ”anchor-less” structures: f-f beam are beneficial
    - Balanced tuning fork structure
    - Circular resonator

2. Custom set impedance level

- Serial ”motional resistance” R_Q is often high
- Value of resistance should be matched directly to other transceiver components
  - Components before and after resonator
- Should be ~ minimized
  - Realistic requirements: some hundred Ω´s
  - Value depends on how small the gap, d, can be made

Resonator impedance

- ”Motional” impedance and gap for 2-resonator structures
  - Ex. By reducing gap (ca. 140 → 70 Å) the resonance impedance will be **reduced** from 5000 Ω → 300 Ω (870 MHz)
  - BUT this will also **degrade** linearity
  - **→ important to balance linearity requirements to impedance requirements**

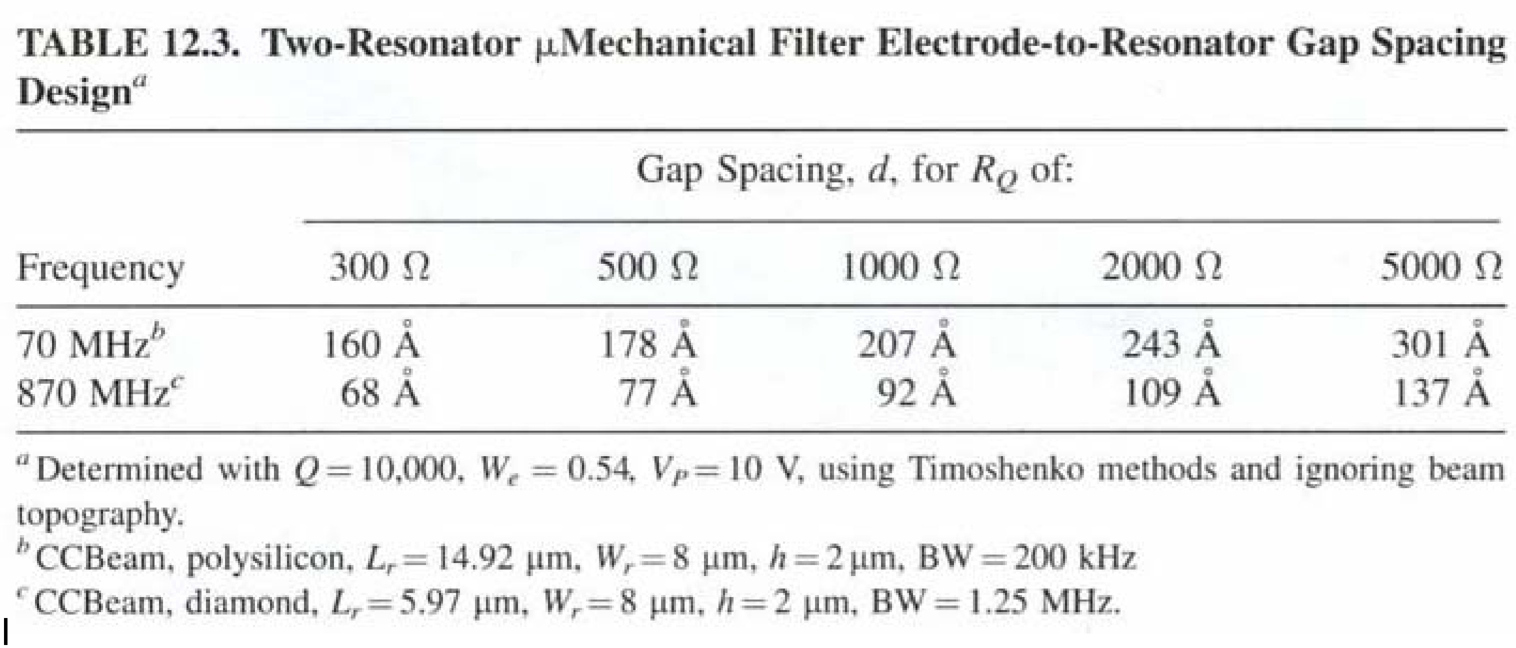


TABLE 12.3. Two-Resonator µMechanical Filter Electrode-to-Resonator Gap Spacing Design[a]

	Gap Spacing, d, for R_Q of:				
Frequency	300 Ω	500 Ω	1000 Ω	2000 Ω	5000 Ω
70 MHz[b]	160 Å	178 Å	207 Å	243 Å	301 Å
870 MHz[c]	68 Å	77 Å	92 Å	109 Å	137 Å

[a] Determined with $Q = 10{,}000$, $W_e = 0.54$, $V_P = 10$ V, using Timoshenko methods and ignoring beam topography.

[b] CCBeam, polysilicon, $L_r = 14.92$ µm, $W_r = 8$ µm, $h = 2$ µm, BW = 200 kHz

[c] CCBeam, diamond, $L_r = 5.97$ µm, $W_r = 8$ µm, $h = 2$ µm, BW = 1.25 MHz.

Itoh et al

Example of compromise

- If impedance matching means that a smaller gap has to be used than linearity requirements allow:
  - Eg. d_min for desired impedance matching < d_min for desired linearity
- Solution: **use several micromachined parallel filters**
  - With identical frequency response
  - F.ex. 10 filters in parallel with R_Q = 2000 Ω give R_Q_total = 2000 Ω /10 = 200 Ω
- Parallel filters also increase power capability! →
  - 10 filters in parallel with 10 mW each, give totally 100 mW

3. Linearity and power capability

- Linearity and power capability are reduced when dimensions get smaller
  - Present ceramic or SAW filters have very high linearity
- MEMS structures based on c-c beams have OK linearity
  - Good enough, except for some standards allowing **simultaneous** transmit and receive
    - Ex. CDMA needs transmit-reject filter in front of the receiver filter bank

- Increased power capability
  - Use alternative geometries
  - Use alternative transduction
    - Piezoelectric
    - Magnetostrictive
  - Parallel units

4. Efficient integration methods

- Critical research topics
  - Combination of MEMS with transistors on-chip
    - Monolithic integration!
  - Jmfr. Lecture on integration and packaging
    - L15

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