Super-Regenerative Receiver

Ultra low-power RF Transceiver for high input power & low-data rate applications

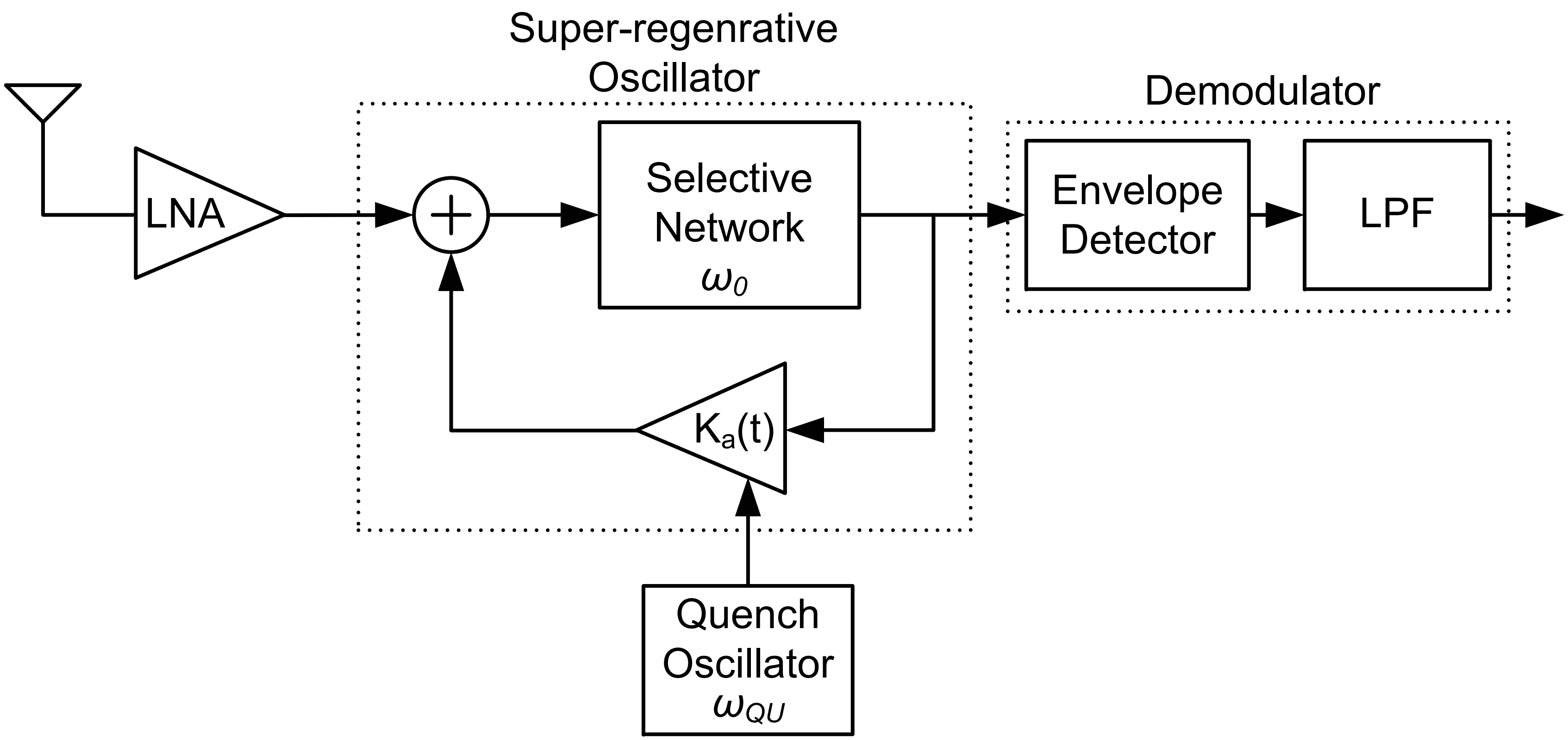
Thanks to this material to Felix Fernandez

ECEN 665 TAMU AMSC

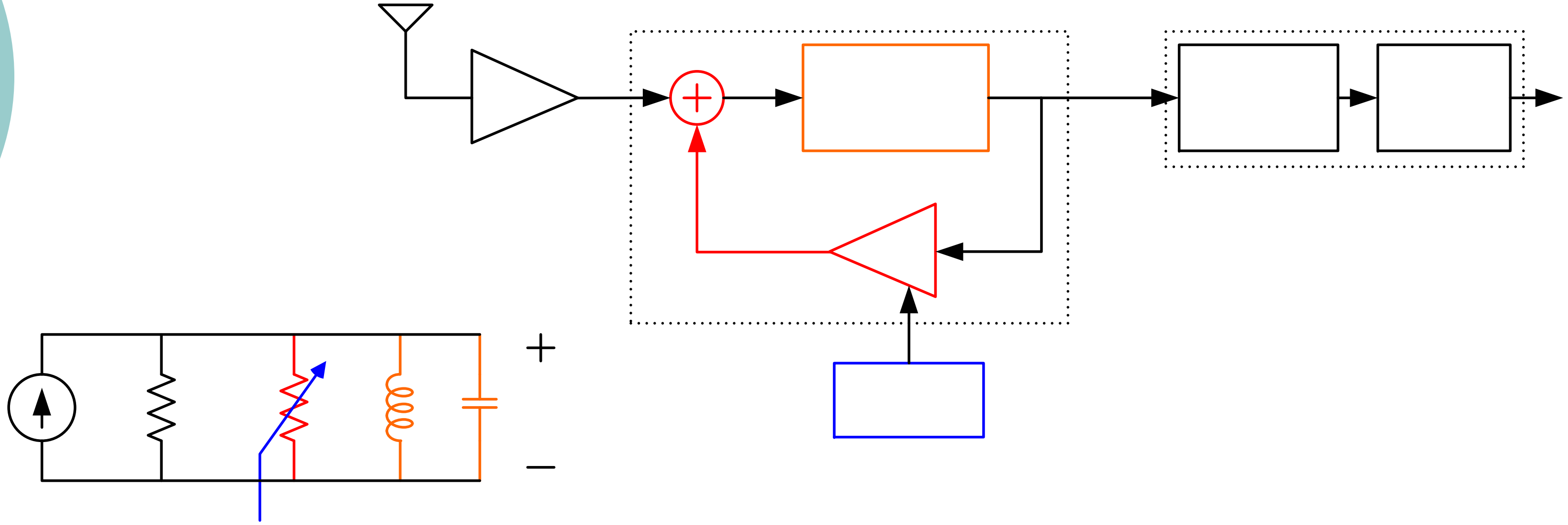
Overview

- Invented by Armstrong in 1922 and widely used in vacuum tube circuits until the 1950's
- It was replaced by the super-heterodyne receiver due to its poor selectivity and sensitivity
- Pros:
  - Small number of components allow for high integration
  - Low power
  - High energy efficiency
- Cons
  - poor sensitivity
  - poor selectivity
  - low data-rate
  - limited demodulation capability

Super-regenerative Receiver Block Diagram



Super-regenerative Receiver Block Diagram & Basic Model



$$C\frac{d^2V}{dt^2}+G\frac{dV}{dt}+\frac{V}{L}=A\omega\cos(\omega t)$$

$$\alpha=\frac{G}{2C}$$

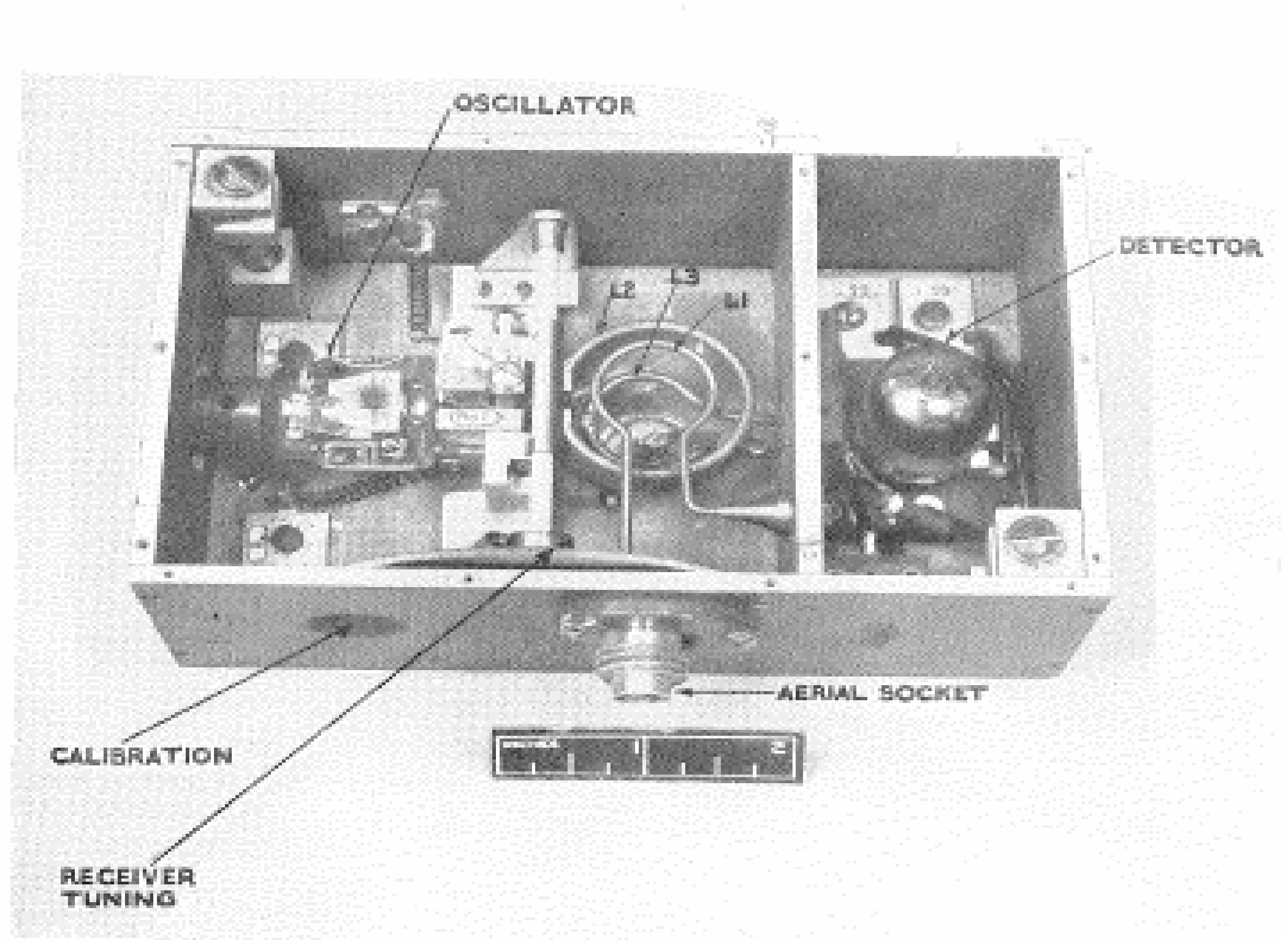
$$\omega_d=\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}=\sqrt{\omega_0^2-\alpha^2}$$

$$V=\frac{A\omega_0}{2j\omega_d G}e^{(-\alpha+j\omega_d)t}-\frac{A\omega_0}{2j\omega_d G}e^{(-\alpha-j\omega_d)t}+\frac{A\sin(\omega_0 t)}{G}$$

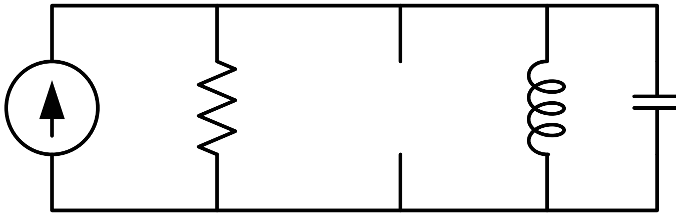
$$=\frac{A\omega_0}{G\omega_d}e^{\frac{-Gt}{2C}}\sin(\omega_d t)+\frac{A}{G}\sin(\omega_0 t)$$

WWII –German Air Interception

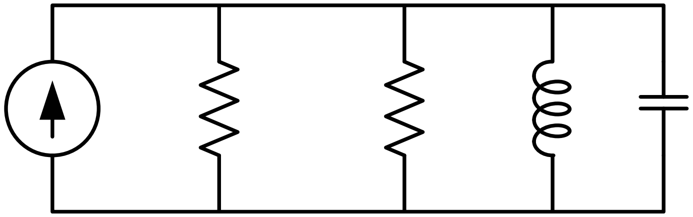
(first generation SRR, circa 1940)



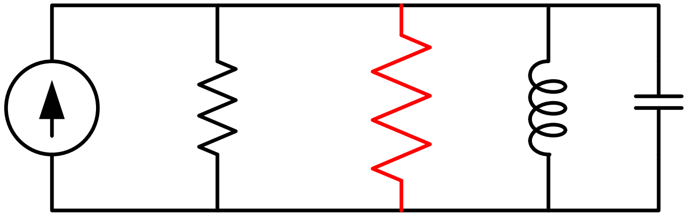
Operation Fundamentals



$G_a(t) = 0$ [Ga(t) is a negative conductance]

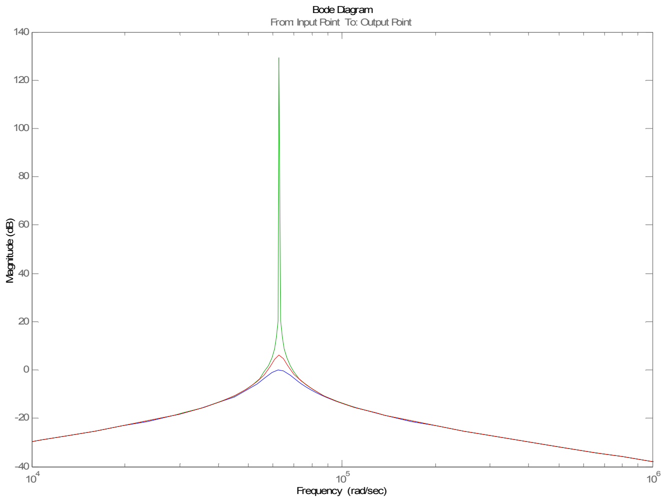


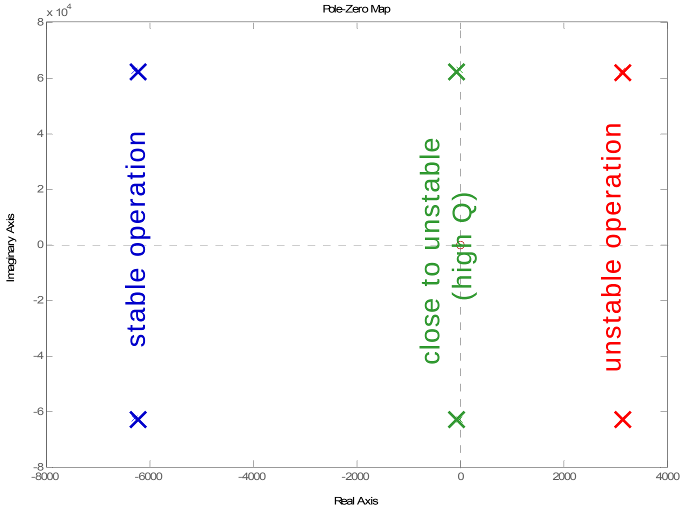
$G_a(t) = G_0$



$$G(t) = \frac{i(t)}{v(t)}$$

$G_a(t) >> G_0$





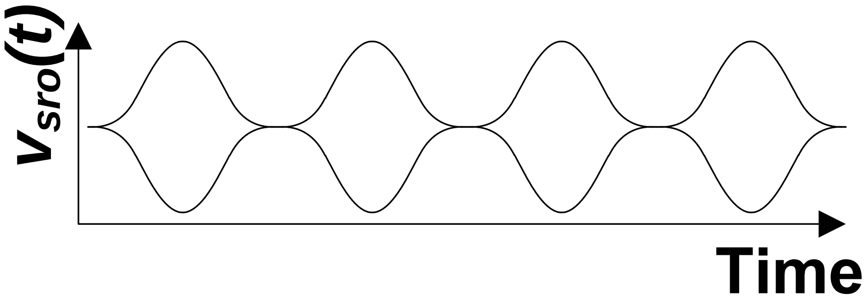
i(t)

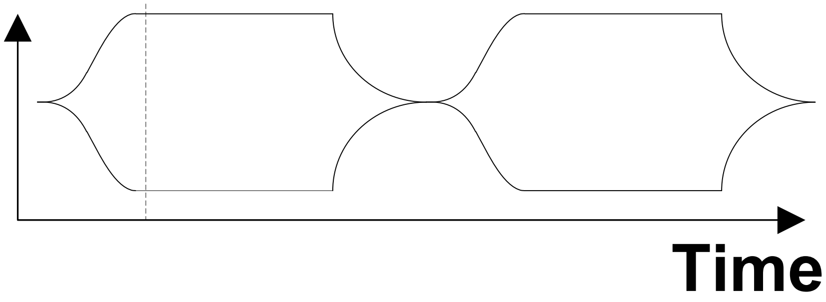
G

Operation Modes

- Linear: The self sustained oscillations are quenched before they reach their maximum amplitude. The height of the SRO output has a linear relationship with the RF input power.

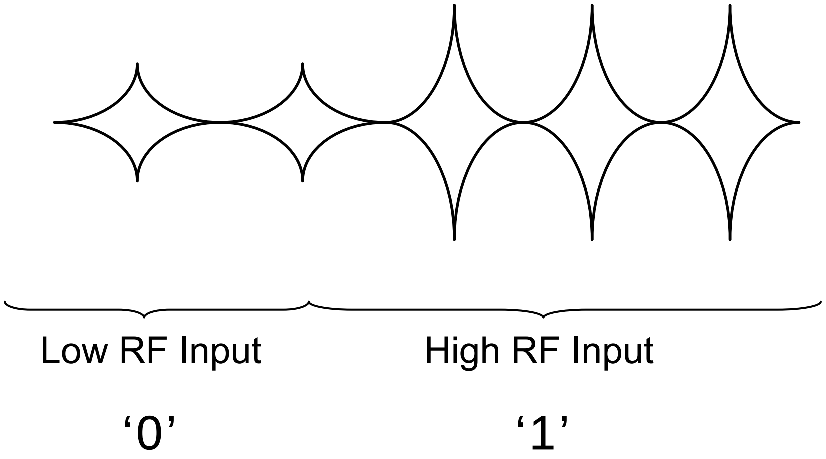
- Logarithmic: The self sustained oscillations are allowed to reach their maximum amplitude. The area enclosed by the envelope of the SRO output has a logarithmic relationship with the RF input power



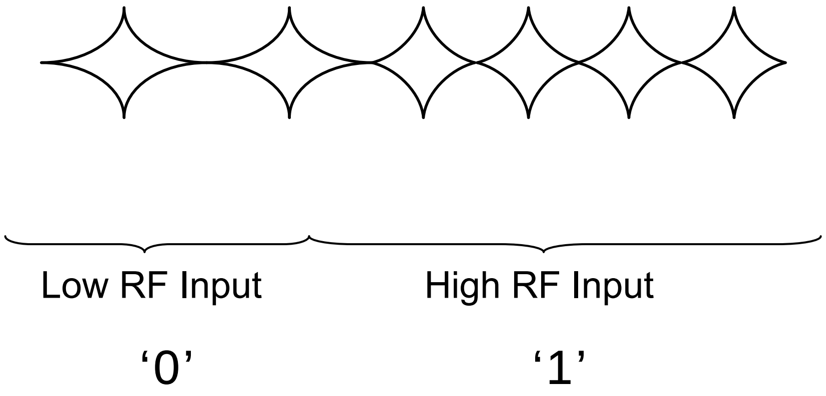


Quenching Mode

- External Quenching:
  - The oscillations of the SRO are quenched by an external oscillator that controls the negative admittance at a fixed frequency



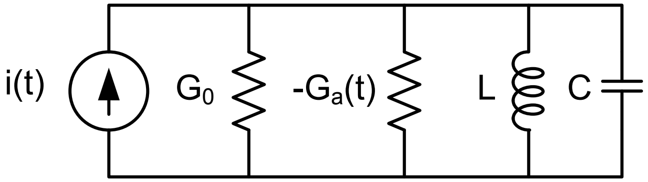
- Self Quenching
  - The oscillation of the SRO are controlled by a feedback network which quenches the oscillation after they have reached a certain threshold

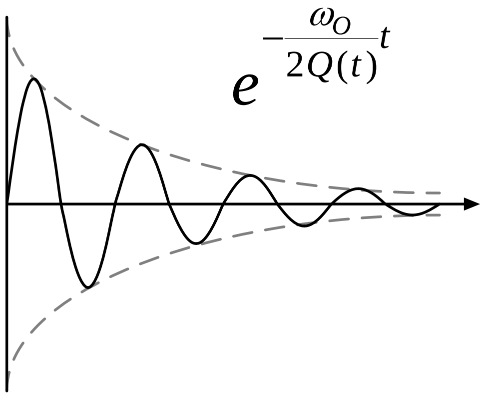


Building Blocks Operation

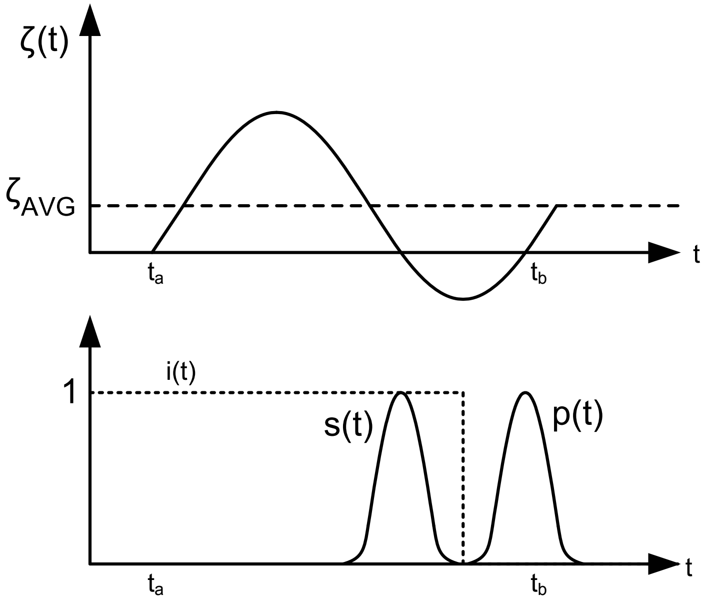
- LNA
  - Feeds the RF input to the SRO
  - Provides antenna matching
  - Isolates SRO oscillations from the antenna
- SRO
  - Generate the oscillations needed for the super-regenerative operation
- Quench Oscillator
  - Quench the SRO oscillations according to the quenching mode
- Demodulator
  - Detect the SRO oscillation envelope and digitize the signal
- Tuning (PLL)
  - Provide tuning ability to the selective network (original tuning scheme was manual tuning)

Super Regenerative System Design Equations





$$e^{-\frac{\omega_O}{2Q(t)}t}$$



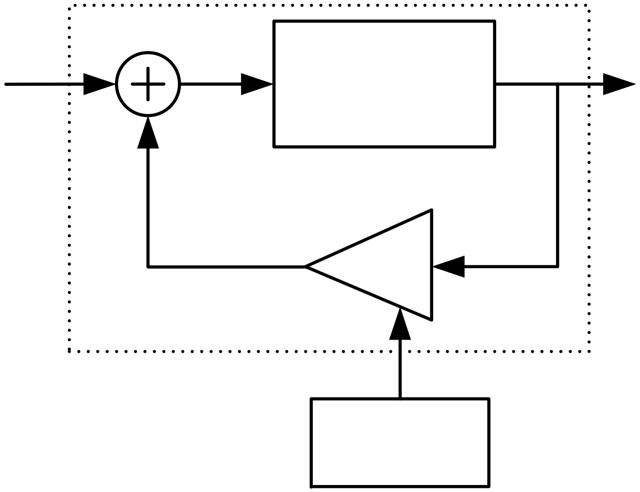
Super regenerative gain $K_s = e^{-\omega_0 \int_0^{t_b} \zeta(t)dt}$

Output pulse shape $p(t) = e^{-\omega_0 \int_{t_b}^{t} \zeta(t)dt}$

Sensitivity function $s(t) = e^{\omega_0 \int_0^{t} \zeta(t)dt}$

$F\{i(t)s(t)\}$ Frequency response is given by the Fourier transform of the RF envelope and the sensitivity function.

Selective Network Design Equations



$$G(s) = K_0 \frac{2\zeta_0 \omega_0 s}{s^2 + 2\zeta_0 \omega_0 s + \omega_0^2}$$

$$H(s) = \frac{G(s)}{1 + G(s) K_a}$$

$$H(s) = K_0 \frac{2\zeta_0 \omega_0 s}{s^2 + 2\zeta_0 \omega_0 \left(1 \pm K_0 K_a^*\right) s + \omega_0^2}$$

±: depends on the quench control signal

K_0: maximum amplification
$K_a(t)$: variable gain controlled by quench signal
ζ_0: quiescent damping factor
ζ_{AVG}: damping factor average value

$$\zeta(t) = \zeta_0 \left(1 - K_0 K_a(t)\right)$$

$$K_a^* = K_a(t)\big|_{t=t_a}$$

$$Q(t) = \frac{1}{2\zeta(t)}$$

Super-re

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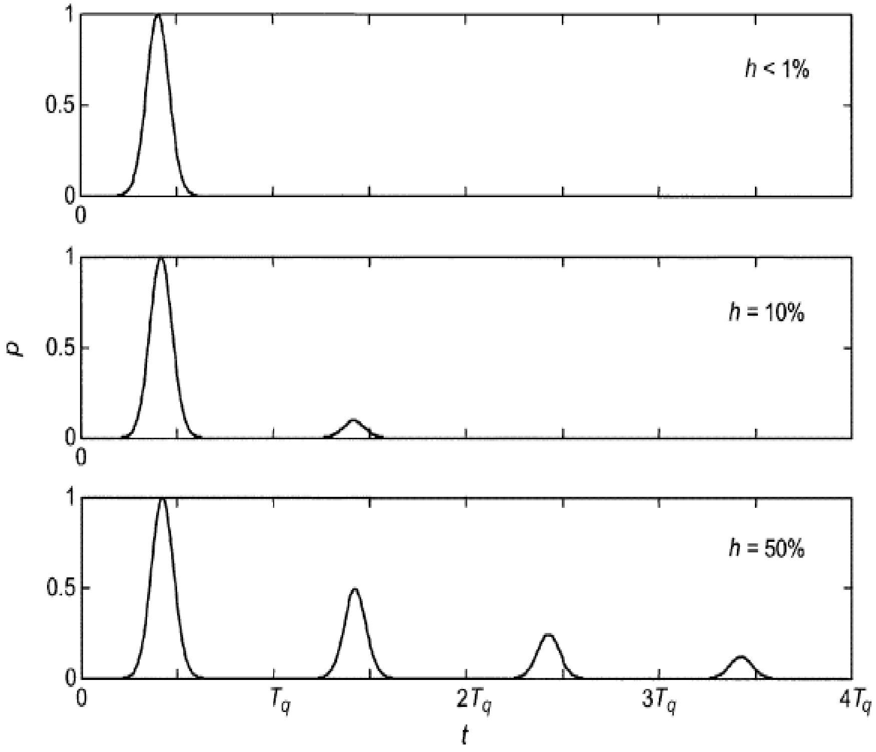
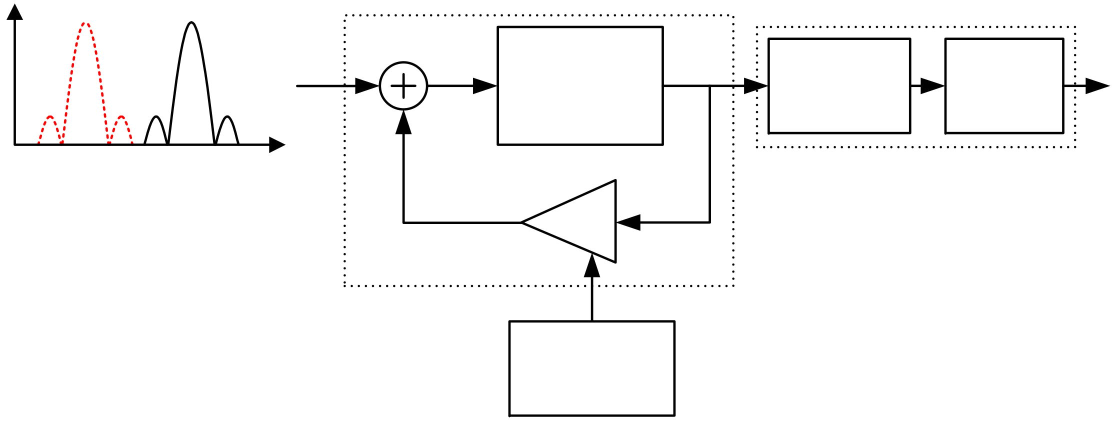
Quench signal frequency limitations

- Avoid resonance from previous cycles (a.k.a. hangover)
- The hangover coefficient is the relationship between the amplitudes of the first cycle and the second (unwanted) one.

$$h = e^{-2\pi\zeta_{AVG}\frac{\omega_0}{\omega_{QU}}}$$



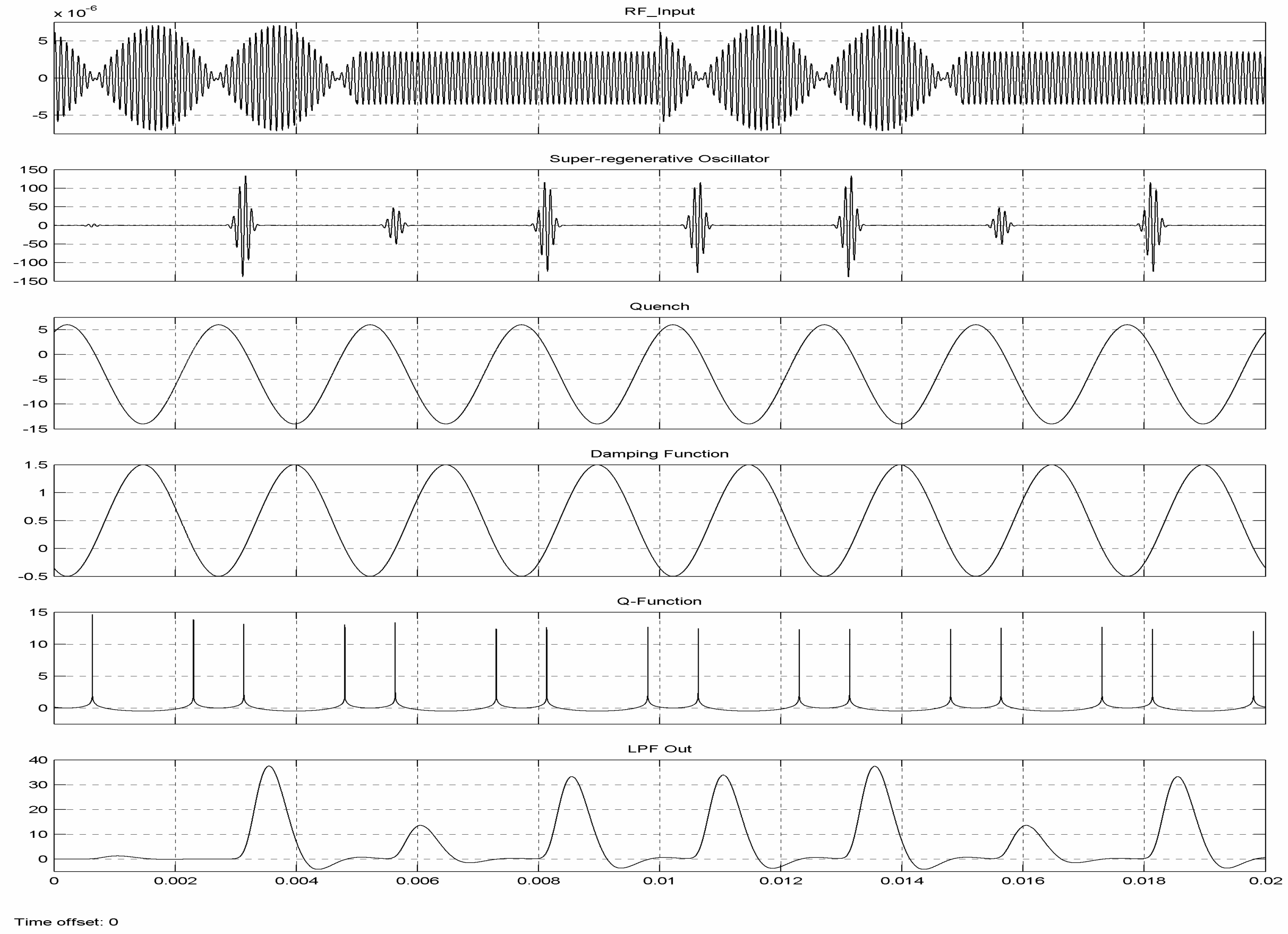
Examples



- Setup
  - $F_{RF} = 10kHz$
  - $F_{INT} = 10.5kHz$
  - $F_{QUENCH} = 100Hz$
  - $Q = 5$
  - LPF: 3^{RD} order Butterworth with f_{3dB} 800Hz
  - Several quench signals

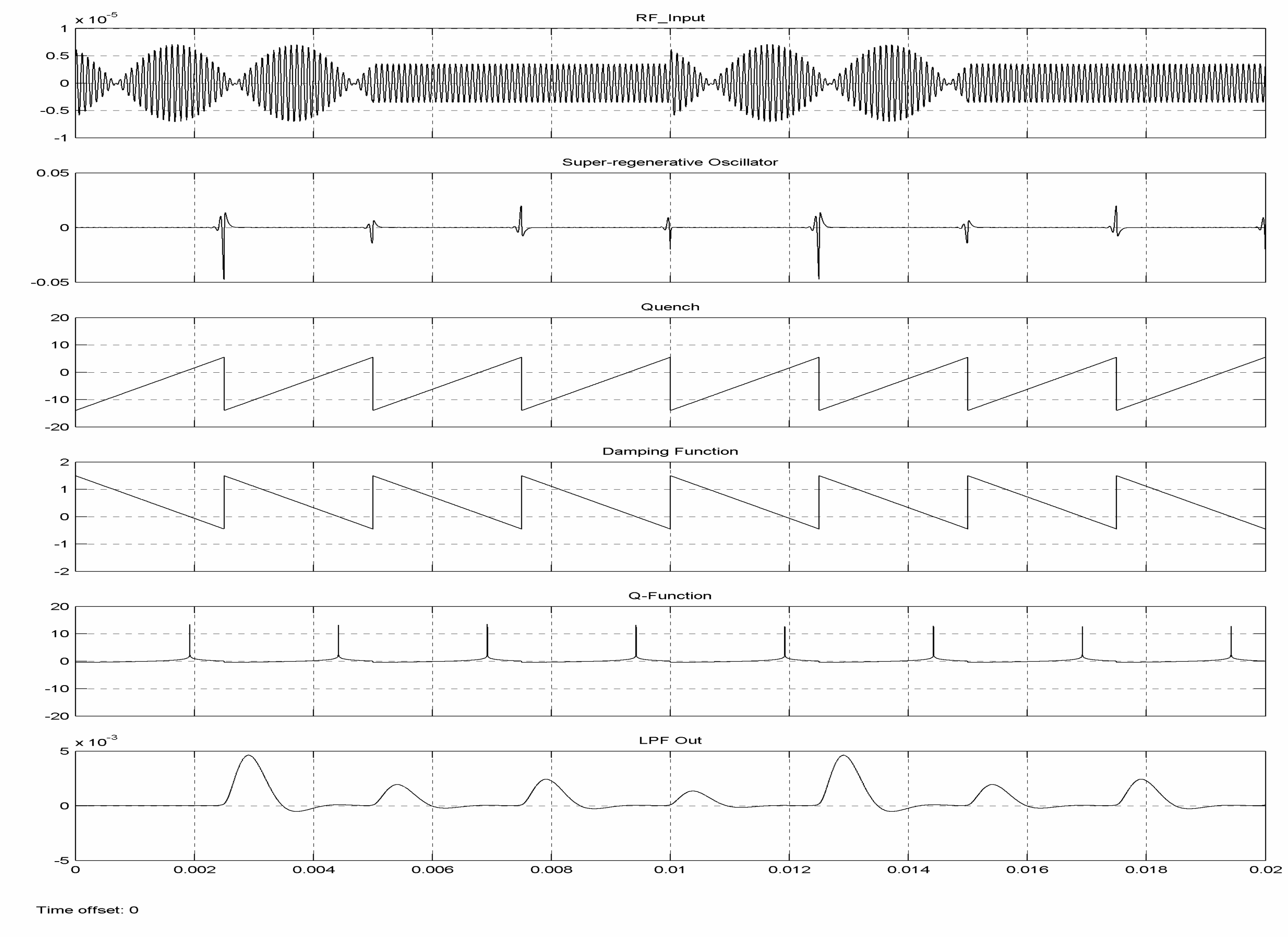
- System was simulated using MatLab’s Simulink.

Sine Quench

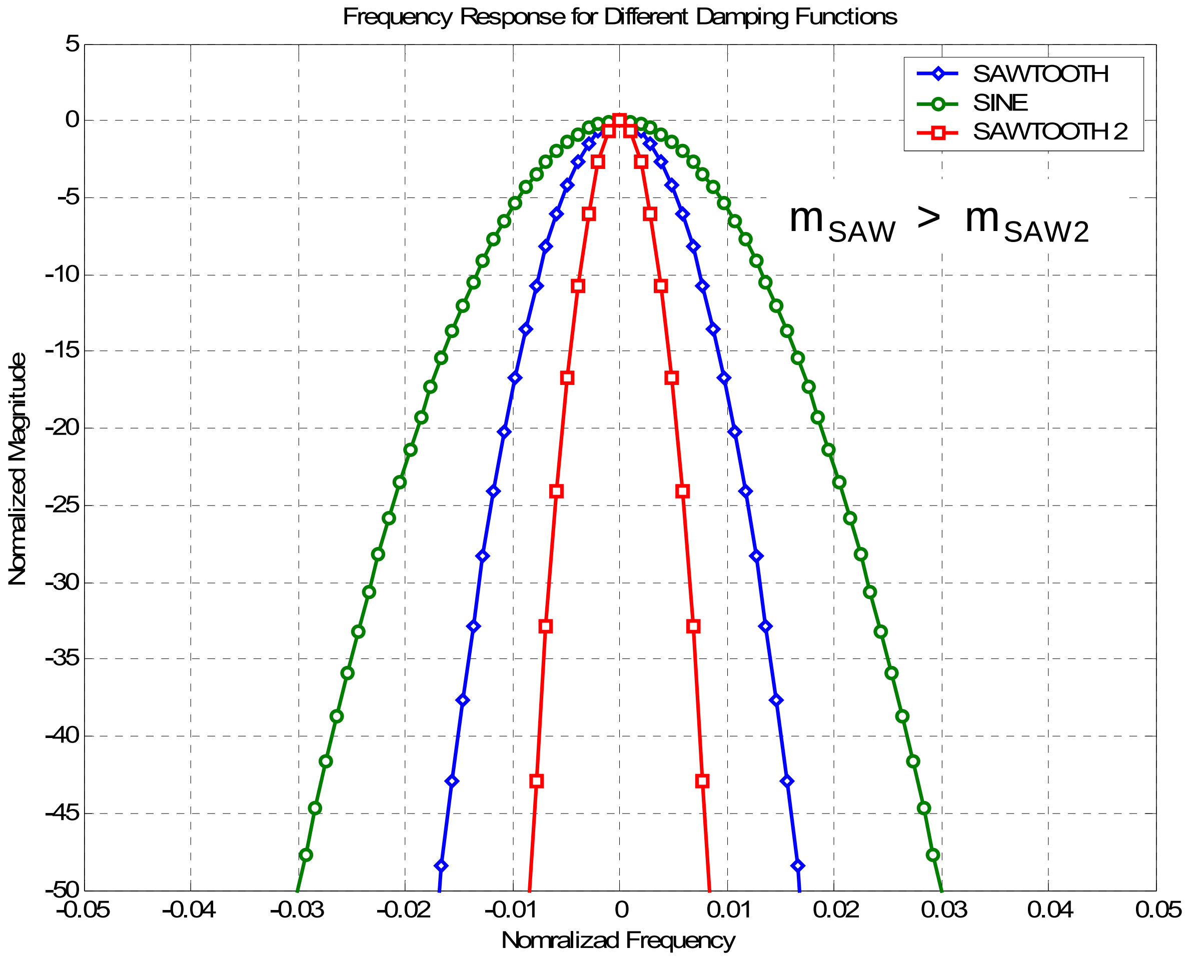


RF_Input
× 10^-6
5
0
-5
Super-regenerative Oscillator
150
100
50
0
-50
-100
-150
Quench
5
0
-5
-10
-15
Damping Function
1.5
1
0.5
0
-0.5
Q-Function
15
10
5
0
LPF Out
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
Time offset: 0

Sawtooth Quench



Different Damping Functions $\zeta(t)$

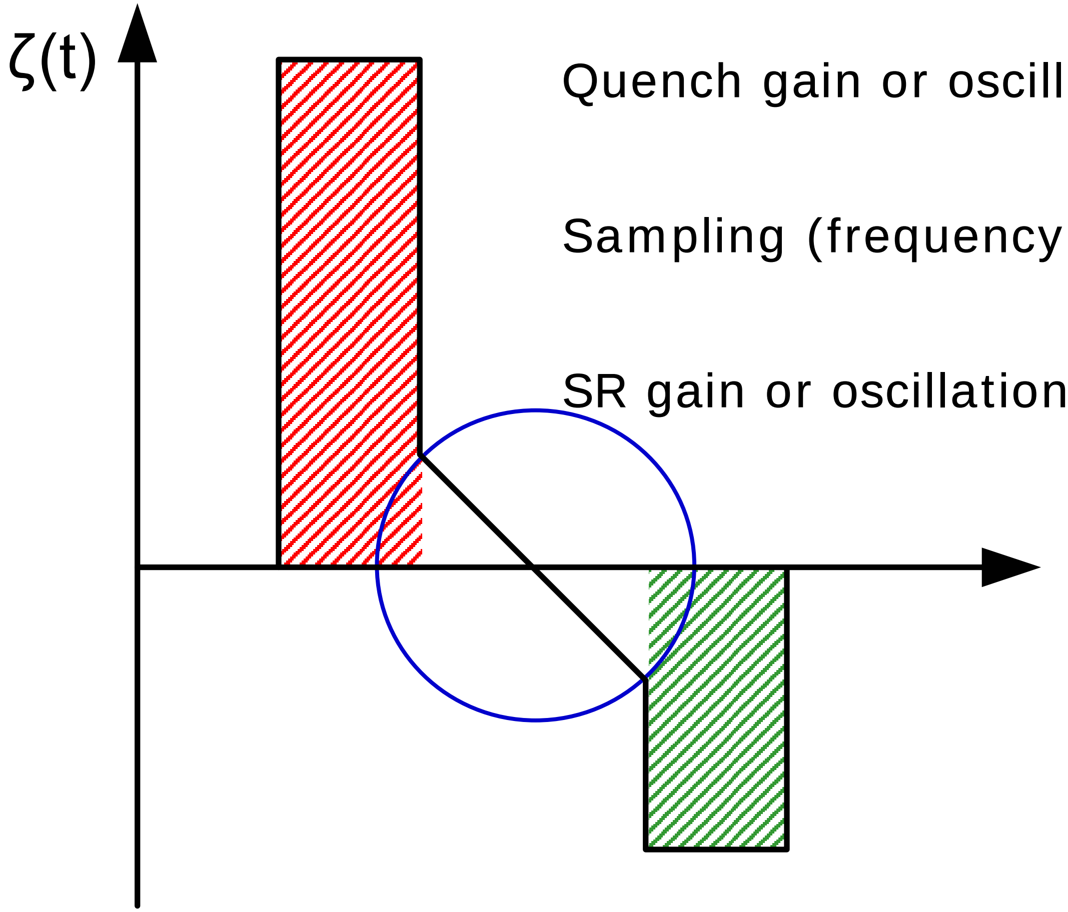


As the transition slope is reduced the SRR shows an narrower frequency response or an increase selectivity

SRR selectivity is controlled mainly by the slope at the transition point

Better selectivity implies better performance under the presence of interferers

Which is the optimal (better selectivity) damping function for a give application?



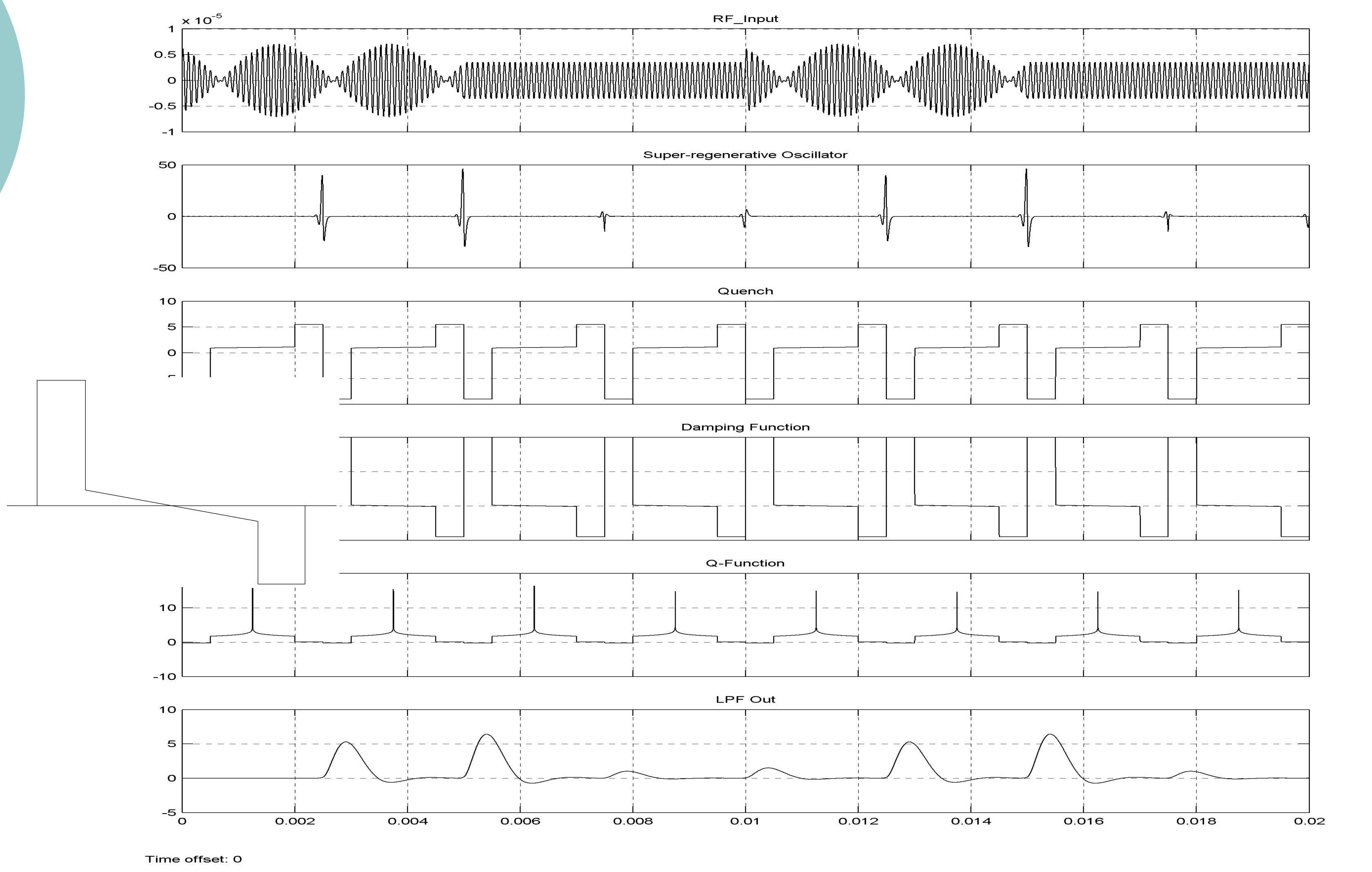
Quench gain or oscillation’s death rate

Sampling (frequency selectivity)

SR gain or oscillation’s growth rate

Find the Optimum for a Given Application !

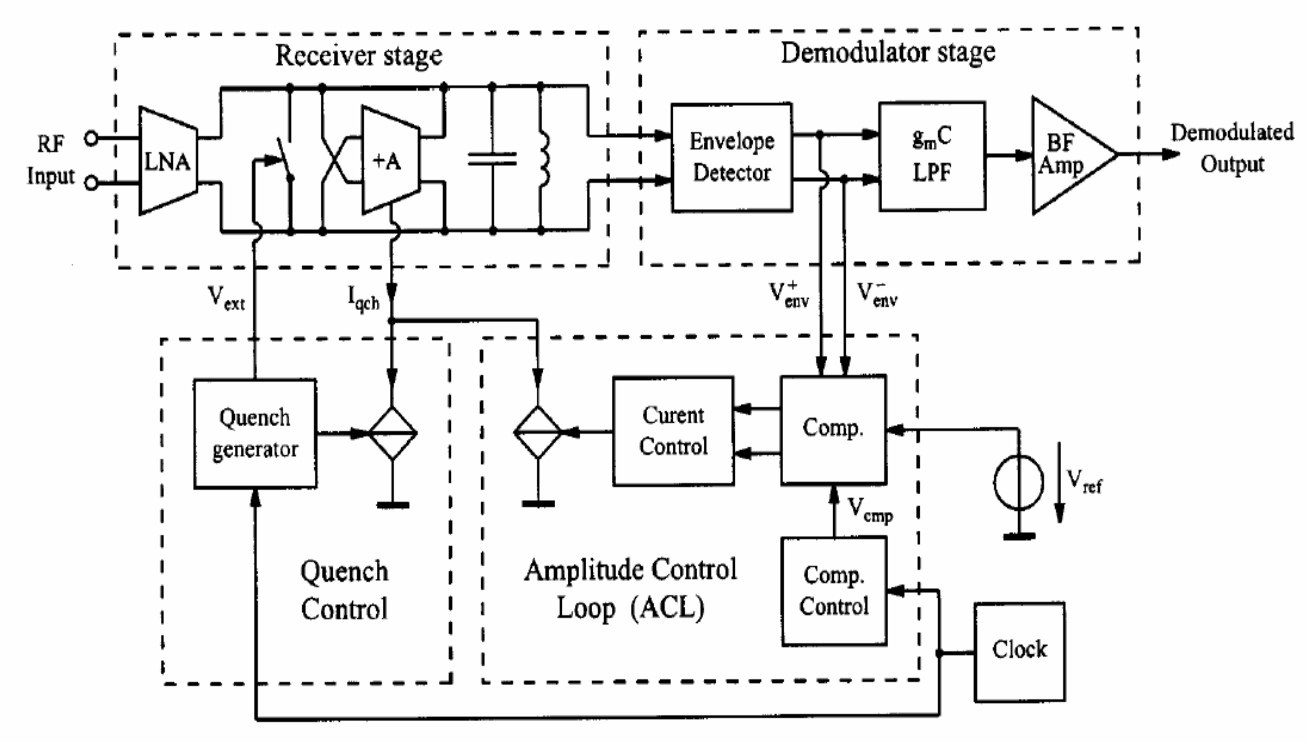
Optimal damping for this case



Modern Applications

- SRR today:
  - Ultra low power communication require minimum energy consumption during the RF communication
- Application fields:
  - short-distance data-exchange wireless link with medium data-rate, such as sensor network, home automation, robotics, computer peripherals, or biomedicine.

Case Studies [6]



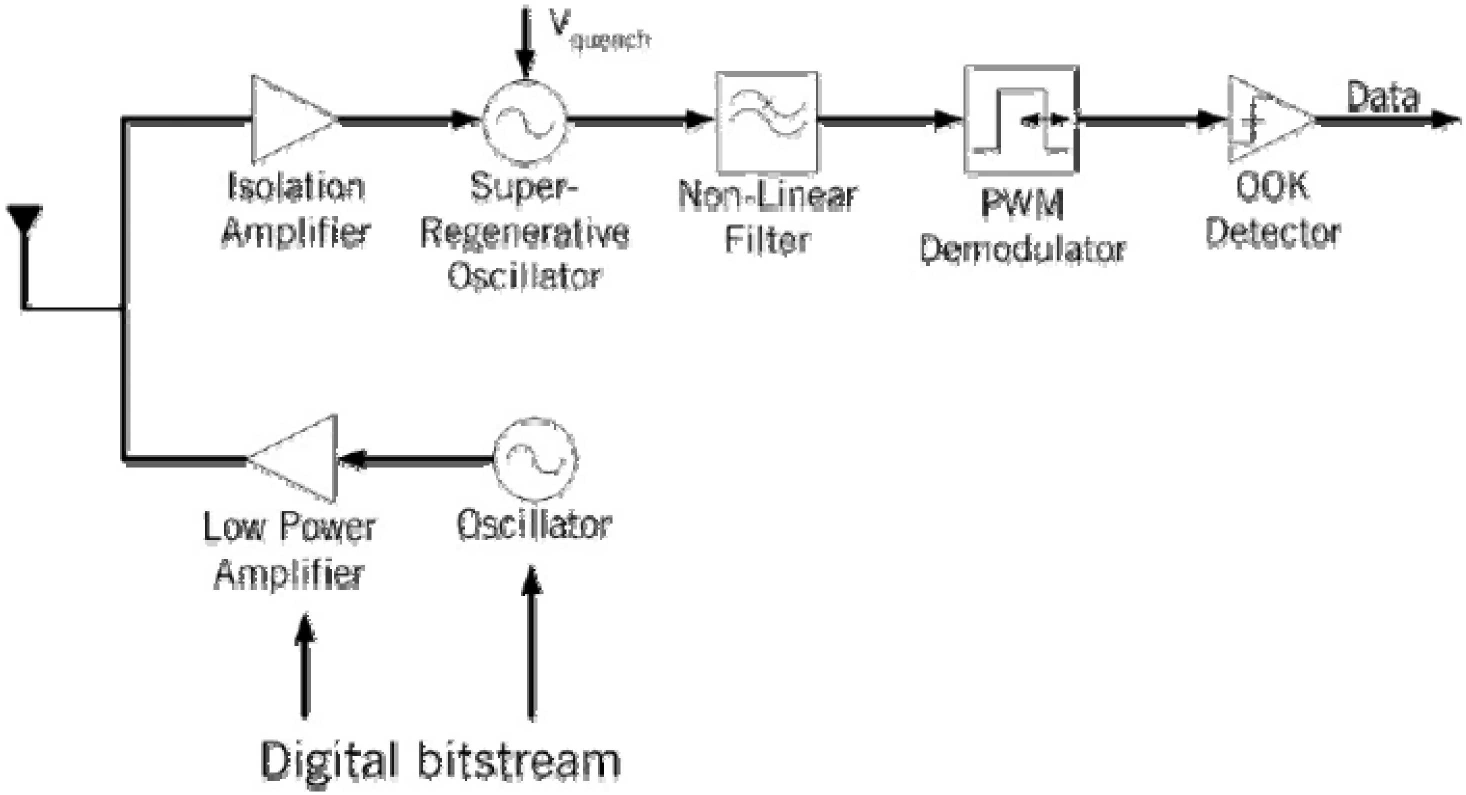
A low-power 1-GHz super-regenerative transceiver with time-shared PLL control

- The SRR behaves like a PLL for a short amount of time to:
  - Tune the frequency
  - Find the optimal transition point

Case Studies [6]

Operating Voltage:	2.4v
Current of RX mode:	1.5mA
Sensitivity:	-105dBm
Selectivity (-5dB attenuation):	150kHz
Data-Rate:	150kbits/s
Frequency Range:	300-1500MHz

Case Studies [5]



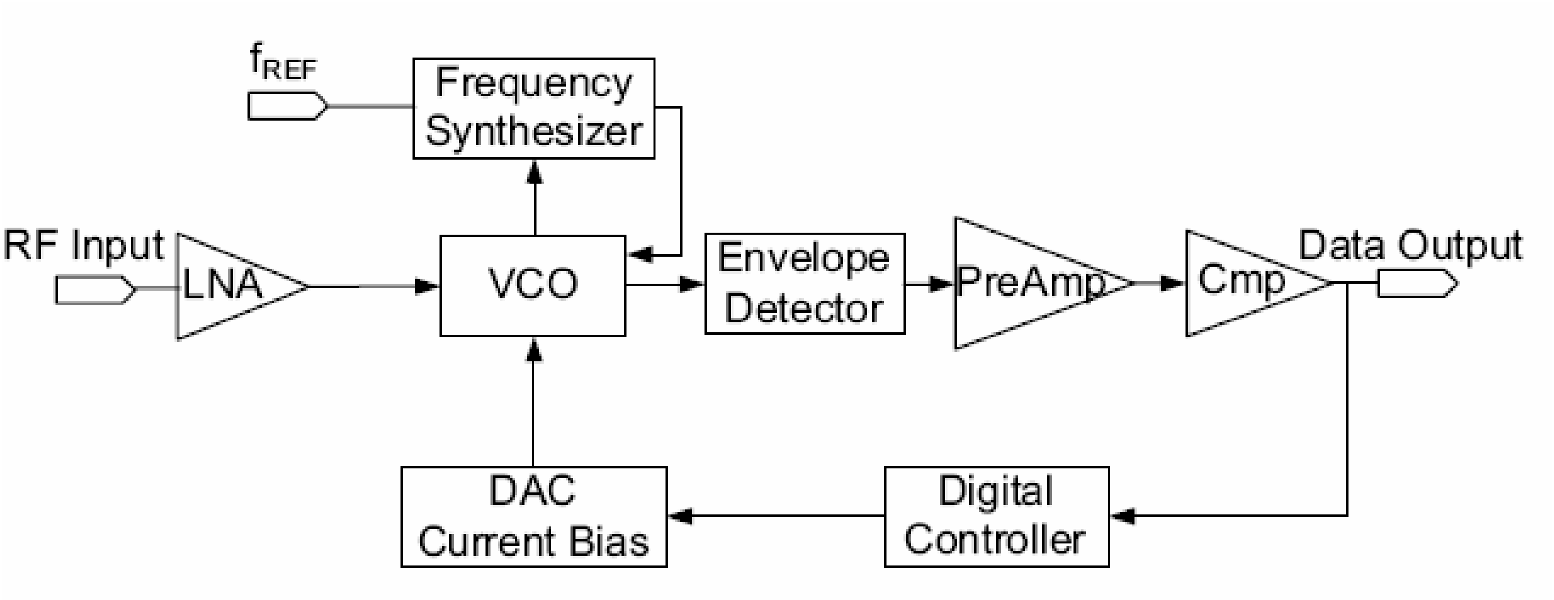
A 400uW-RX, 1.6mW-TX Super-Regenerative Transceiver for Wireless Sensor Networks

The SRO is based on a extremely high-Q BAW resonator thus reducing the required resolution on the Q controlling scheme.

Case Studies [5]

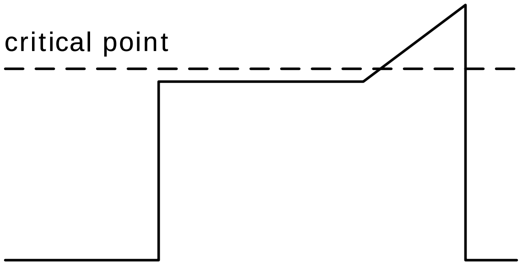
Operating Voltage:	1v
Current of RX mode:	400uA
Sensitivity:	-100.5dBm
Bandwidth:	500kHz
Data-Rate:	5kbits/s
Frequency:	1.7GHz

Case Studies [4]



A 3.6mW 2.4-GHz Multi-Channel Super-Regenerative Receiver in 130nm CMOS

Similar to case study [1] but the quench/damp signal generated is shaped by the digital controller to improved the selectivity.



Case Studies [4]

Operating Voltage:	1.2v
Current of RX mode:	3mA
Sensitivity:	-80dBm
Selectivity (channel space):	10MHz
Data-Rate:	500kbits/s
Frequency Range:	2.4GHz ISM

Challenges:

- Selectivity:
  - Maximize control of quench shape and frequency
- Sensitivity:
  - 5-20dB lower than heterodyne ones
- LC tank tuning:
  - Low-power tuning
- Data rate:
  - How to decrease the quench to modulation frequency ratio
- Integration level:
  - On-chip LC tank with enhanced Q (SAW, BAW)
- Spread spectrum:
  - PN synchronization and frequency de-hopping

References:

[1] E. H. Armstrong, “ Some recent developments of regenerative circuits,” *Proc. IRE*, vol. 10, pp. 244-260, Aug. 1922

[2] J. R. Whitehead, *Super-Regenerative Receivers*. Cambridge Univ. Press, 1950.

[3] F.X. Moncunill-Geniz, P. Pala-Schonwalder, O. Mas-Casals, “A generic approach to the theory of superregenerative reception,” *IEEE Transactions on Circuits and Systems-I*, vol. 52, No.1, pp:54 – 70, Jan. 2005.

[4] J.Y. Chen, M. P. Flynn, and J. P. Hayes, “A 3.6mW 2.4-GHz multi-channel super-regenerative receiver in 130nm CMOS,” *In Proc. IEEE Custom Integrated Circ. Conference*, pp. 361-364, Sep. 2005.

[5] B. Otis, Y. H. Chee, and Y. Rabaey, “A 400uW-RX, 1.6mW-TX super-regenerative transceiver for wireless sensor networks,” *Digest of Technical Papers of the IEEE Int. Solid-State Circ. Conference*, vol. 1, pp. 396-397 and p. 606, San Francisco, Feb. 2005.

[6] N. Joehl, C. Dehollain, P. Favre, P. Deval, M. Declerq, “A low-power 1-GHz super-regenerative transceiver with time-shared PLL control,” *IEEE J. of Solid-State Circuits*, vol. 36, pp:1025 – 1031, Jul. 2001.

[7] P. Favre, N. Joehl, A. Vouilloz, P. Deval, C. Dehollain, M.J. Declercq, “A 2-V 600- µ A 1-GHz BiCMOS super-regenerative receiver for ISM applications,” *IEEE J. of Solid-State Circuits*, vol. 33, pp:2186 – 2196, Dec. 1998.

[8] F.X. Moncunill-Geniz, P. Pala-Schonwalder, C. Dehollain, N. Joehl, M. Declercq, “A 2.4-GHz DSSS superregenerative receiver with a simple delay-locked loop,” *IEEE Microwave and Wireless Components Letters*, vol 15, pp:499 – 501, Aug. 2005.

[9] A. Vouilloz, M. Declercq, C. Dehollain, “A low-power CMOS super-regenerative receiver at 1 GHz,” *IEEE J.Solid-state circuits*, vol. 36, pp:440 – 451, Mar. 2001.

[10] A. Vouilloz, M. Declercq, C. Dehollain, “Selectivity and sensitivity performances of superregenerative receivers,” *Proc. ISCAS’98,* vol.4, pp:325-328, Jun. 1998.

[11] F.X. Moncunill-Geniz, C. Dehollain, N. Joehl, M. Declercq, P. Pala-Schonwalder, “A 2.4-GHz Low-Power Superregenerative RF Front-End for High Data Rate Applications,” *Microwave Conference, 2006. 36th European*, pp:1537 – 1540, Sept. 2006