컴퓨터및 회로설계 특론

Receiver Design

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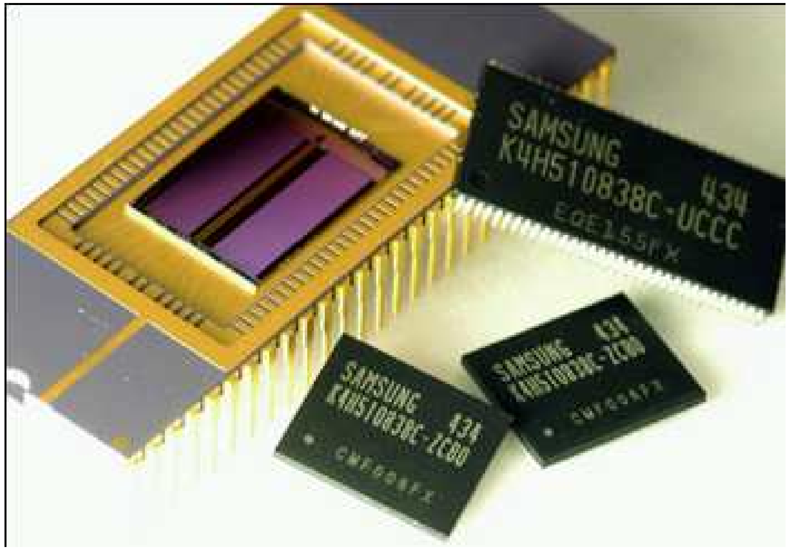
Wireless SOC

Major Products of Korea.

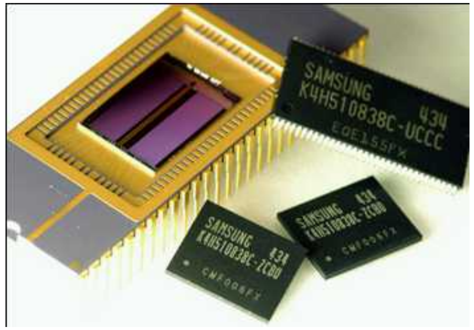
Cell phone

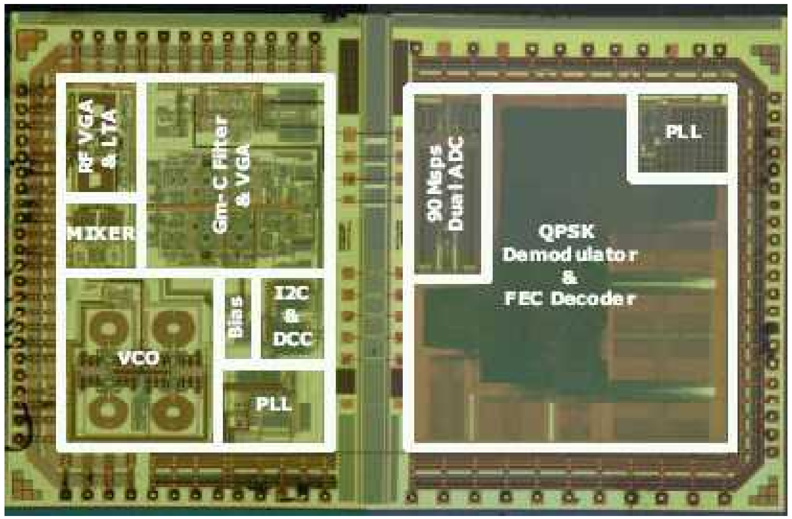


Semiconductor

Wireless SOC; where warm/cold water meet

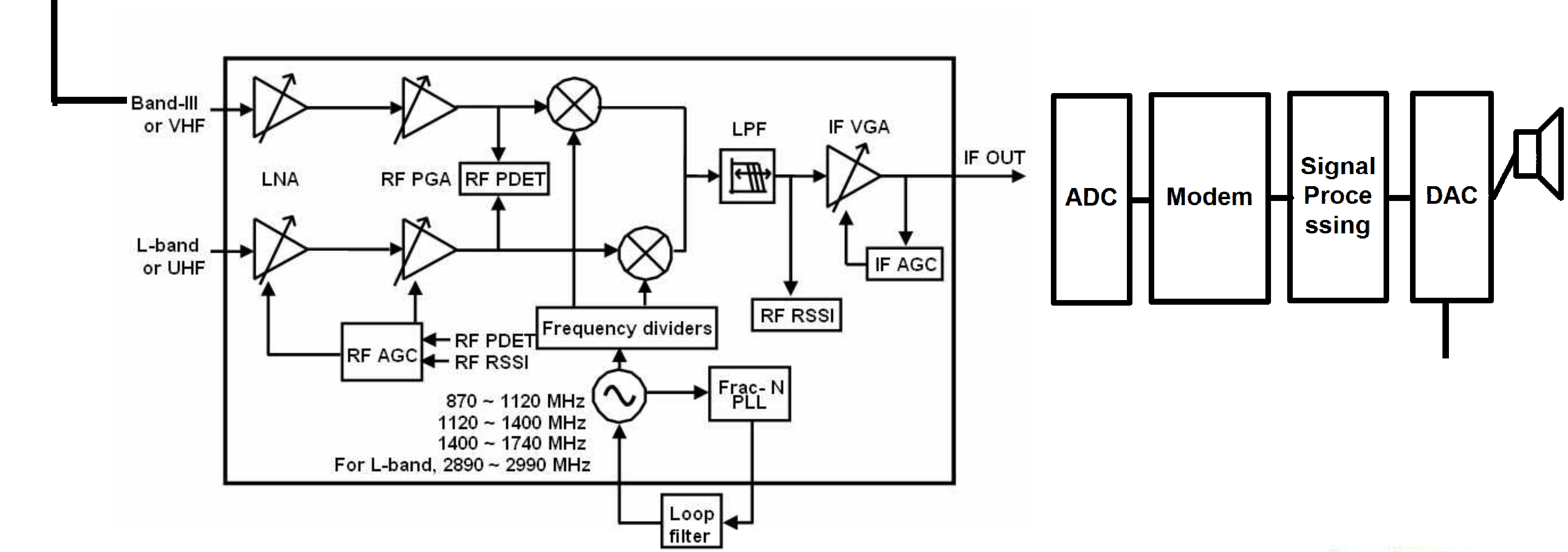
+

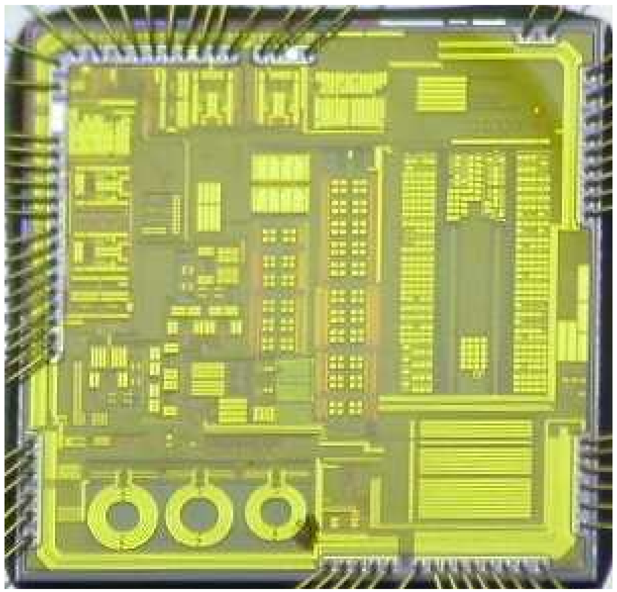


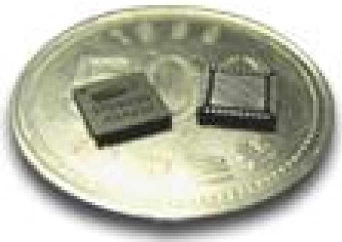


Wireless SOC

Receiver Design; T-DMB







0.18μm CMOS
1.8 V
3.3 x 3.4 mm^2

Receiver Fundamental

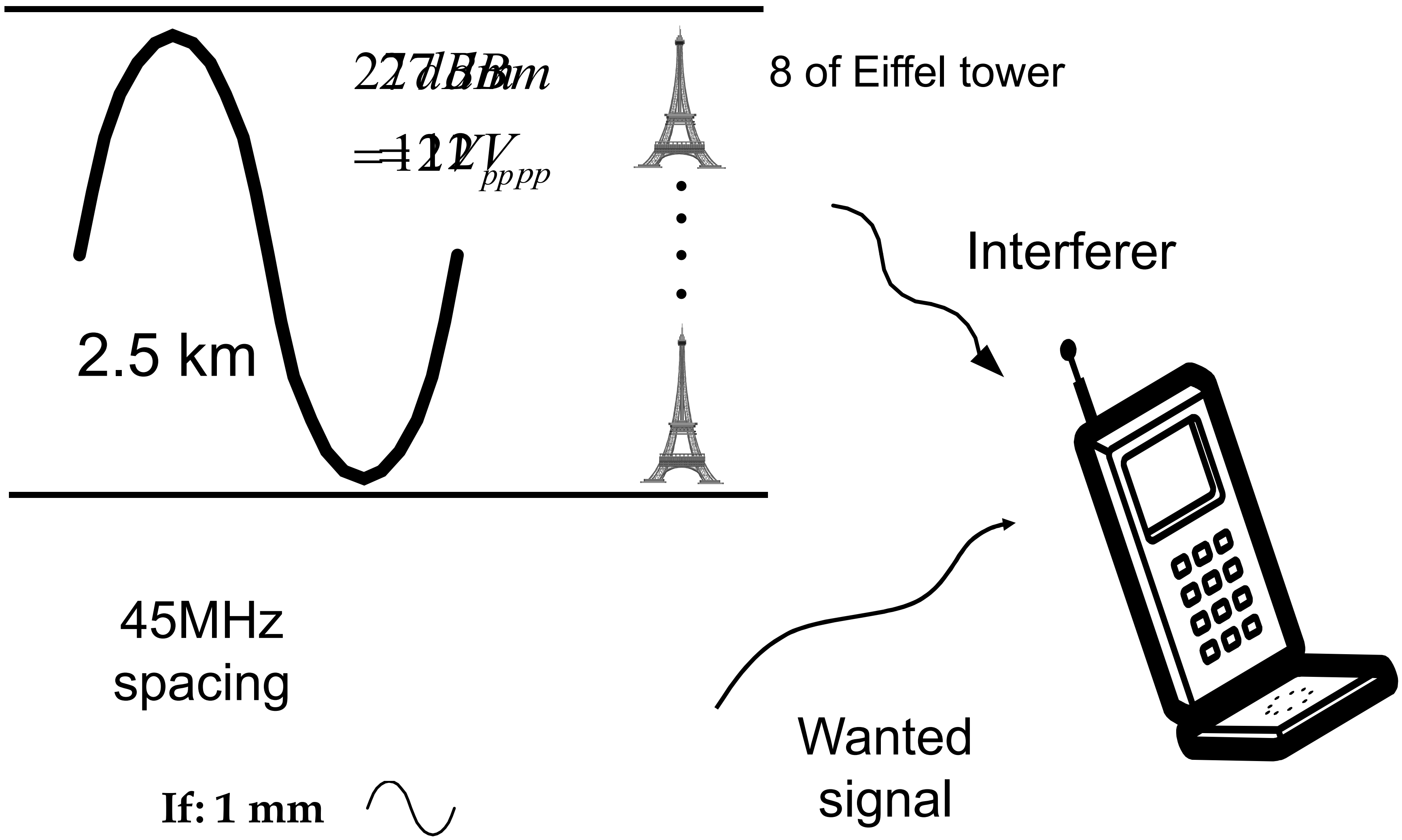
Trade-off between
Sensitivity/Selectivity

Outline

Receiver

- Receiver Fundamental, Selectivity/Sensitivity
- Receiver Budgeting
- Receiver Architecture
- Receiver Architecture Case study

What happens in your mobile phone?



$-101\,dBm = 6\,\mu V_{rms}$
$-101\,dBm = 6\,\mu V_{rms}$

Sensitivity/Selectivity

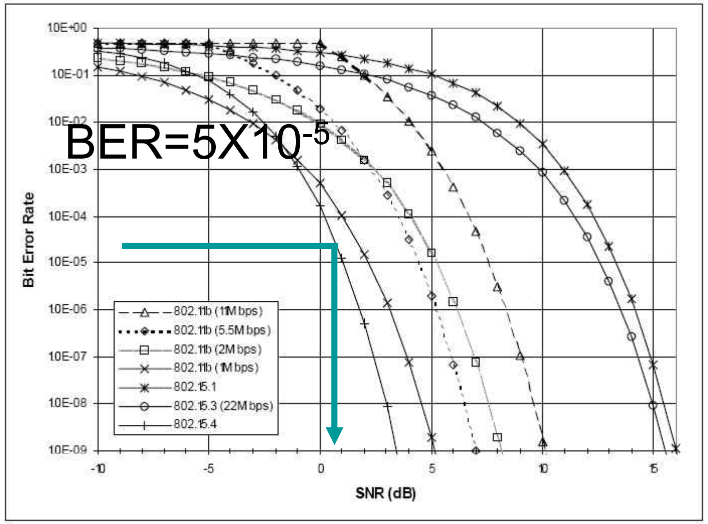
Thus, Receiver Design can be summarized into;

How small signal can Rx detect? :Sensitivity
How large interferer can Rx reject?: Selectivity

Sensitivity : NF

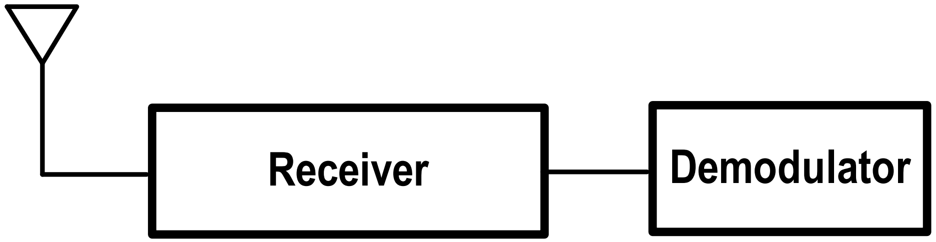
Selectivity : Linearity (IIP3)

Sensitivity (NF) in Receiver



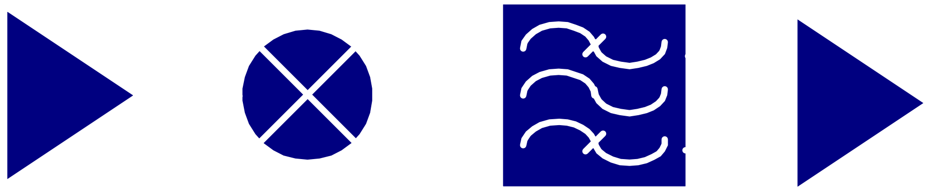
SNR_{min}=2dB (RF BW=2MHz 기준)

- Input SNR (Ex. ZigBee)
  - Reference sensitivity = -85dBm
  - No = -174dBm
  - BW = 10log(2MHz) = 63
  - SNR_{IN} = S-N = – 85 + 174 – 63 = 26 dB
  - SNR_{MIN} =2 dB
  - NF < 24 dB



Standard	SNR_{in}	BER	SNR_{out}	Required NF
ZigBee	26 dB	$5X10^{-5}$	2 dB	24 dB
GSM	19dB	10^{-3}	9 dB	9 dB

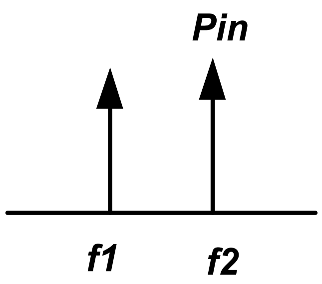
Sensitivity (NF) in Receiver

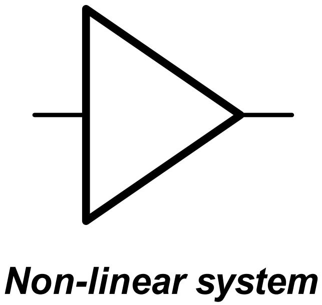


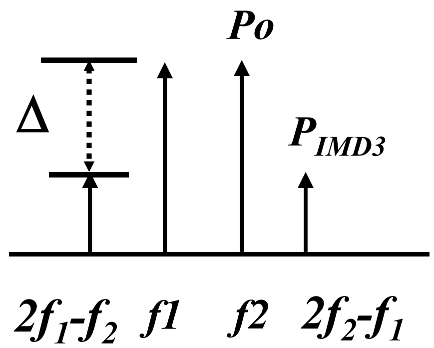
$$NF_{cas} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} \cdots$$

High gain in front / Low NF in front stage

Linearity in RF system





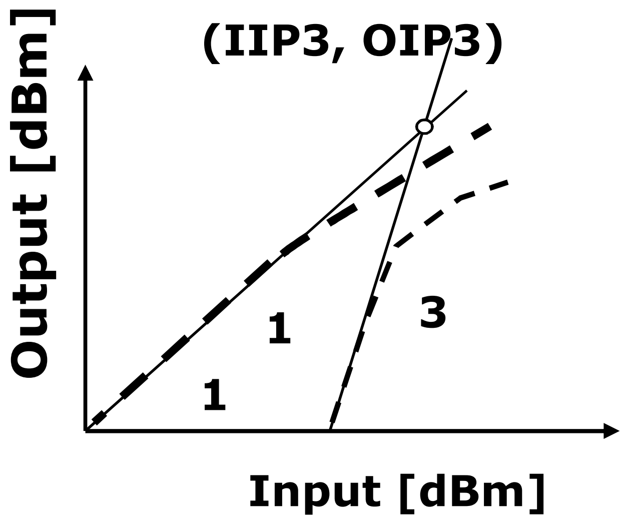


- Nonlinear Device Characteristics

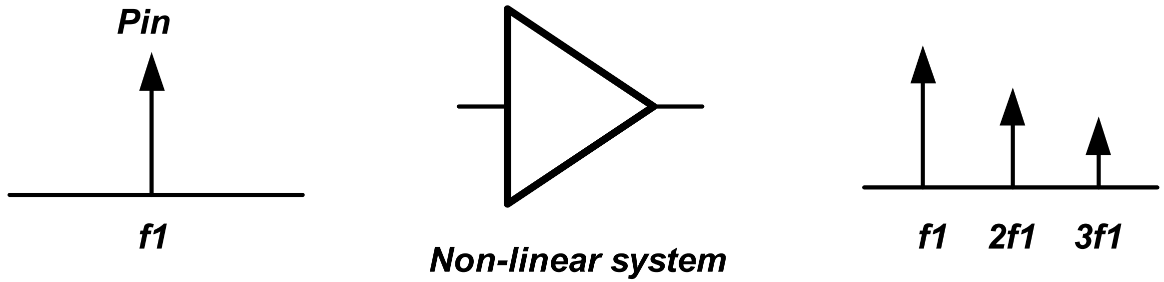
$$V_o(t) = k_0 + k_1 \cdot V_i(t) + k_2 \cdot V_i(t)^2 + k_3 \cdot V_i(t)^3 + \cdots$$

- 3rd -Order intermodulation product

$$IIP3 = P_{in} + \frac{P_o - P_{IMD3}}{2}$$



Harmonic Distortion.



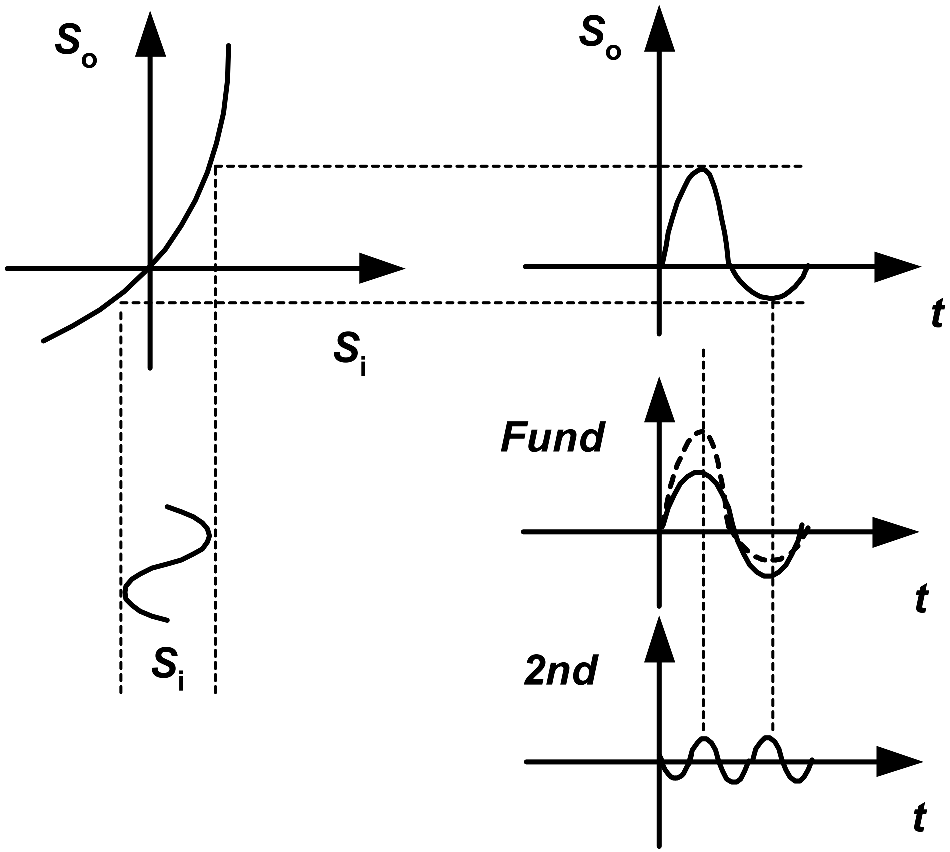
$$S_i = S_1 \cos \omega t \qquad\qquad S_o = a_1 S_i + a_2 S_i^{\,2} + a_3 S_i^{\,3} + \cdots$$

$$S_o = a_1 S_1 \cos \omega t + a_2 S_1^{\,2} \frac{1}{2}\left\{\cos(\omega_1 + \omega_1)t + \cos(\omega_1 - \omega_1)\right\}$$

$$+ a_3 S_1^{\,3} \frac{1}{4}\left\{\cos(\omega_1 + \omega_1 + \omega_1)t + 3\cos \omega_1 t\right\} + \cdots$$

$$HD2 = \frac{2nd\ \ harmonic}{fundamental} = \frac{a_2 S_1^{\,2}\,\frac{1}{2}}{a_1 S_1} = \frac{1}{2}\frac{a_2 S_1}{a_1} \qquad HD3 = \frac{3rd\ order\ harmonic}{fundamental} = \frac{a_3 S_1^{\,3}\,\frac{1}{4}}{a_1 S_1} = \frac{1}{4}\frac{a_3 S_1^{\,2}}{a_1}$$

2nd order distortion waveform

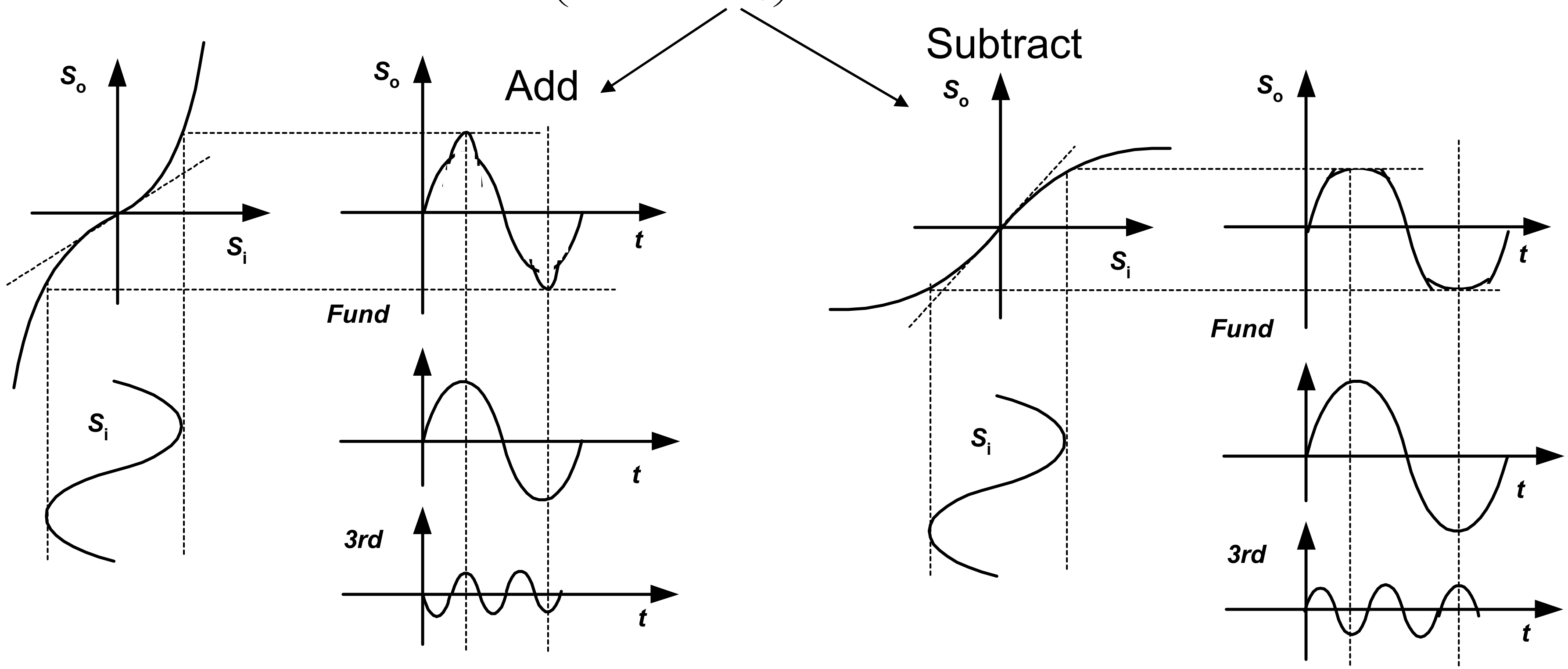


3rd order distortion waveform

$$S_o = a_1 S_1 \cos \omega t + a_2 S_1^{\,2}\,\frac{1}{2}\left\{\cos(\omega_1 + \omega_1)t + \cos(\omega_1 - \omega_1)\right\}$$

$$+ a_3 S_1^{\,3}\,\frac{1}{4}\left\{\cos(\omega_1 + \omega_1 + \omega_1)t + 3\cos \omega_1 t\right\} + \cdots$$

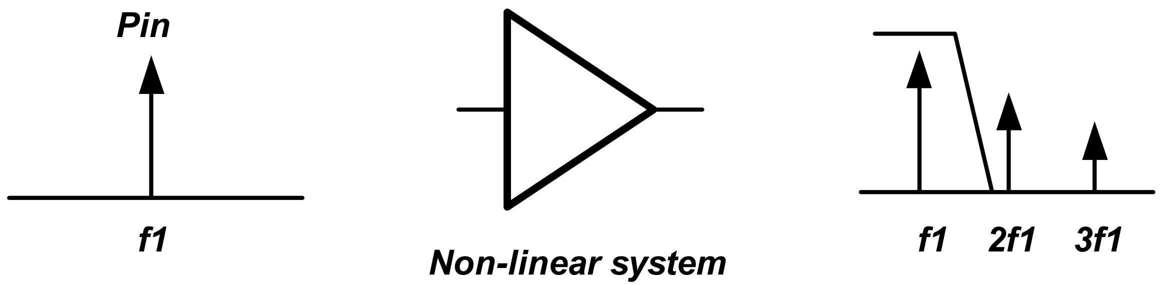
$$= \left(a_1 S_1 + a_3 S_1^{\,3}\,\frac{3}{4}\right)\cos \omega_1 t$$



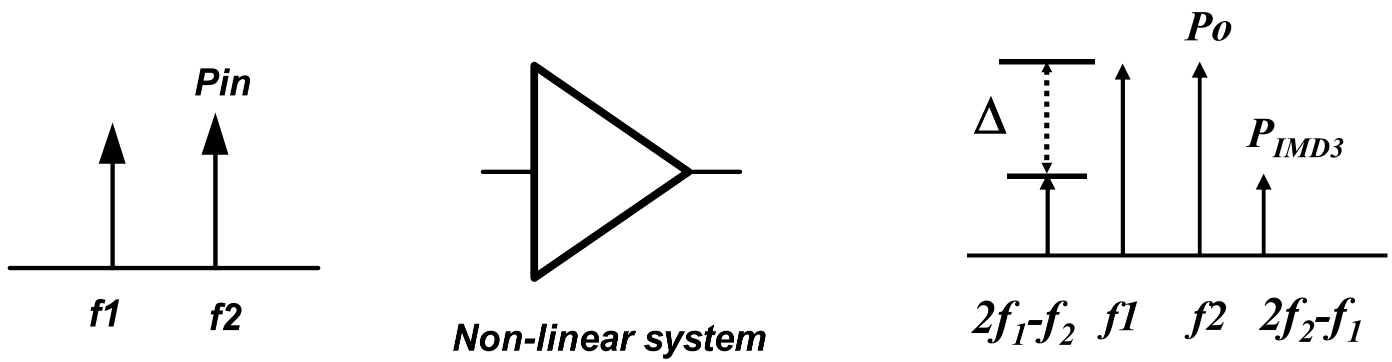
gain expansion

gain compression

Intermodulation Distortion (IMD)

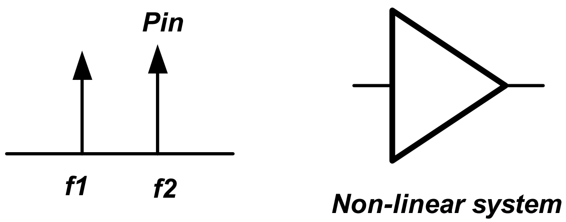


HD2 and HD3 can be rejected by Filter



Narrow band filter : High cost, bulky; impractical

Two tone test



$$S_i = S_1 \cos \omega_1 t + S_2 \cos \omega_2 t \qquad S_o = a_1 S_i + a_2 S_i^{\,2} + a_3 S_i^{\,3} + \cdots$$

$$S_o = a_1\left(S_1 \cos \omega_1 t + S_2 \cos \omega_1 t\right) + a_2\left(S_1 \cos \omega_1 t + S_2 \cos \omega_1 t\right)^2$$
$$+ a_3\left(S_1 \cos \omega_1 t + S_2 \cos \omega_1 t\right)^3 + \cdots$$

$$a_2\left(S_1 \cos \omega_1 t + S_2 \cos \omega_2 t\right)^2$$
$$= a_2\left(S_1^{\,2} \cos \omega_1 t \cos \omega_1 t + S_1 S_2 \cos \omega_1 t \cos \omega_2 t + S_2^{\,2} \cos \omega_2 t \cos \omega_2 t\right)$$
$$= a_2 S_1^{\,2} \frac{1}{2}\left(\cos 2\omega_1 t + 1\right) + a_2 S_2^{\,2} \frac{1}{2}\left(\cos 2\omega_2 t + 1\right)$$
$$+ 2a_2 S_1 S_2 \left\{ \frac{1}{2}\left(\cos\left(\omega_1 + \omega_2\right)t\right) + \frac{1}{2}\left(\cos\left(\omega_1 - \omega_2\right)t\right) \right\}$$

HD2 and DC

Second order Intermodulation Distortion

Third order intermodulation distortion

$$(a+b)^3 = a^3 + 3a^2b + 3ab^2 + b^3$$

$$a_3\left(S_1\cos\omega_1 t + S_2\cos\omega_2 t\right)^3$$

$$= a_3\begin{pmatrix} S_1^{\ 3}\cos^3\omega_1 t + 3S_1^{\ 2}S_2\cos^2\omega_1 t\cos\omega_2 t \\ +3S_2^{\ 2}S_1\cos\omega_1 t\cos^2\omega_2 t + S_2^{\ 3}\cos^3\omega_2 t \end{pmatrix}$$

$$= \frac{a_3S_1^{\ 3}}{4}\left(\cos 3\omega_1 t + 3\cos\omega_1 t\right) + \frac{a_3S_2^{\ 3}}{4}\left(\cos 3\omega_2 t + 3\cos\omega_2 t\right)$$

Same as single input HD3

$$+\frac{3}{4}S_1S_2^{\ 2}\left(2\cos\omega_1 t + \cos\left(2\omega_2 \pm \omega_1\right)t\right)$$

$$+\frac{3}{4}S_1^{\ 2}S_2\left(2\cos\omega_2 t + \cos\left(2\omega_1 \pm \omega_2\right)t\right)$$

IMD3

$$2\omega_2 \pm \omega_1$$

$$2\omega_1 \pm \omega_2$$

IM3, IIP3, OIP3

$$IM3 = \frac{3rd\ \ IM}{fundamental} = \frac{3}{4}\frac{a_3 S_1^{\ 3}}{a_1 S_1}$$

$$= \frac{3}{4}\frac{a_3 S_1^{\ 2}}{a_1},\ (S_1 = S_2)$$

$$= 3HD_3$$

$$= HD_3(dB) + 10dB$$

$$IM3 = \frac{3}{4}\frac{a_3}{a_1}S_1^{\ 2} = \frac{3}{4}\frac{a_3}{a_1^{\ 2}}S_o^{\ 2}\ \left(S_o = a_1 S_1\right)$$

$$IIP3 = input\ \ power\ at\ IM3 = 1$$

$$IIP3 = S_1 = \sqrt{\frac{4}{3}\left|\frac{a_1}{a_3}\right|}$$

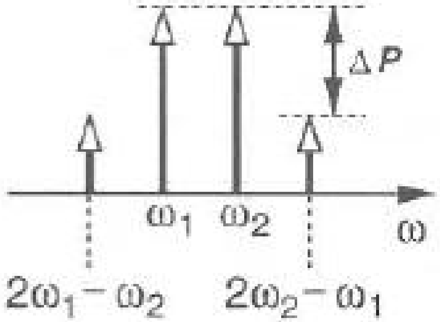
$$OIP3 = output\ \ power\ at\ IM3 = 1$$

$$OIP3 = \sqrt{\frac{4}{3}\left|\frac{a_1^{\ 2}}{a_3}\right|} = IIP3 \times Gain$$

$$dB\ relationship$$

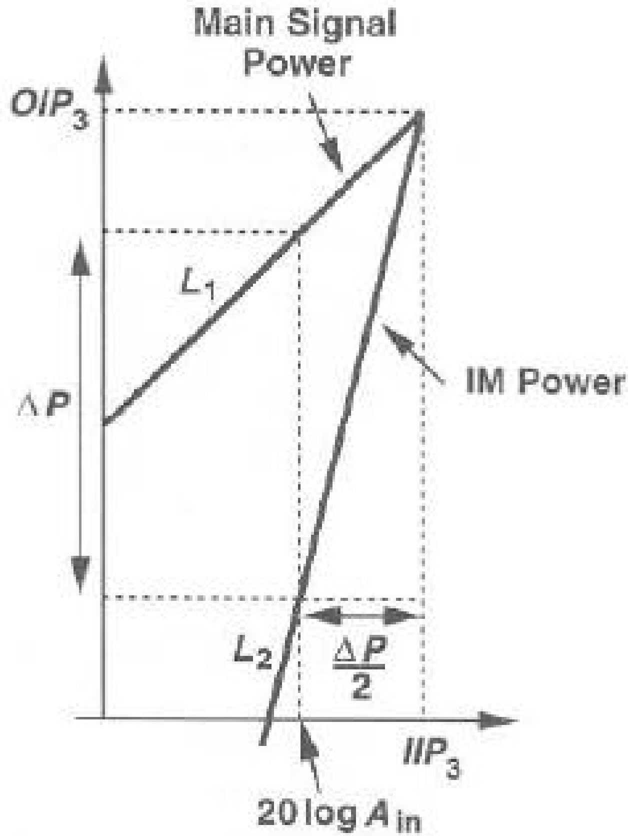
$$OIP3 = IIP3 + Gain\ \ (dB)$$

Two tone test



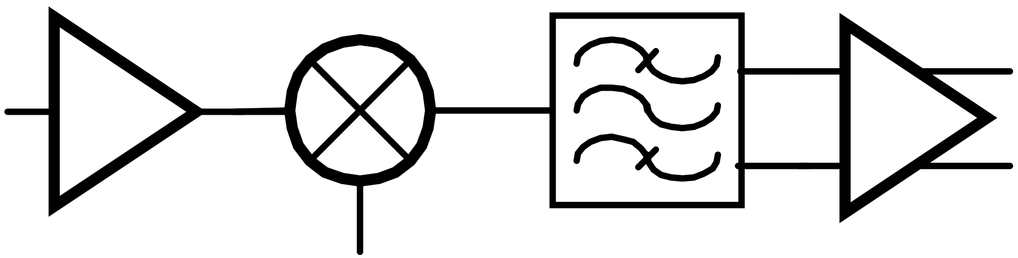
$$IIP_3\big|_{dBm} = \frac{\Delta P\big|_{dB}}{2} + P_{in}\big|_{dBm}$$

(a)



(b)

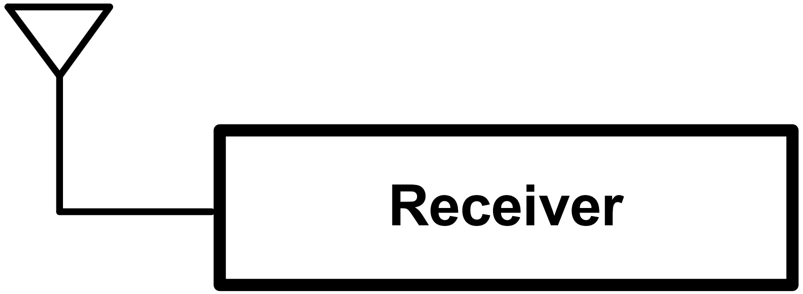
Selectivity (IIP3) in Receiver



$$\frac{1}{IIP3_{cas}} = \frac{1}{IIP3_1} + \left(\frac{Gp_1}{IIP3_2} \right) + \left(\frac{Gp_1 \cdot Gp_2}{IIP3_3} \right) + \ldots$$

Low gain in front stage / High IIP3 at rear stage

Trade-off between Sensitivity and Selectivity



NF

High gain @ front stage

IIP3

Low gain @ front stage

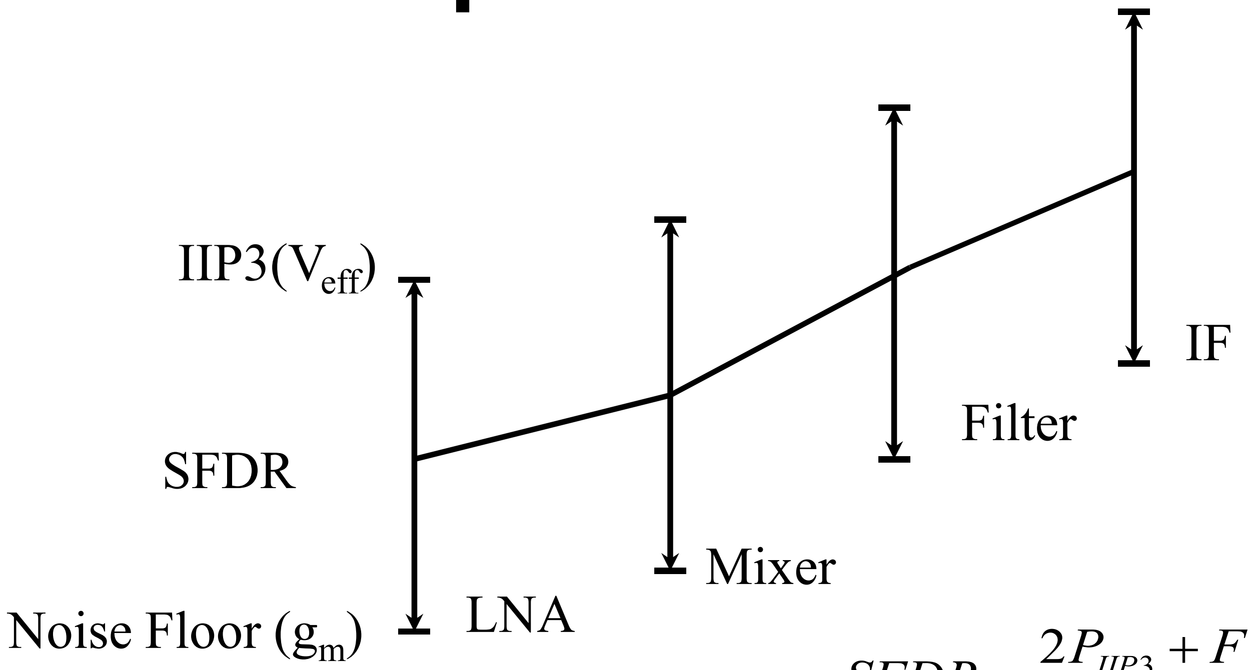
Architecture Considerations

Architecture	Inherent Merits	Inherent Demerit	Spurious Problems	Conclusion
Double IF (super heterodyne)	-Long history of experience -Best choice in selectivity & sensitivity	-Need external Duplex /RF IR / IF filters -Worst in integration bigger size, larger power consumption		Still most popular
Zero IF (DCR)	-Higher degree of Integration	-Hard to optimize selectivity/sensitivity	-DC-offset -LO-emission -1/f noise etc.	Maybe O.K. for wideband system
Single IF with DCR	-DCR at lower frequency: spurious problems in DCR can be solved much easier -Relaxed IR filter requirement with larger IF -Better selectivity/sensitivity optimization than DCR	-Worse selectivity/sensitivity optimization than double IF	-DCR problems still exist, but much more relaxed	Most promising for wideband system

Architecture Considerations(2)

Architecture	Inherent Merits	Inherent Demerit	Spurious Problems	Conclusion
Hartley IF with low IF	-Same degree of integration as that of DCR	-Selectivity/sensitivity performance similar to DCR -Limited poly-phase filter accuracy	-LO emission	Look best for extremely low power narrow band system
Weaver IR with low 2nd IF	-Much less requirement for IR filter	-Similar to single IF	-Hardware complexity	
Weaver IR with low 1st IF	-Can have precise IR using DSP	-Selectivity/sensitivity performance similar to DCR	-Hardware complexity -LO emission -Compensation for entire BW and temperature change	Most promising for narrow band system

SFDR (Spurious Free Dynamic Range) Optimization



$$SFDR = \frac{2P_{IIP3} + F}{3} - (F + SNR_{\min})$$

$$F = -174dBm + NF + 10\log B$$

Optimization Procedure

- Find out required DR of whole Receiver
- Let each block have same DR
- Proper gain distribution to satisfy DR alignment (center)

Receiver Budgeting (GSM example)

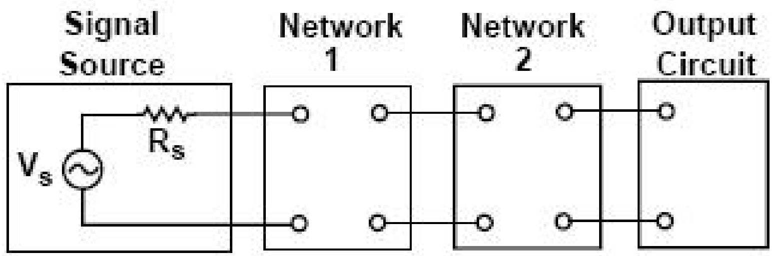
	Antenna	RF Filter	T/R Switch	Balun	LNA	Mixer (LO1)	Mixer (LO2)	AA Filter	ADC
Gain-Power	0	-2	-1	-1					
Gain-Av (dB)	0	-2	-1	-1	22	10	10	12	0
Gain (Av/Av)^2	1	0.630957	0.79432823	0.7943282	158.4893192	10	10	15.848932	1
Gain (Av/Av)	1	0.794328	0.89125094	0.8912509	12.58925412	3.16227766	3.16227766	3.9810717	1
Gain (Total)		-2	-3		19	29	39	51	51
Avail. Noise Power (dBm)	-120.7897	-120.7897	-120.7897	-120.7897					
Avail. Noise Level (dBV) (200kHz)	-133.7897	-133.7897	-133.7897	-133.7897	-109.4057467	-98.87172092	-88.6014715	-76.39653	-76.27816
Avail. Noise Power (watts) (200kHz BW)									
Minimum Signal Level Output (dBm)	-102	-104	-105	-106					
Minimum Signal Level Output (V^2) (dBV)	-115.0103	-117.0103	-118.0103	-119.0103	-97.01029996	-87.01029996	-77.01029996	-65.0103	-65.0103
Minimum Signal Level Output (Vrms^2)	3.15E-12	1.99E-12	1.58E-12	1.256E-12	1.99054E-10	1.99054E-09	1.99054E-08	3.155E-07	3.155E-07
Minimum Signal Level Output (Vrm)	1.78E-06	1.41E-06	1.26E-06	1.12E-06	1.41E-05	4.46E-05	1.41E-04	5.62E-04	5.62E-04
Minimum Signal Level Output (Vo-p)	2.5119E-06	2E-06	1.7783E-06	1.585E-06	1.99526E-05	6.30957E-05	0.000199526	0.0007943	0.0007943
Impedance	50	50	50	50	400	500	4000		
Vrms^2 (V^2/Hz) (Input Source Noise)					8.3E-19				
Req (Noise Equivalent Resistance) Input	12.5	12.5	12.5	12.5	9.2	4.50E+02	2.50E+03	2.00E+04	190000
Req (Noise Equivalent Resistance) Source									
Req (Noise Equivalent Resistance) Source					3439.218228	38892.18228	413892.2122	6876728.1	7066728.1
Vrms^2 (V^2) in 200kHz BW Noise	4.1675E-14	4.17E-14	4.1675E-14	4.168E-14	1.14664E-11	1.29667E-10	1.37992E-09	2.293E-08	2.356E-08
Block Noise Contribution (Receiver Input)				12.5	9.2	2.83930805	1.575525063	1.2619147	0.7564036
Noise Factor	5.65338251	3.567043	2.83340314	2.2506521					
Noise Figure	7.52308371	5.523084	4.52308371	3.5230837					
SNR (dB) (dBV/dBV) (GSM Sensitivity Test)	18.7794001	16.7794	15.7794001	14.7794	12.39544675	11.86142096	11.59117154	11.386226	11.26786
Adjacent Channel Interferer (dBm)	-49	-47	-46	-45					
Adjacent Channel Interferer (dBV)	-62.0103	-60.0103	-59.0103	-58.0103	-36.01029996	-26.01029996	-16.01029996	-4.0103	-4.0103
Adjacent Channel Interferer (Vrms^2)	6.29E-07	9.98E-07	1.26E-06	1.58E-06					

- Optimal Receiver Budgeting w.r.t System
- As large as possible SFDR w.r.t building block

Ref: Rudell

Receiver Budgeting (2) Integrated NF

$$F_n = F_1 + \frac{(F_2 - 1)}{G_1} + \ \dots + \frac{F_n - 1}{\prod_{i=1}^{n} G_i}$$



(EQ 20)

$$R_{Integrated} = R_{LNA} + \frac{R_{Mixer1}}{Av_{LNA}^{2}} + \frac{R_{Mixer2}}{(Av_{LNA} \cdot Av_{Mixer1})^2} + \frac{R_{BB}}{(Av_{LNA} \cdot Av_{Mixer1} \cdot Av_{Mixer2})^2}$$

(EQ 21)

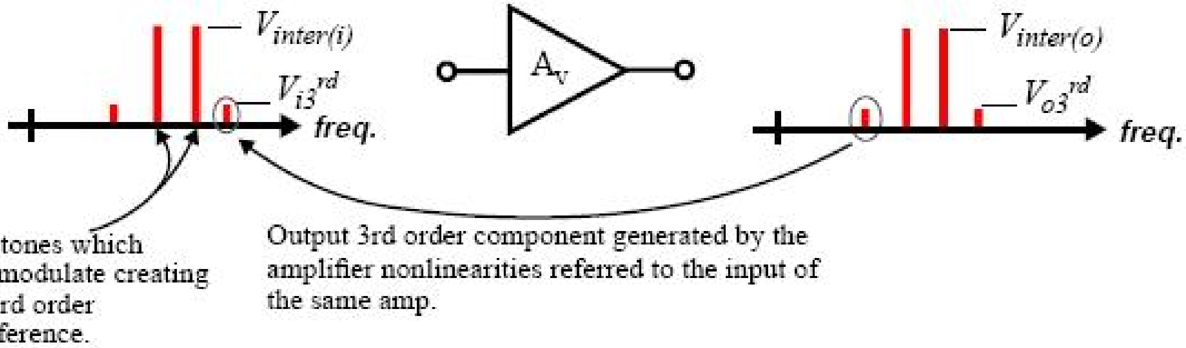
$$F_{Integrated} = \frac{R_{board} + R_{LNA} + \frac{R_{Mixer1}}{Av_{LNA}^{2}} + \frac{R_{Mixer2}}{(Av_{LNA} \cdot Av_{Mixer1})^2} + \frac{R_{BB}}{(Av_{LNA} \cdot Av_{Mixer1} \cdot Av_{Mixer2})^2}}{R_{board}}$$

$$F_{Receiver} = F_{RFfilter} + \frac{F_{TR}}{G_{RF}} + \frac{F_{Balun}}{G_{RF}G_{TR}} + \frac{F_{Integrated}}{G_{RF}G_{TR}G_{Balun}}$$

Receiver Budgeting (3) Integrated IIP3

$$V_{o3^{rd}} = \frac{V_{inter(o)}^{\ 3}}{V_{IP3o}^2}$$

$$V_{i3^{rd}} = \frac{V_{inter(i)}^{\ 3}}{V_{IP3i}^2}$$



$$V_{in}^{3rd} = \frac{A_{v3} \cdot A_{v2} \cdot V_{o1}^{3rd} + A_{v3} \cdot V_{02}^{3rd} + V_{o3}^{3rd}}{A_{v1} \cdot A_{v2} \cdot A_{v3}}$$

$$V_{out}{}^{3rd} = A_{v3} \cdot A_{v2} \cdot V_{o1}^{3rd} + A_{v3} \cdot V_{02}^{3rd} + V_{o1}^{3rd}$$

$$\frac{V_{in}^3}{(V_{iIP3cas})^2} = \frac{A_{v2} \cdot A_{v3} \cdot \frac{(V_{o1})^3}{(V_{IP3o1})^2} + A_{v3} \cdot \frac{(V_{02})^3}{(V_{IP3o2})^2} + \frac{(V_{o3})^3}{(V_{IP3o3})^2}}{A_{v1} \cdot A_{v2} \cdot A_{v3}}$$

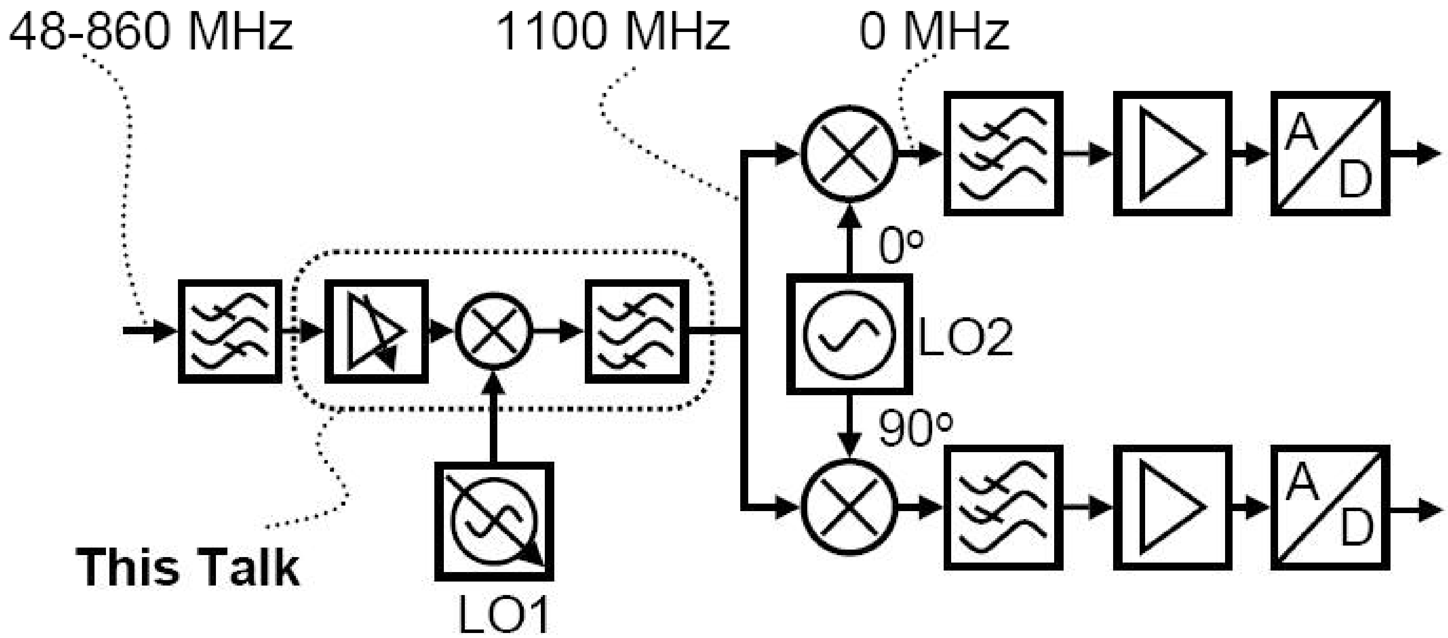
$$\frac{1}{(V_{iIP3cas})^2} = \frac{1}{(V_{IP3i1})^2} + \frac{A_{v1}{}^2}{(V_{IP3i2})^2} + \frac{(A_{v1} \cdot A_{v2})^2}{(V_{IP3i3})^2}$$

Case Study 1. Heterodyne

25.2 A CMOS Up-Conversion receiver Front-End For Cable and Terrestrial DTV Applications

Guido Retz[1], Phil Burton[2]

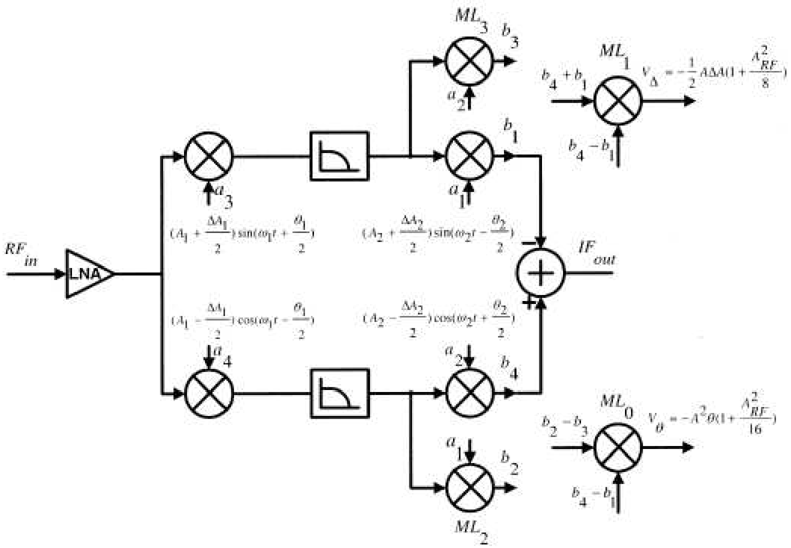
High-IF Direct-Downconversion Receiver

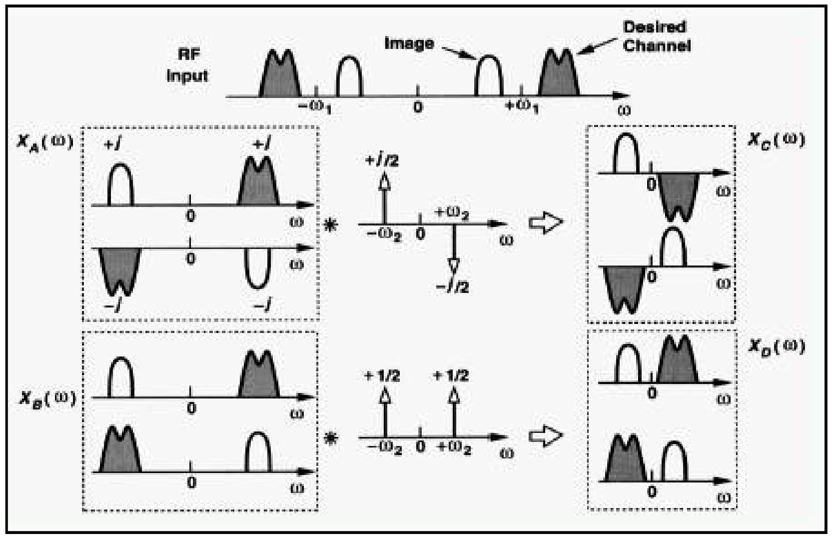


Case Study 2. Low-IF

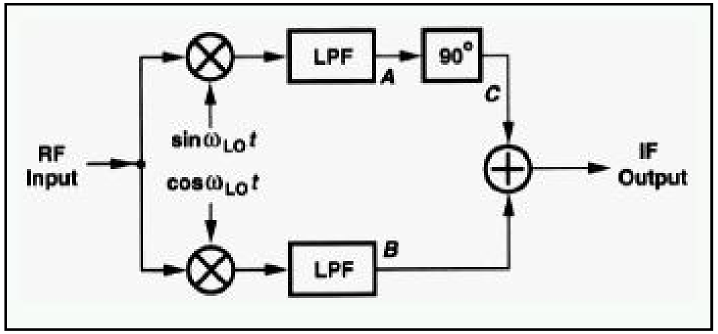
Calibration of Phase and Gain Mismatches
in Weaver Image-Reject Receiver

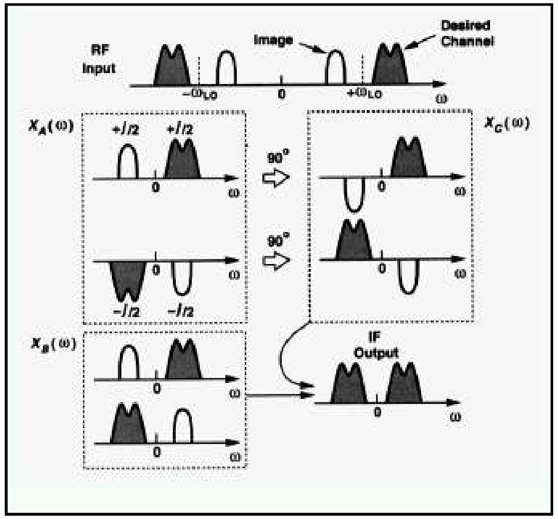
Mostafa A. I. Elmala, *Member, IEEE*, and Sherif H. K. Embabi, *Fellow, IEEE*

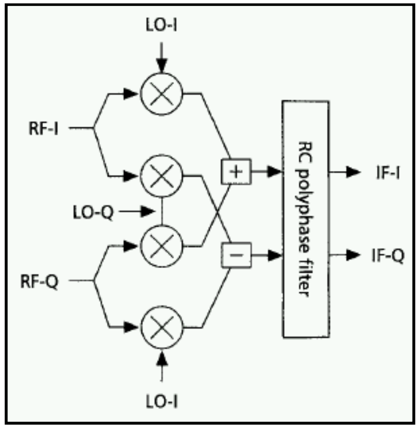


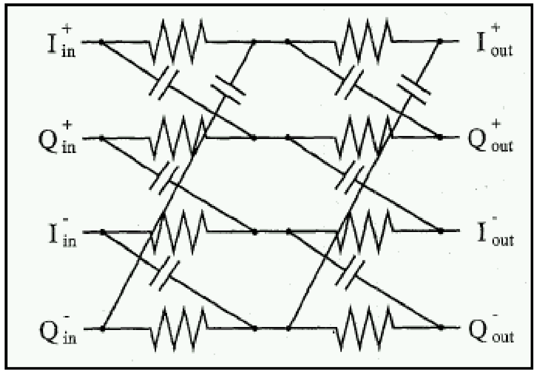


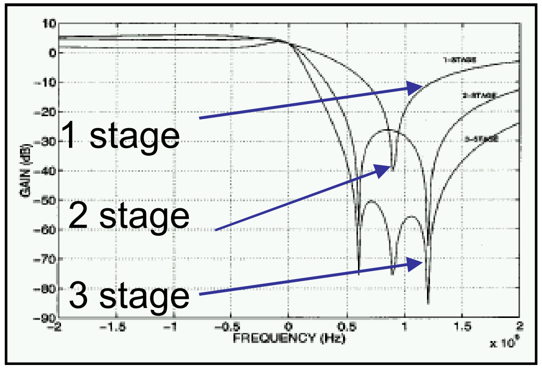
Case Study 3. Low-IF(2)

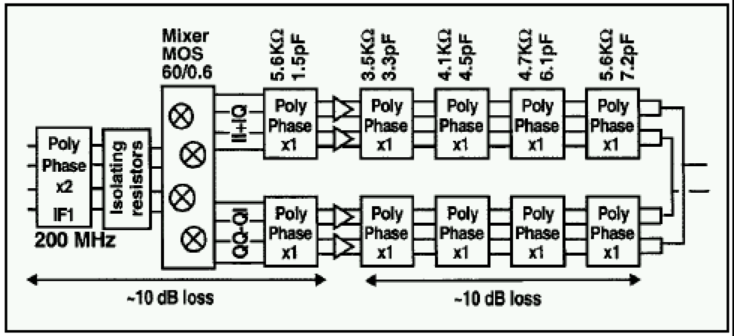


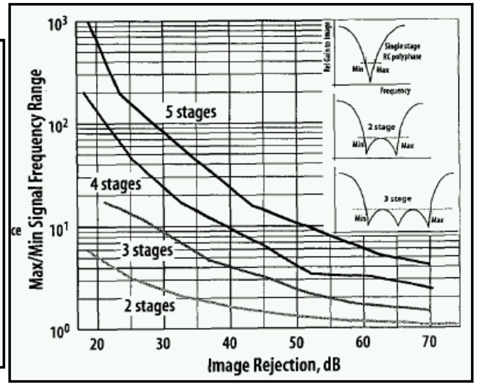




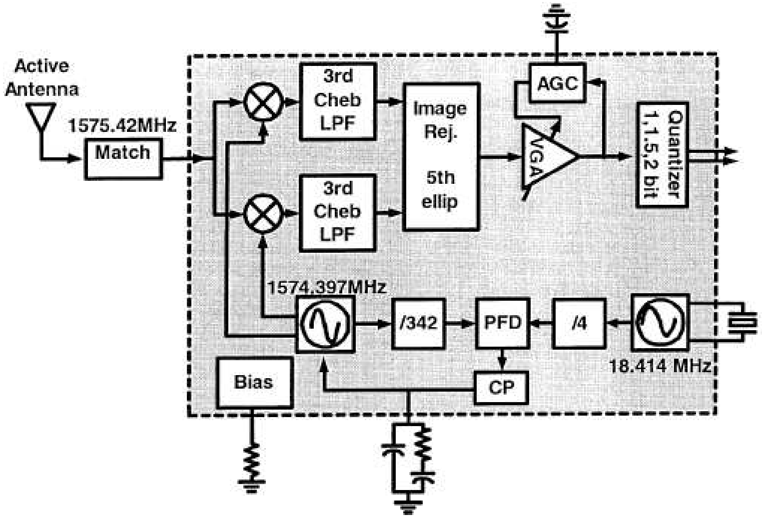


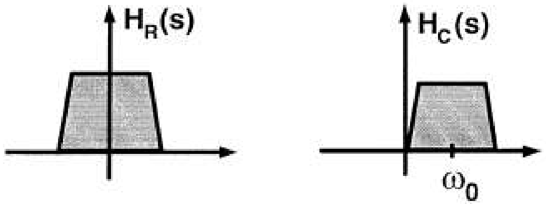




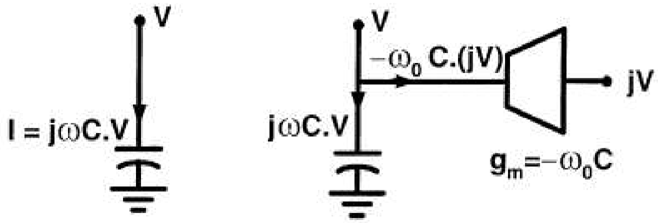


Case Study 3. Low-IF(2)





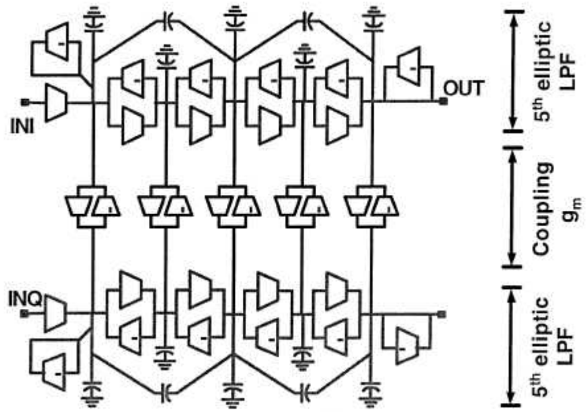
(a)



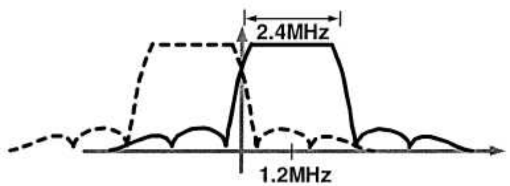
(b)

A Fully Integrated Low-IF CMOS GPS Radio With On-Chip Analog Image Rejection

Farbod Behbahani, *Member, IEEE*, Hamid Firouzkouhi, *Member, IEEE*, Ramesh Chokkalingam, Siamak Delshadpour, Alireza Kheirkhahi, Mohammad Nariman, *Student Member, IEEE*, Matteo Conta, and Saket Bhatia

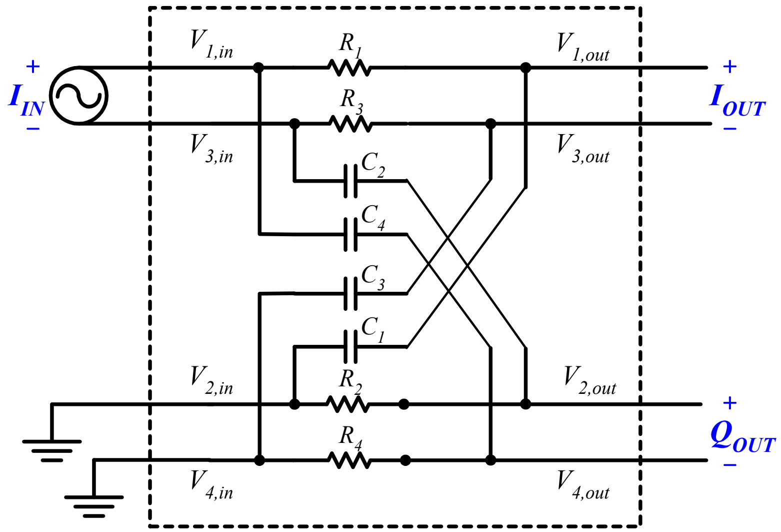


(a)



(b)

Case Study 3. Low-IF(3)



$$I_{OUT} = \frac{1}{1+sCR} I_{IN} + \frac{sCR}{1+sCR} Q_{IN}$$

$$Q_{OUT} = \frac{-sCR}{1+sCR} I_{IN} + \frac{1}{1+sCR} Q_{IN}$$

$$\begin{bmatrix} I_{IN}(t) \\ Q_{IN}(t) \end{bmatrix} = \begin{bmatrix} 0 \\ A\cos\omega t \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} I_{IN}(t) \\ Q_{IN}(t) \end{bmatrix} = \begin{bmatrix} A\cos\omega t \\ 0 \end{bmatrix}$$

$$\frac{Q_{OUT}(s)}{I_{OUT}(s)} = sCR \qquad \frac{Q_{OUT}(s)}{I_{OUT}(s)} = -sCR$$

$$\left| \frac{Q_{OUT}(j\omega)}{I_{OUT}(j\omega)} \right| = \omega CR \qquad \arg\left(\frac{Q_{OUT}(j\omega)}{I_{OUT}(j\omega)} \right) = \pm\frac{\pi}{4}$$

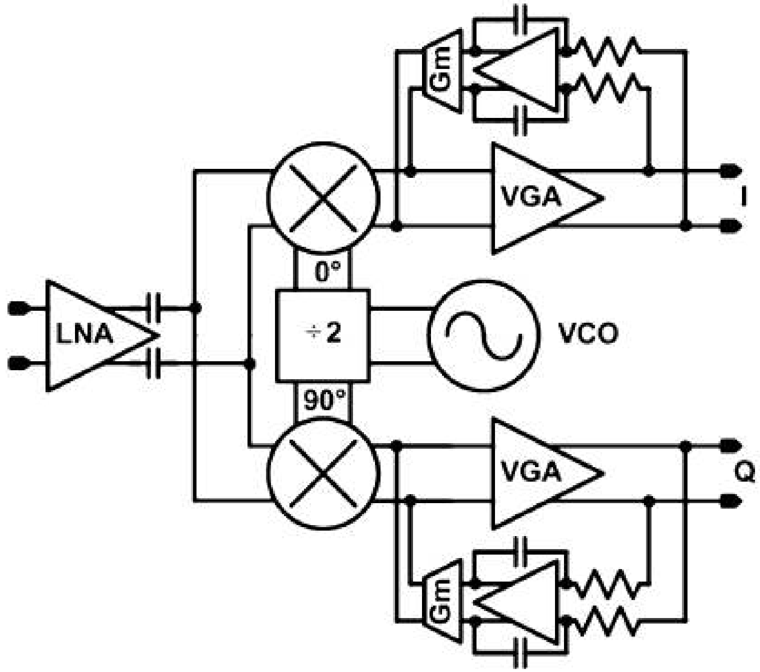
$$IF_{OUT}(j\omega) = I_{OUT}(j\omega) + Q_{OUT}(j\omega) = \frac{(1-j\omega CR)I_{IN}(j\omega) + (1+j\omega CR)Q_{IN}(j\omega)}{1+j\omega CR}$$

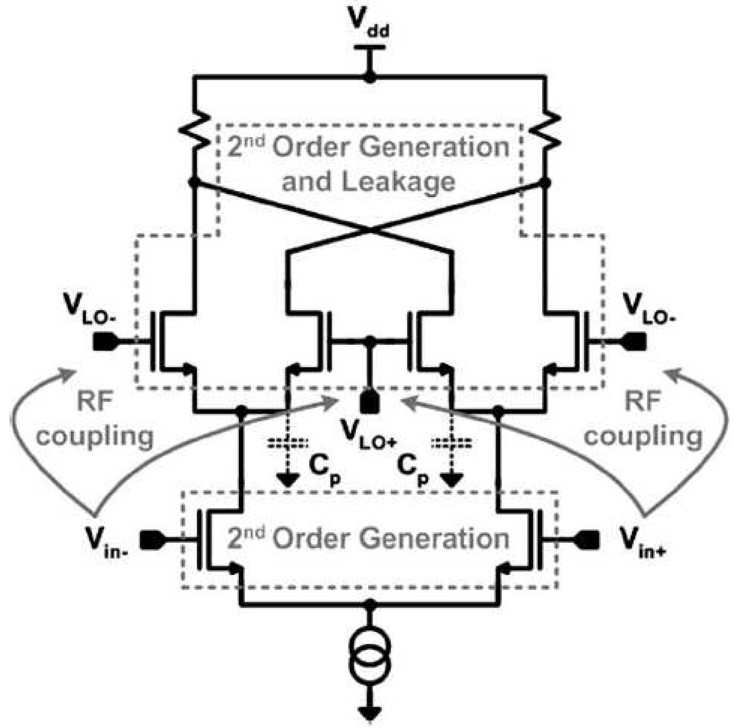
$$IF_{OUT}(j\omega) = \frac{(1-j)A + j(1+j)A}{1+j} = 0$$

$$IF_{OUT}(-j\omega) = \frac{(1+j)A + j(1-j)A}{1-j} = 2A\left(\frac{1+j}{1-j}\right)$$

$$I_{IN}(j\omega) = A\angle 0 \qquad Q_{IN}(j\omega) = A\angle\frac{\pi}{2} \qquad \omega = 1/RC$$

Case Study 4. DCR





Receiver System Design Summary

Receiver

- Receiver Design = Selectivity/Sensitivity
- Find Architecture w.r.t S/S, Power, Size
- Optimal budgeting w.r.t S/S