Transceivers Architectures for Mobile & Wireless Applications

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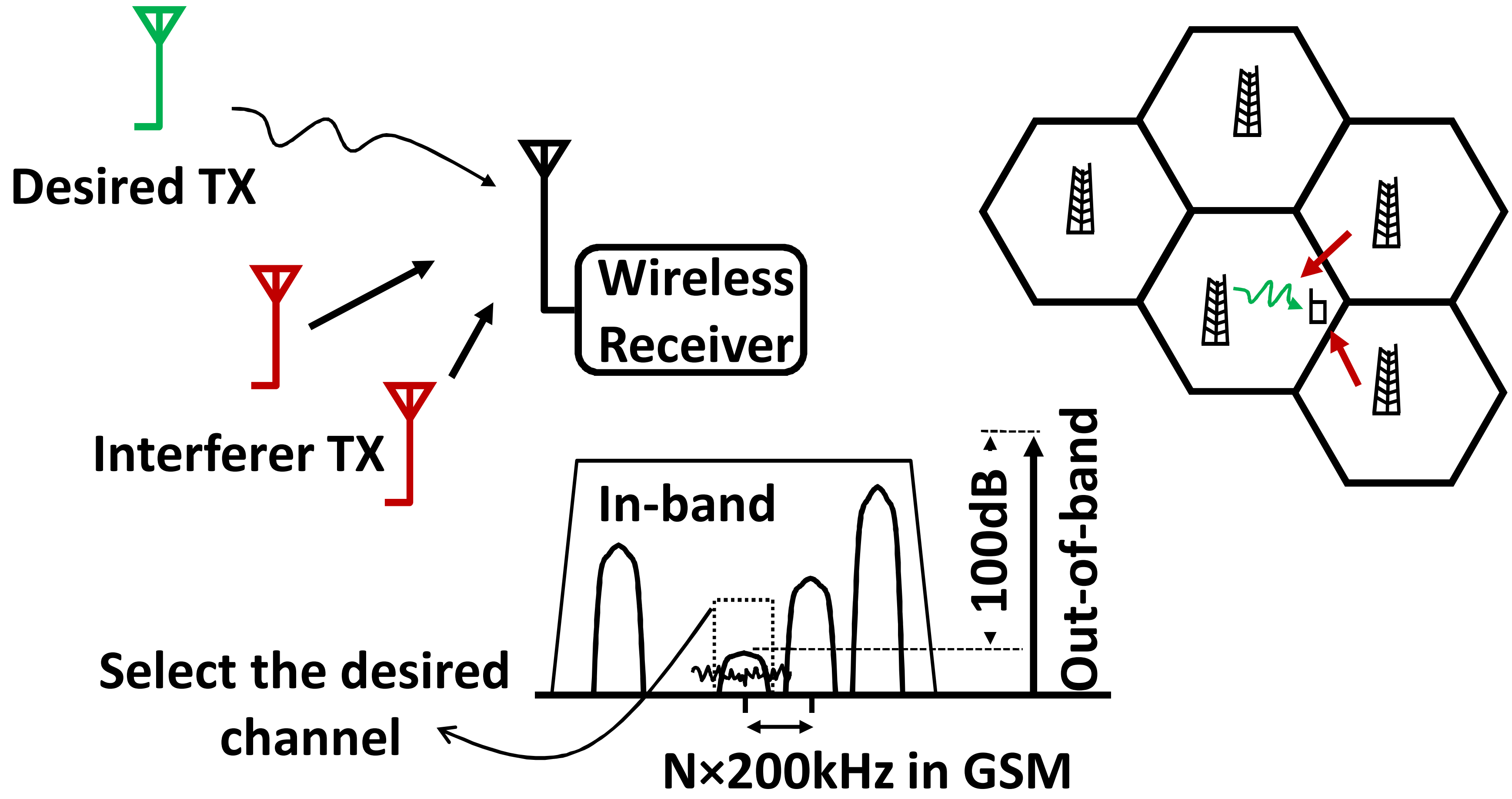
Wireless Transceiver Challenges

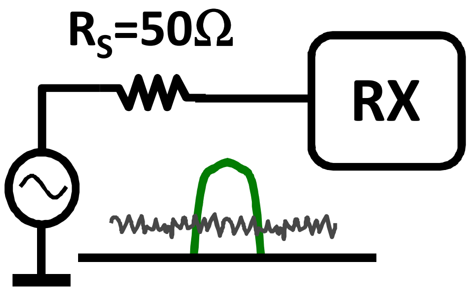


- Stringent linearity, phase noise, selectivity on RX
- Stringent mask, far-out noise on TX

Receiver Requirements

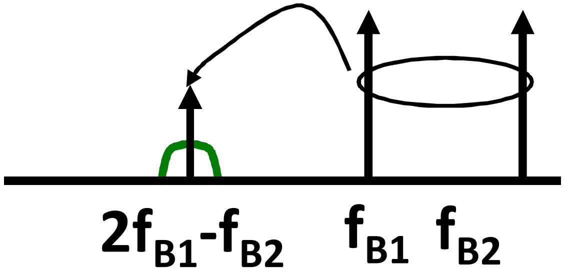
- **Receiver NF sets the sensitivity, range:**

$$\text{Sensitivity} = \underbrace{-174}_{\text{10Log(KT), dBm/Hz}} + \text{NF} + \underbrace{\text{10Log(BW)} + \text{SNR}}_{\text{Set by the standard}}$$

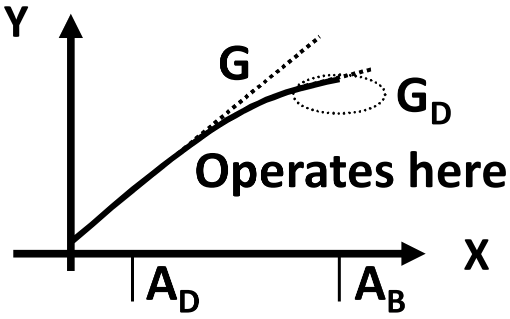


Blockers: In/Out-Band

- **Small signal linearity:**
  - IIP_2, IIP_3



- **Large signal linearity:**
  - Gain compression



- **Harmonic mixing**
- **Reciprocal mixing: BNF = 174 – P_B -PN**

Transmitter Requirements

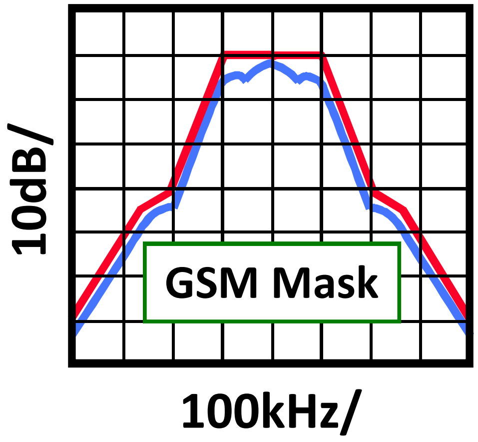
RX Equivalent

NF:
Range

- **Output power**

Blockers:
Co-existence

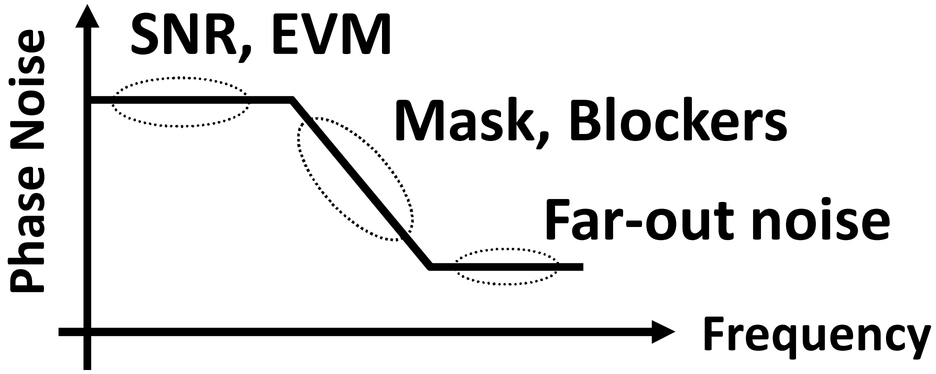
- **Spectrum Mask**
  - –Sets the modulator quality
  - –Sets the TX linearity
  - –Determines TX phase noise
- **Far-out noise**



SNR:
Thru-put

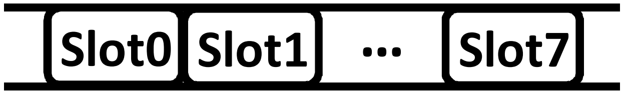
- **Modulation quality: PE, EVM**

- **Phase noise in transceivers:**



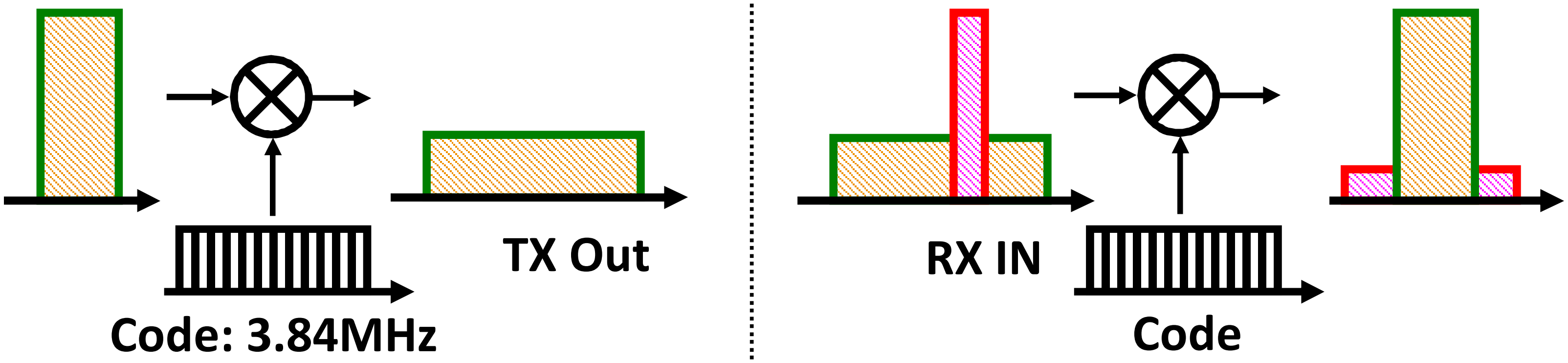
GSM/EDGE/WCDMA

- GSM/EDGE is TDMA, while 3G is CDMA. Both FDD.



Frame: 8×577μS

- CDMA less sensitive to jammers:



	Modulation	Bands	Thru-put	Challenges
GSM	GMSK: 270kbps	4	0.08	Blockers, TX mask, phase noise
EDGE	8PSK: 810kbps	4	0.236	
3G+[1]	QPSK … 64QAM	19	0.384-21	TX leakage

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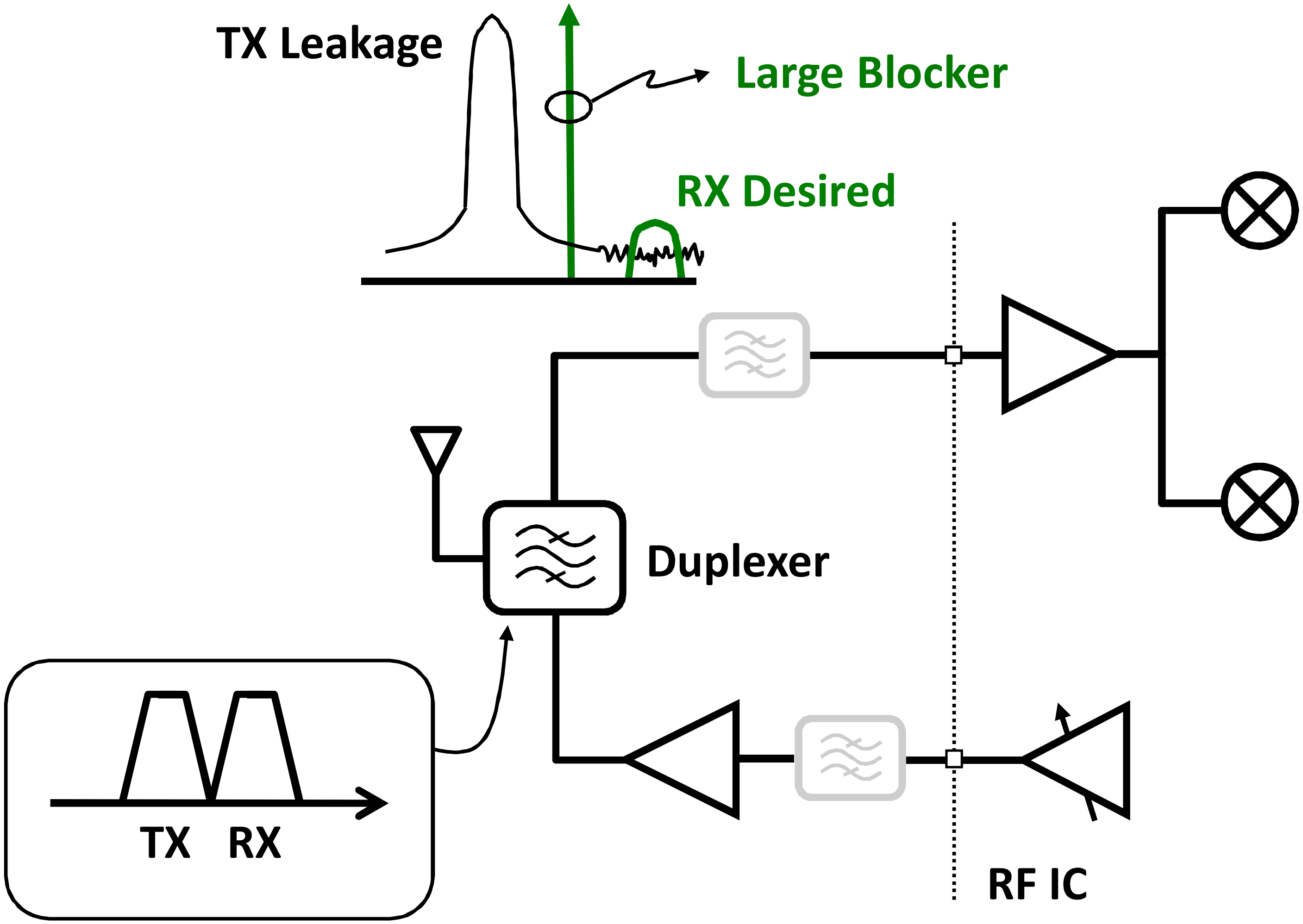
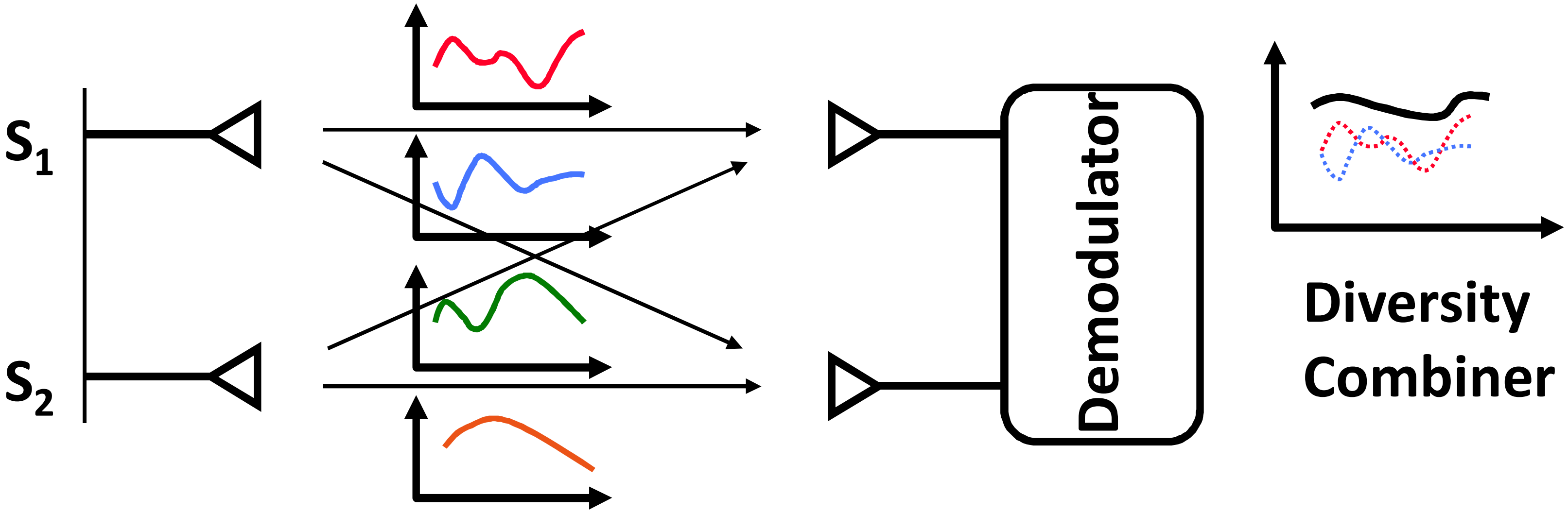
[1] HSPA, HSPA+, up to 21Mbps thru-put

3G Full-Duplex Problem



- **Duplexer is a dual-band filter**

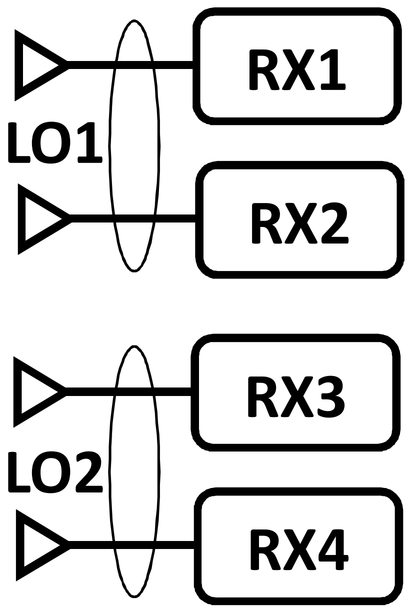
Concept of MIMO

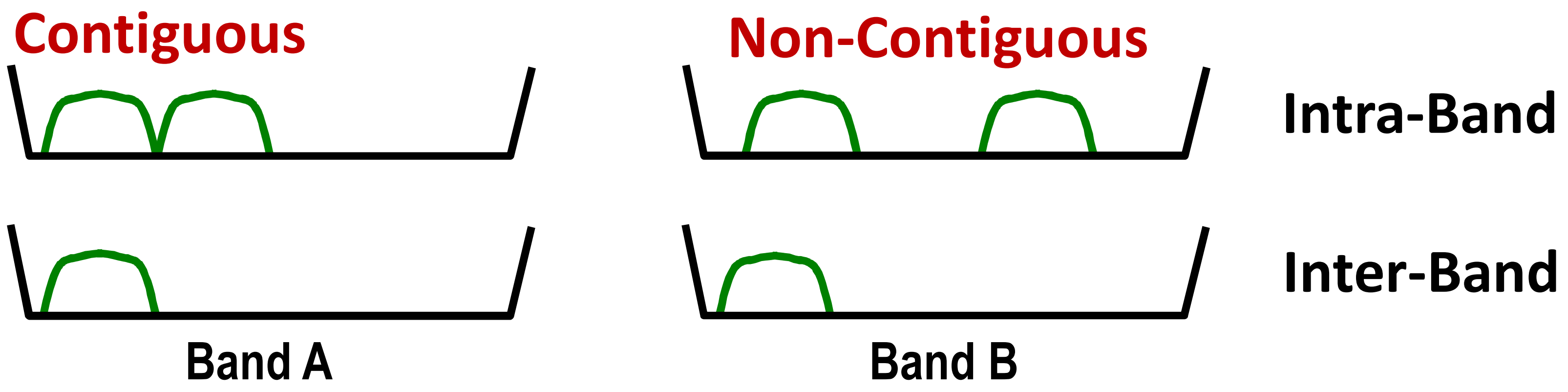


- **Signals received on multiple antennas combined to create a more benign composite channel**
  - **Combined signal energy increases SNR**
  - **Variability across frequency reduces fading**
- **Trading robustness for rate**

LTE Features

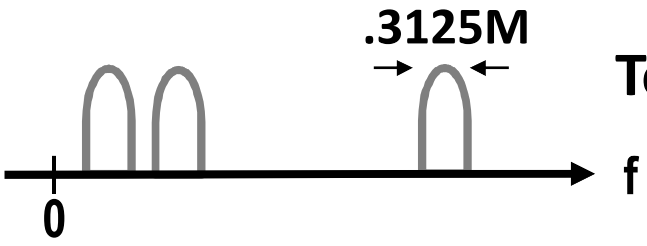
- High data rate: DL 300Mbps, UL 75Mbps
- Flexible bandwidth and modes
  - Over 40 bands
  - 1.4 -20 MHz variable bandwidth
  - Flexible FDD, TDD, & FDD half duplex
- High mobility up to 120 km/h
- Carrier aggregation in LTE-A: 1Gbps





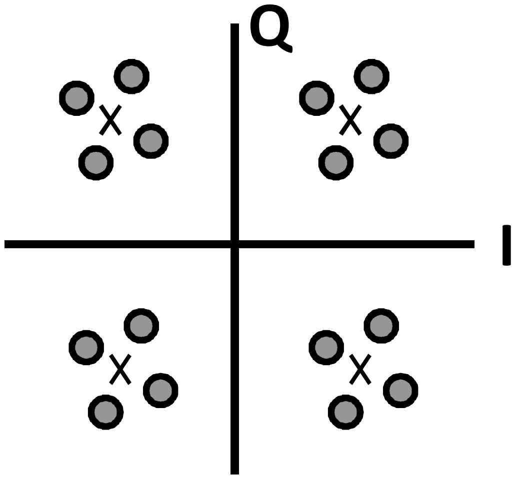
WLAN Design Challenges

- **Bandwidth variability and detection**
  - 20MHz up to 160MHz
  - OFDM

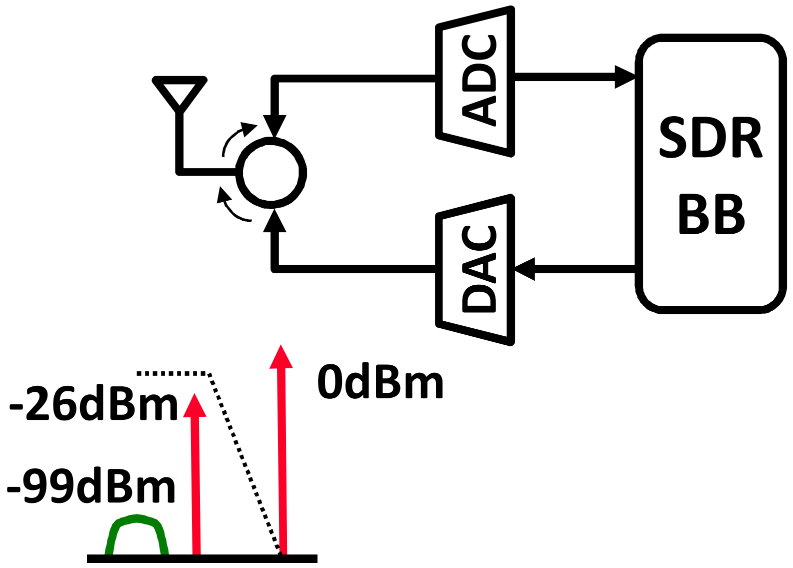


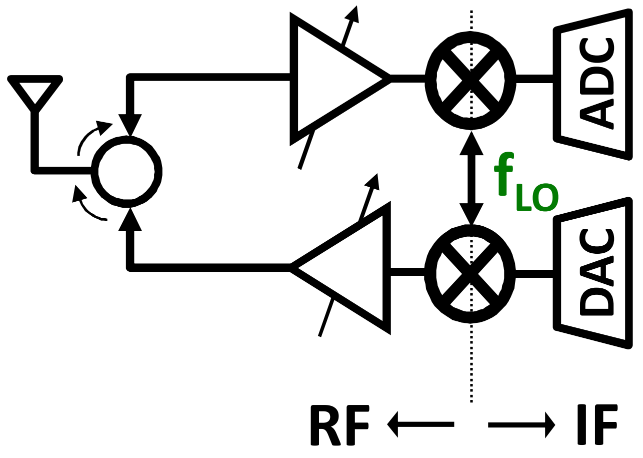
To help multi-path

- **TX PAR of 12dB for 64QAM**
- **High fidelity transmitters**
  - **-28dB EVM for 64QAM**
  - **IQ and in-band phase noise**
- **Receiver SNR and IQ imbalance**
  - LO (fixed) & filters (variable over frequency)
  - Sensitivity: -67dBm for .11g, SNR = 25dB: NF =9dB



Ideal Transceiver





$f_{IF} = f_{IN} - f_{LO}$

- Filter only rejects out-of-band blockers
- In-band blockers require a high-resolution ADC
- Power hungry

- Invented by Armstrong in 1918
- *Frequency-conversion* relaxes IF signal processing
- Lower power

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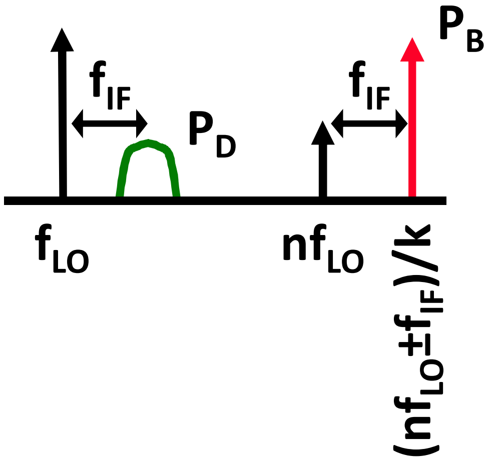
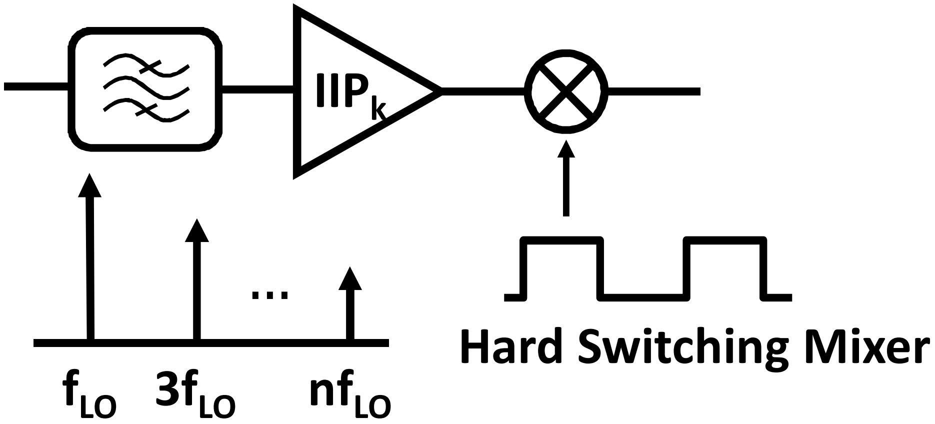
[10] Mitola, 2005

[7] Armstrong, 1924

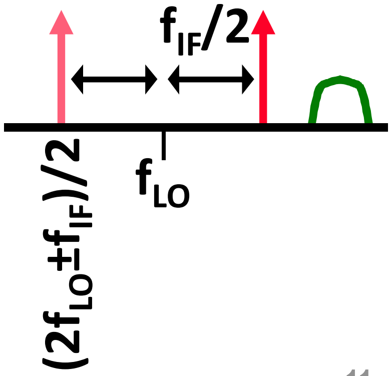
LO Harmonic Mixing Issue

- In a perfectly linear RX, blockers still problematic





- Sets LNA IIP_k , filter attenuation, range of acceptable IF
- Image: n=k=1, Only removed by filtering
- Half-IF: n=k=2, Differential helps



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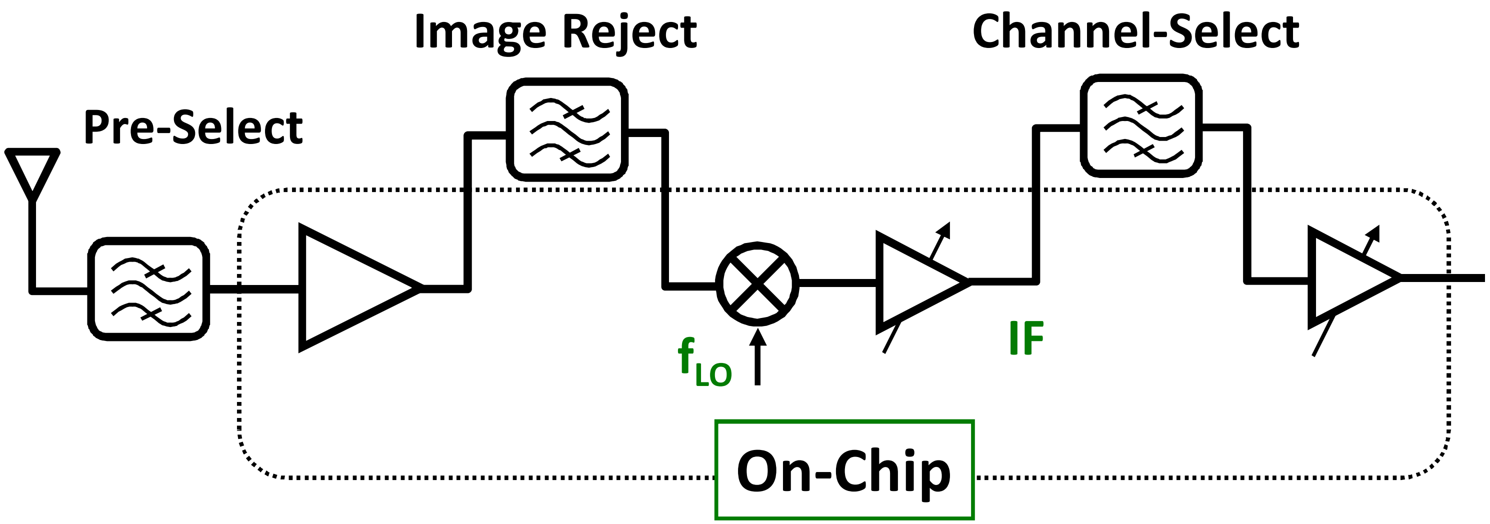
[15] Cijvat, TCAS 2002

Super-Heterodyne Receiver



- Down-conversion relaxes the ADC
- High IF avoids DC offset & low frequency noise
- Needs external filters for image and other blockers

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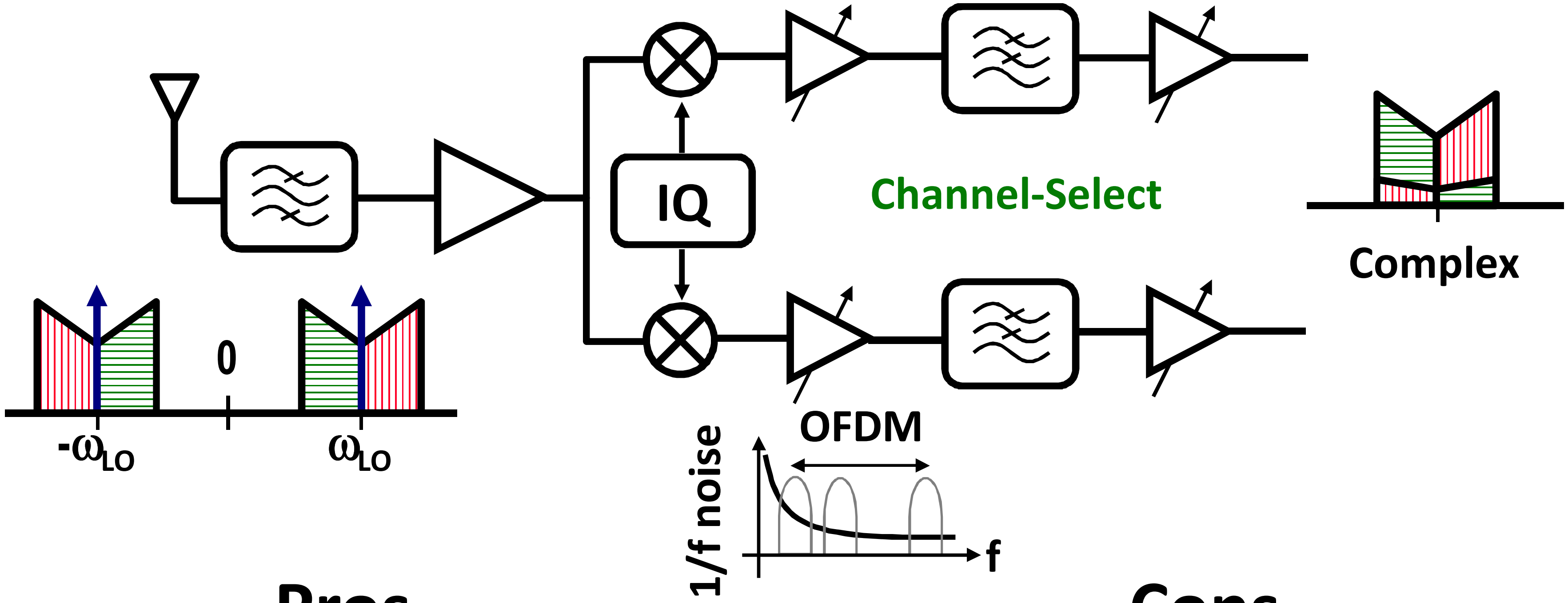
[7] Armstrong, 1924

Zero-IF Receiver



Pros

- Less severe image issue
- Channel selection on-chip
- Suitable for WB: LTE, WiFi

Cons

- Requires quadrature LO
- DC Offset, 1/f noise, IIP_2
- In band IRR

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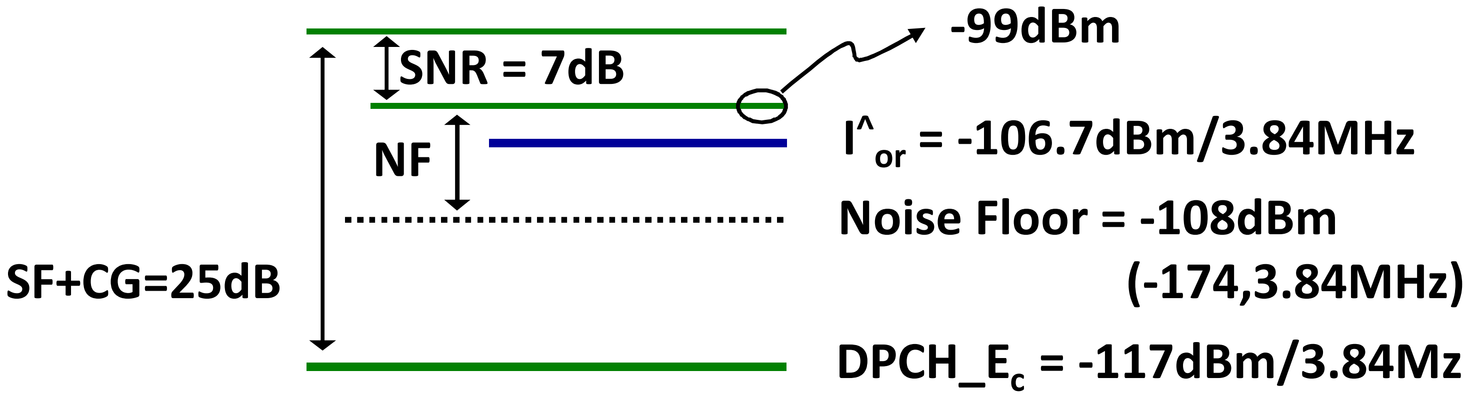
[1] Abidi, JSSC 1995

3G RX NF Requirement

- **For 12.2kbps reference measurement, SF=128, -117dBm sensitivity, required NF = 9dB**



-99dBm

SNR = 7dB

NF

$I^{\wedge}_{or}$ = -106.7dBm/3.84MHz

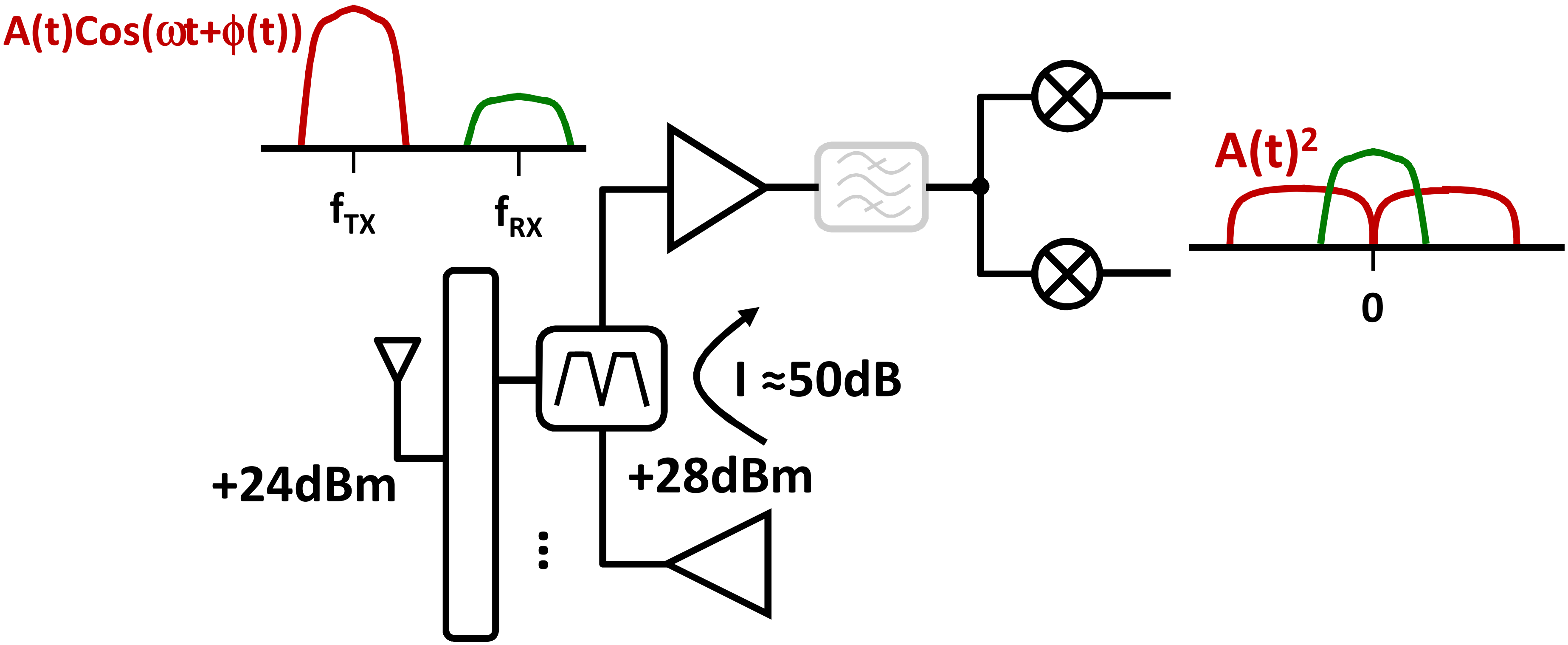
Noise Floor = -108dBm (-174,3.84MHz)

SF+CG=25dB

DPCH_E_c = -117dBm/3.84Mz

- **For a given duplexer, NF depends on:**
  - RX thermal noise
  - RX 2^{nd}-order nonlinearity
  - TX and PA noise at RX band

3G IIP_2 Requirements

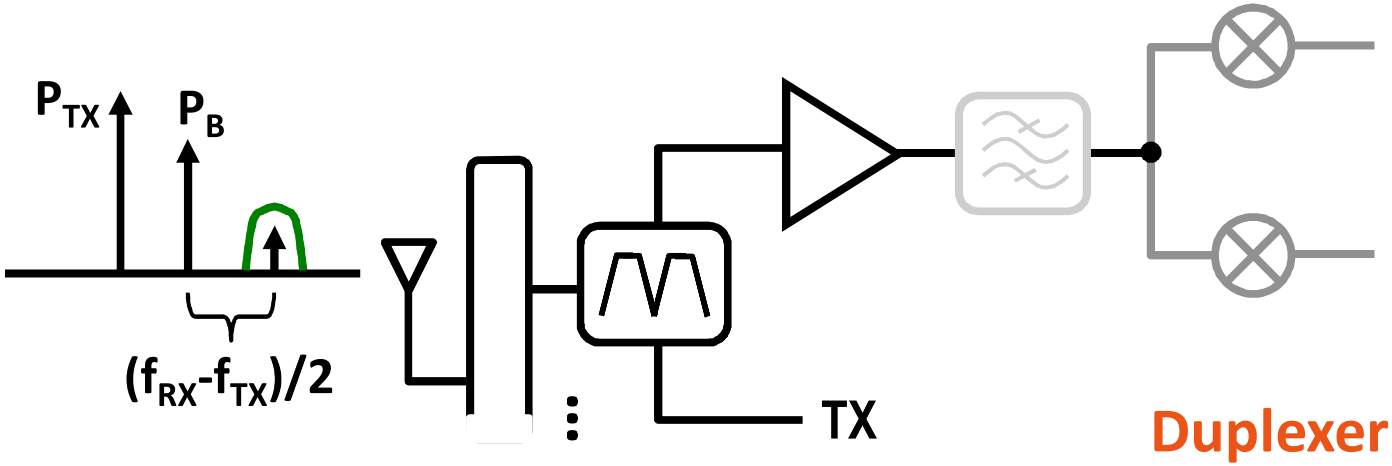


- **TX leakage amplitude demodulated at zero IF**
- **In order not to affect sensitivity IIP_2 > 50dBm**

$$IIP_2 = 2\times(28\text{dBm}-I) - 13\text{dB} - -99\text{dBm}\ \boxed{-10\text{dB}} = +52\text{dBm}$$

Desensitizes by 0.5dB

3G Out-of-Band IIP_3 Requirements



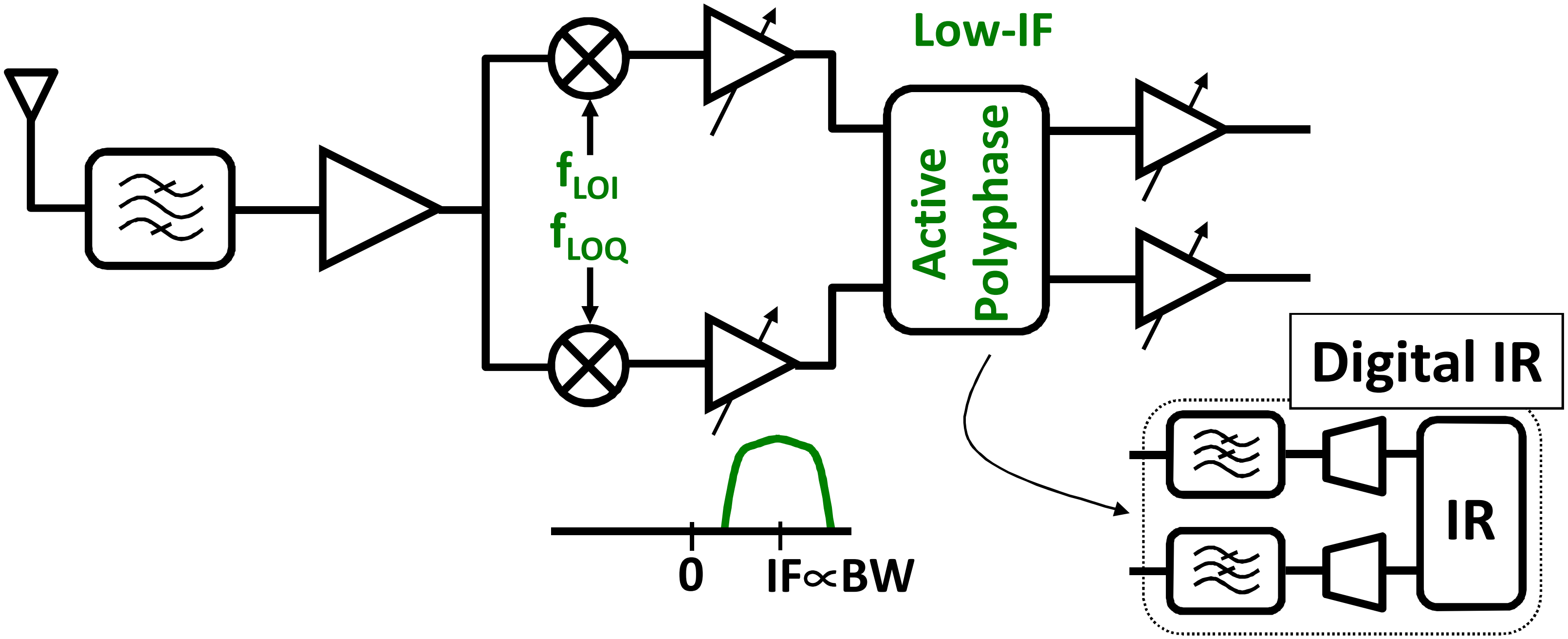
Duplexer Isolation: 50dB
Duplexer Filtering: 30dB

- **Stringent IIP_3 due to TX leakage:**

$$\underbrace{\text{Signal}}_{-99+3-5} = \underbrace{P_{TX}}_{28-50} + 2\times\underbrace{P_B}_{-15-30} - 2\times IIP_3$$

- **IIP_3 = -5.5dBm at the LNA input**
- **Need room for TX noise, 2nd-order nonlinearity …**

Low-IF Receiver



Pros

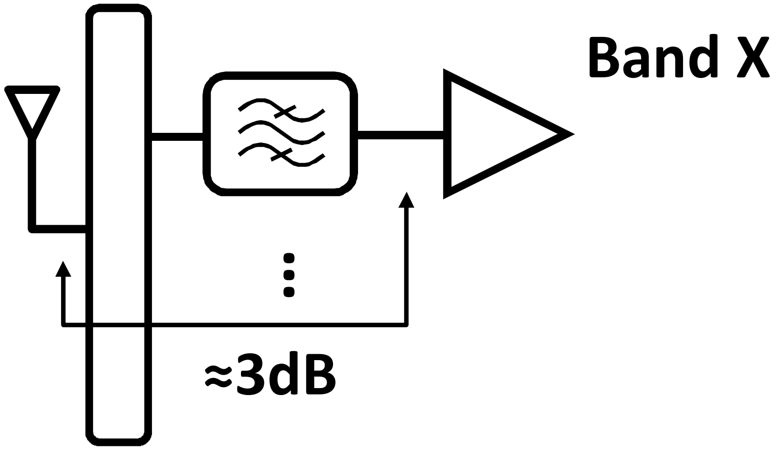
- IIP_2, 1/f less problematic
- Image in-band
- Suitable for NB: GSM, BT

Cons

- Requires quadrature LO
- Higher IF, higher power
- Tighter IRR

GSM Noise Figure

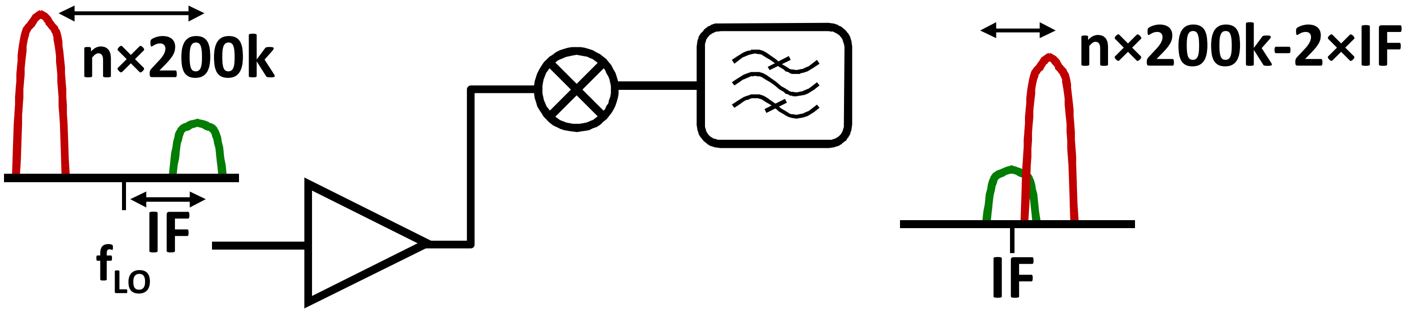
- **The standard requires -102dBm**
- **Receiver NF sets the sensitivity:**



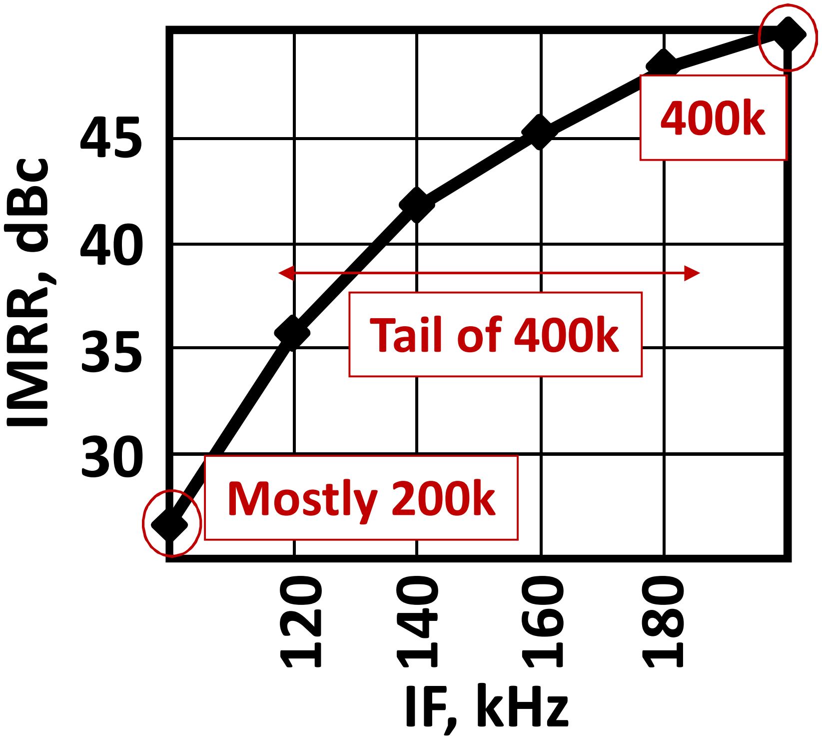
$$\text{Sensitivity} = -174 + \text{NF} + \underbrace{10\text{Log}(\text{BW}) + \text{SNR}}_{\approx 59\text{dB for GMSK}}$$

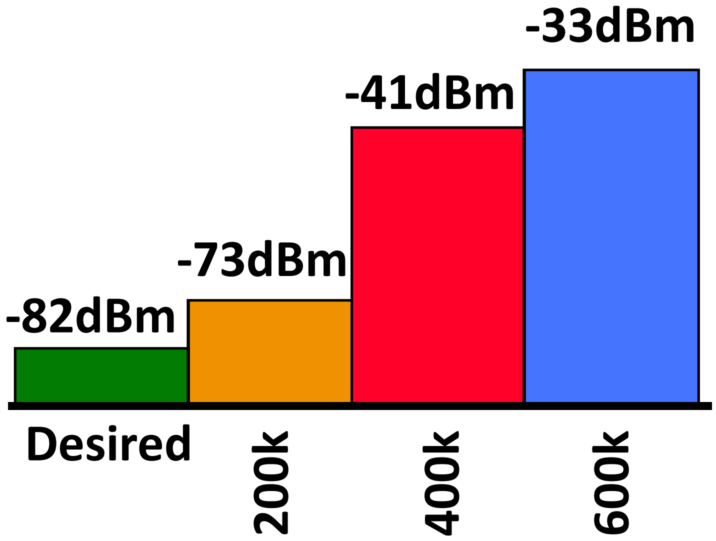
- **Most advanced receivers target for <-109dBm**
- **NF of < 3dB assuming *3dB loss at front-end***

Choice of IF: Adjacent Blockers

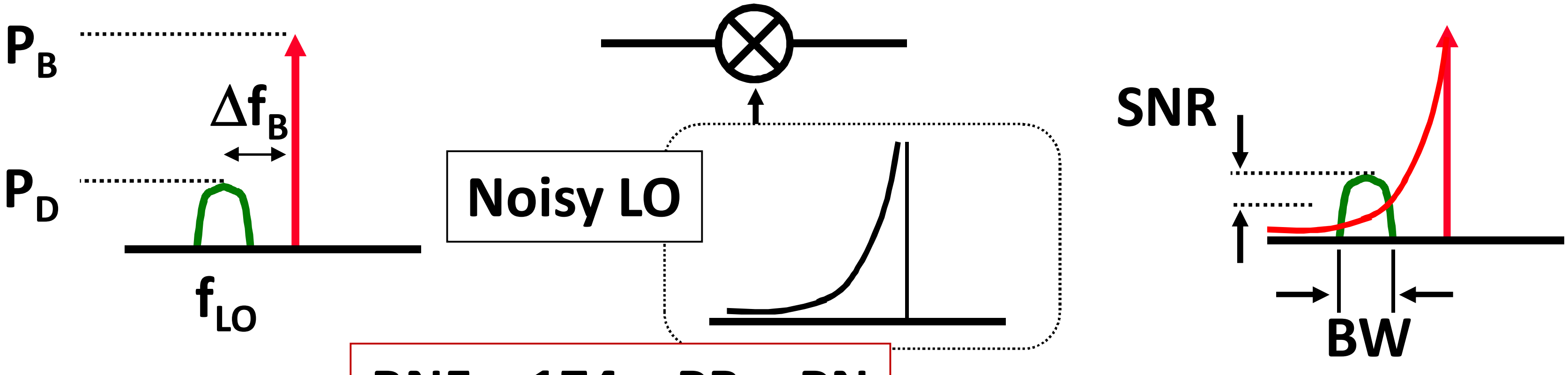


- Trade-off between 1/f noise, IIP_2, … vs. image rejection



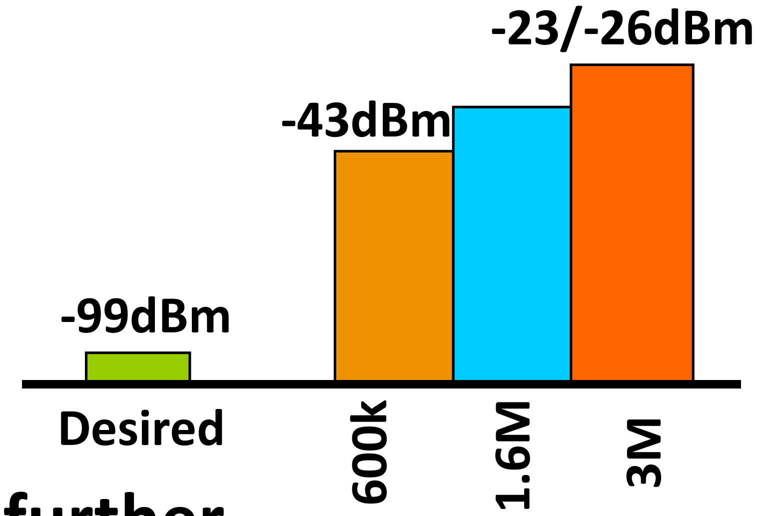


GSM In-Band Blocking Requirements

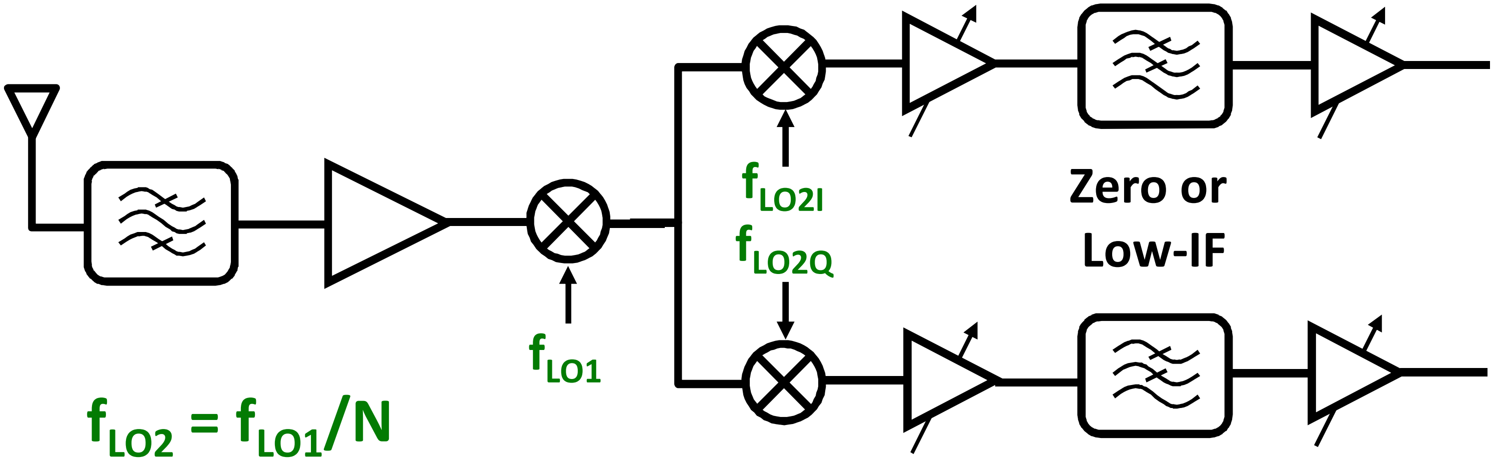


BNF = 174 + PB + PN

- LO PN of -140dBc/Hz at 3MHz
- BNF = 174 – 26 – 140 = 8dB
- RX NF of 6dB: Total BNF ≈ 10dB
- 3GPP NF requirement: 13dB
- Compression degrades the BNF further
  - -26/-23dBm blocker can heavily compress the front-end



Dual-Conversion Receiver



f_{LO2I}

f_{LO2Q}

Zero or Low-IF

f_{LO1}

$f_{LO2} = f_{LO1}/N$

Sliding 1st IF = f_{RF} / N+1

- DC offset and 1/f noise issues less severe
- No high frequency quadrature LO
- Higher power due to 2 mixers in signal path
- First LO image

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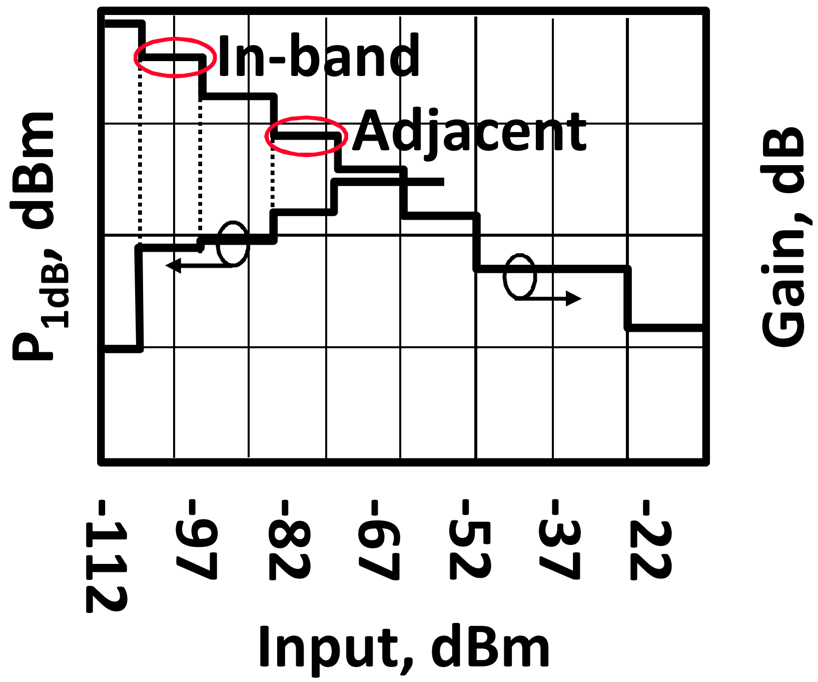
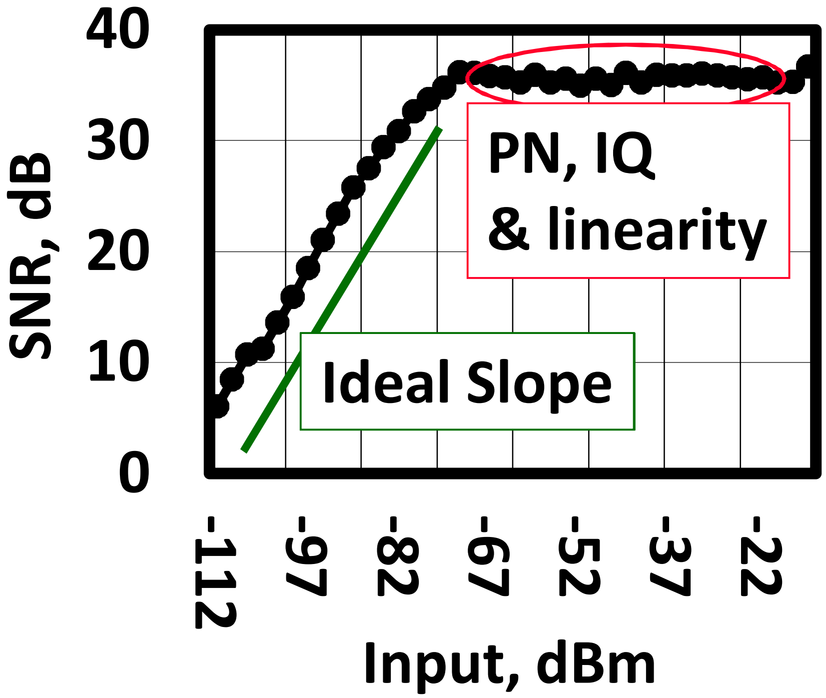
[13] Zargari, JSSC 2002

Gain Control & Receiver SNR

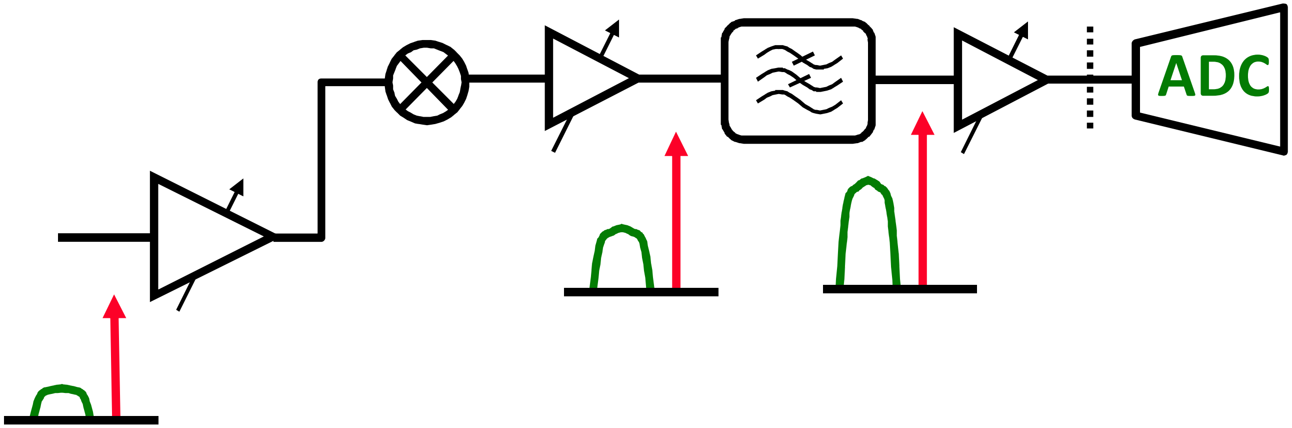
- SNR determines through-put at high input powers



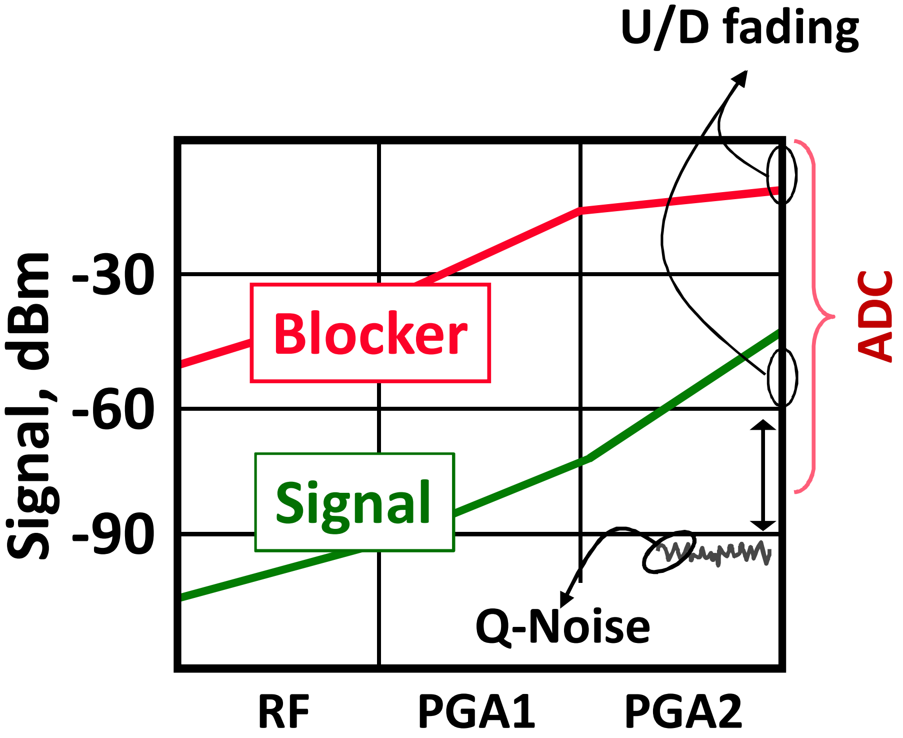


- *Front-end* gain reduction improves P_{1dB}
- But degrades SNR

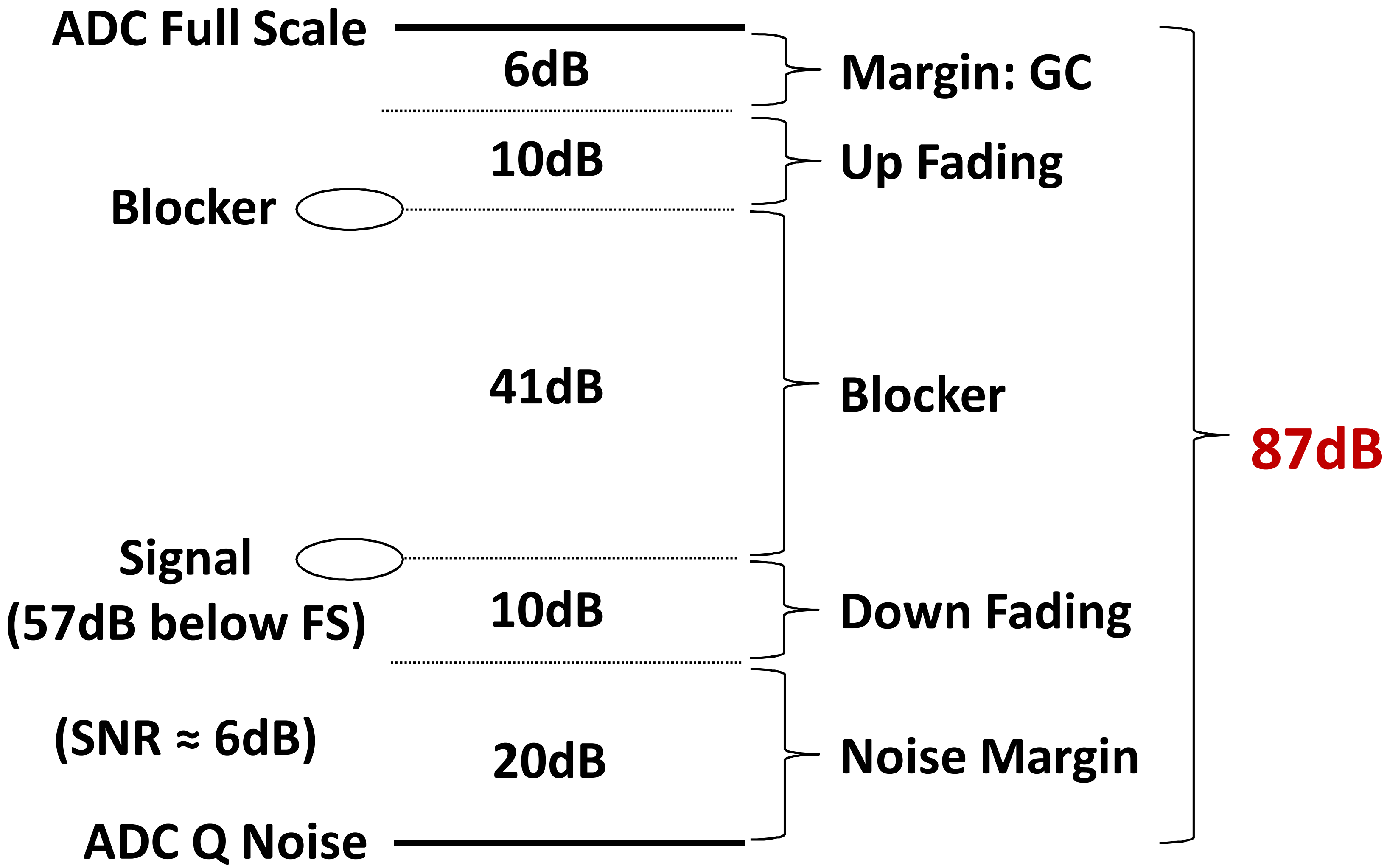
ADC and Filtering



- GC keeps desired signal close to ADC full scale
- Trade-off between filter & ADC
- ADC DR >> receiver SNR



Example: 2G ADC Requirements



ADC Full Scale

6dB

Margin: GC

10dB

Up Fading

Blocker

41dB

Blocker

87dB

Signal

(57dB below FS)

10dB

Down Fading

(SNR ≈ 6dB)

20dB

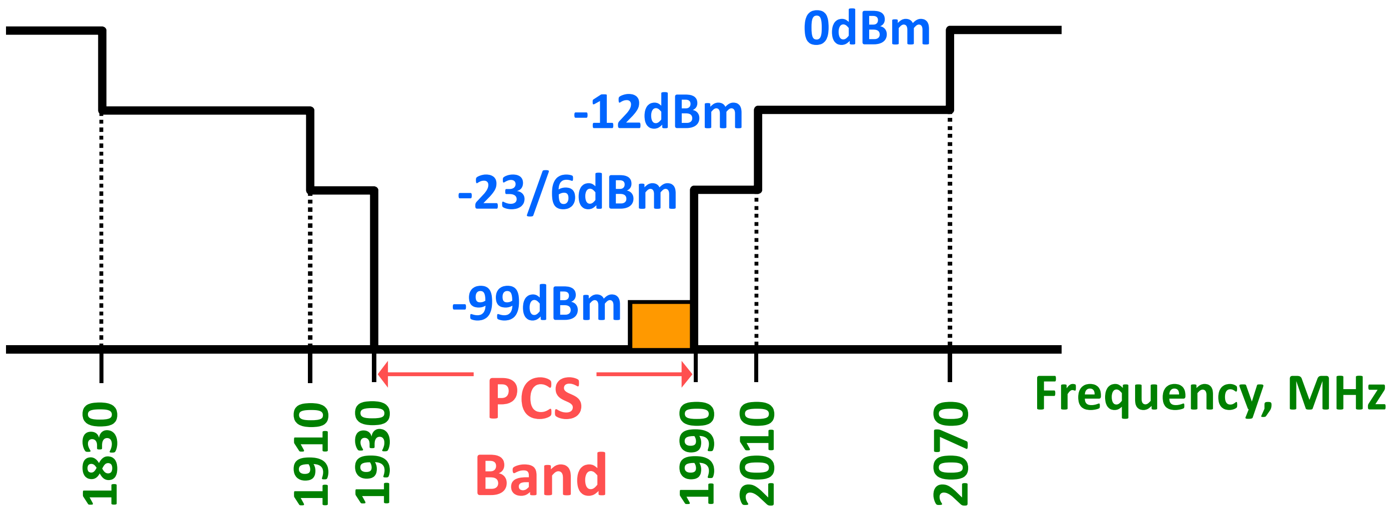
Noise Margin

ADC Q Noise

- -400kHz blocker dominant in low-IF

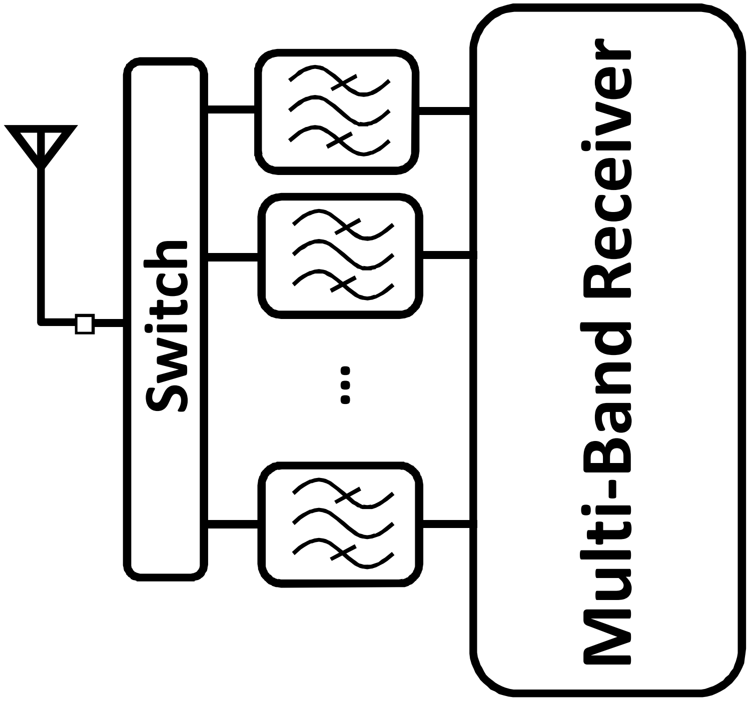
Out-of-Band Blocking Issue

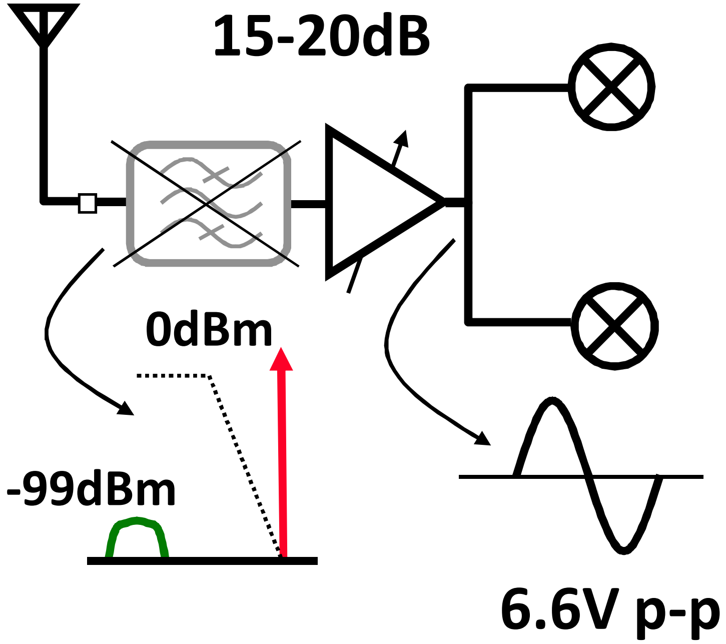
GSM out-of-band blocker profile:



- External SAW filters attenuate out-of-band blockers
- The in-band blocker as high as -23dBm

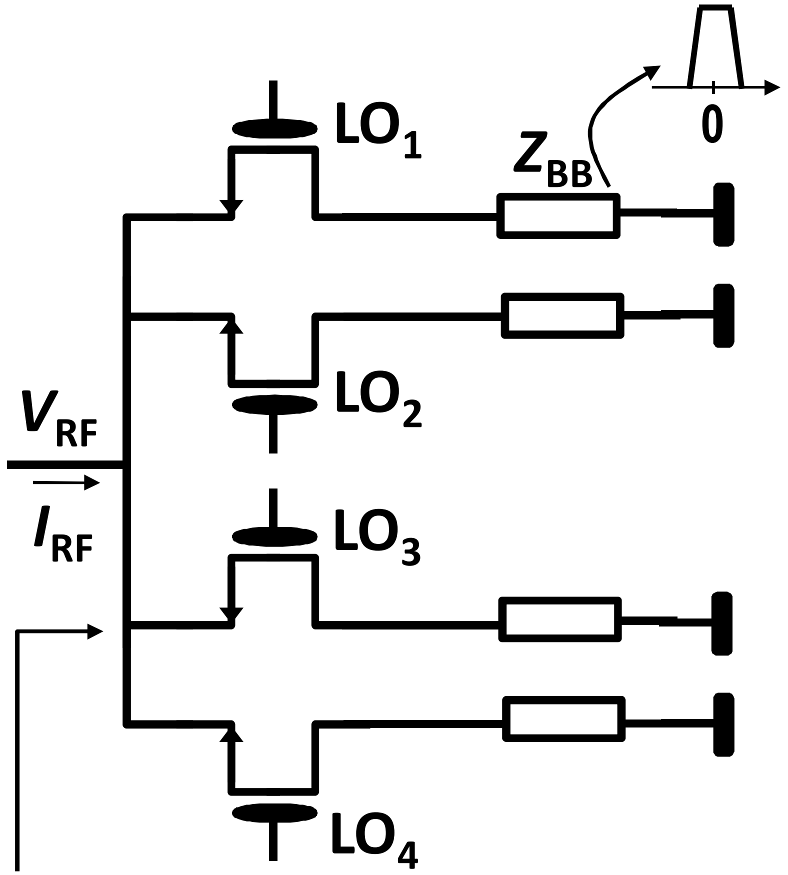
Narrow-Band Filtering Concerns

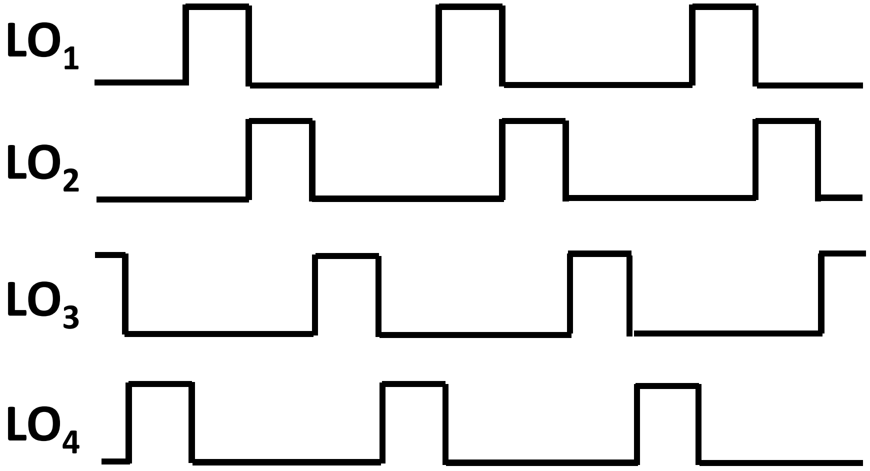


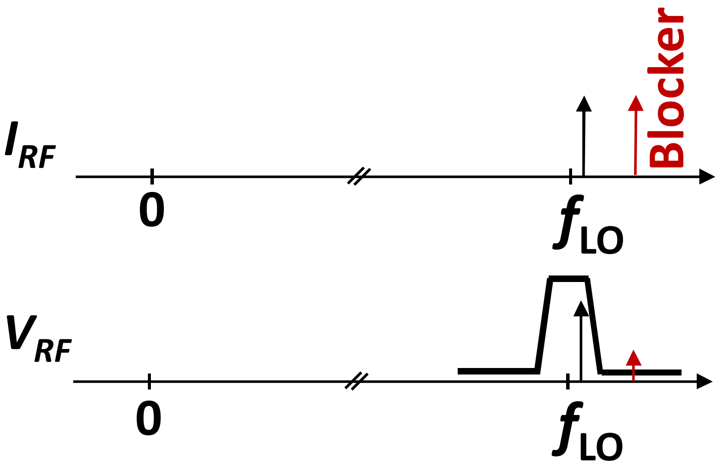


- Large blockers compress the receiver
- Impose stringent far-out phase noise
- External filtering is narrow-band and costly

Passive Mixers as N-Path Filters[4]







$$Z_{in}(s) \approx R_{SW} + \frac{2}{\pi^2}\{Z_{BB}(s-j\omega_{LO})+Z_{BB}(s+j\omega_{LO})\}$$

High-Q BPF from low-Q LPF

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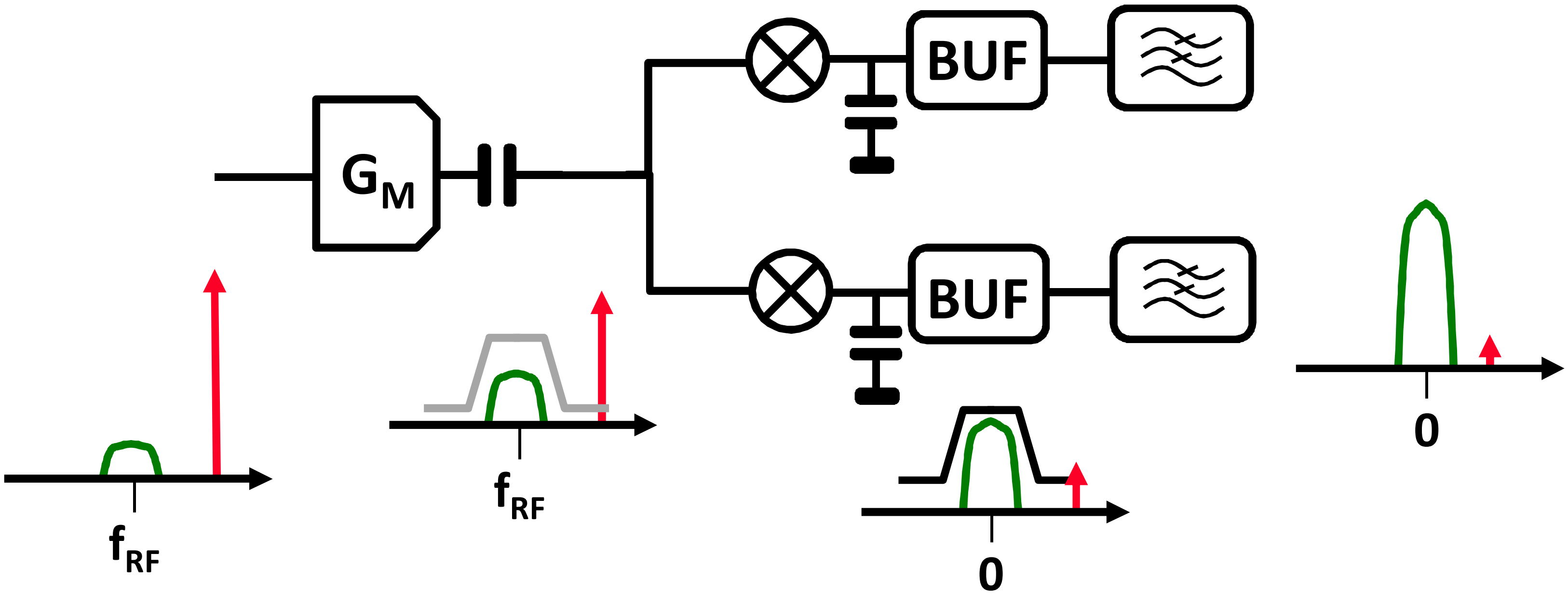
[4] L. Franks, Bell Syst. Tech. J., 1960

[14] Mirzaei, TCAS 2010

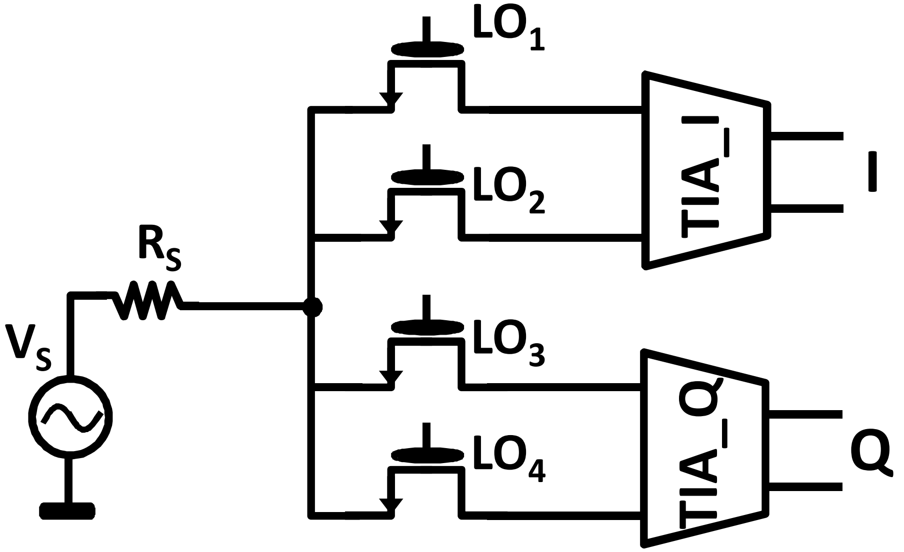
Current-Mode Receivers

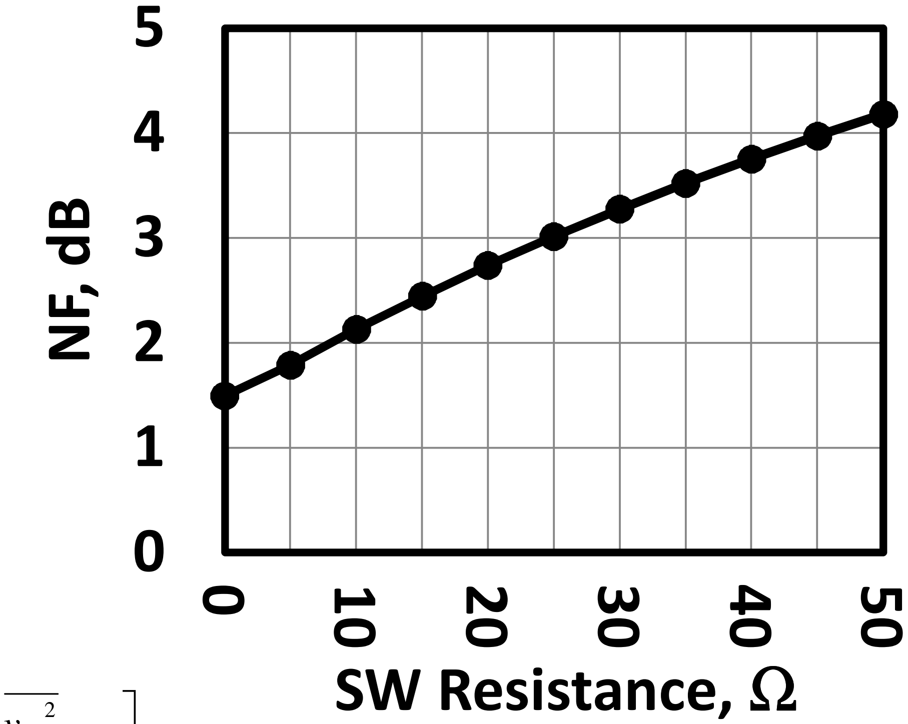


- **Passive mixers to achieve high-Q filtering**
- **Current mode LNA: LNTA**
- **Enhance the blocker tolerance**

🗎 [21,22] **Mikhemar, VLSI 2012**

Mixer-First Receivers

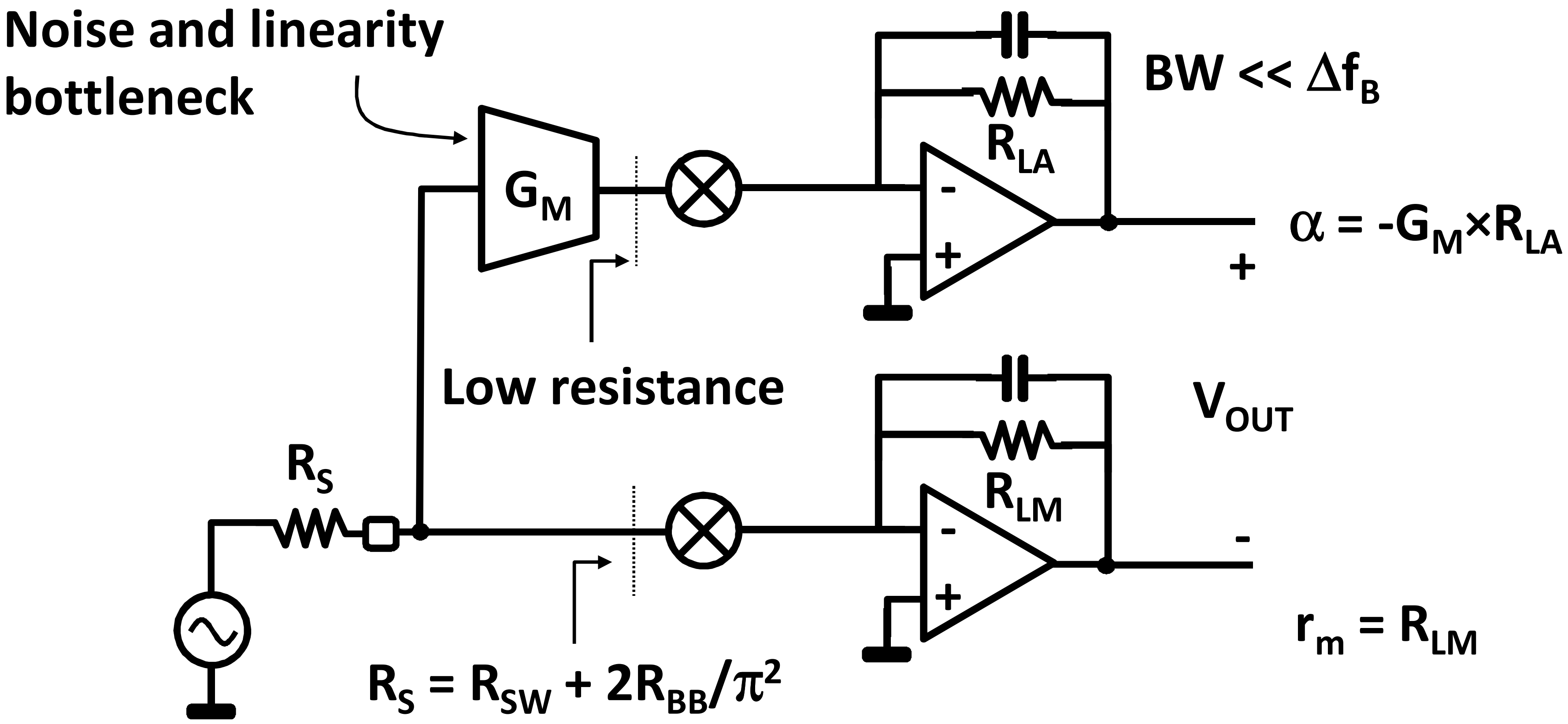




- **For M phases:** $F = \left[1 + \frac{r_{DS}(ON)}{R_S} + \frac{\overline{v_{bb}^{2}}}{M(4KTR_S)} \right] \times N_{Aliasing}$
- **At high frequency noise aliasing degrades NF significantly**
- **NF > 4dB in practice at GHz frequencies**

[18,19] Andrews, JSSC 2010

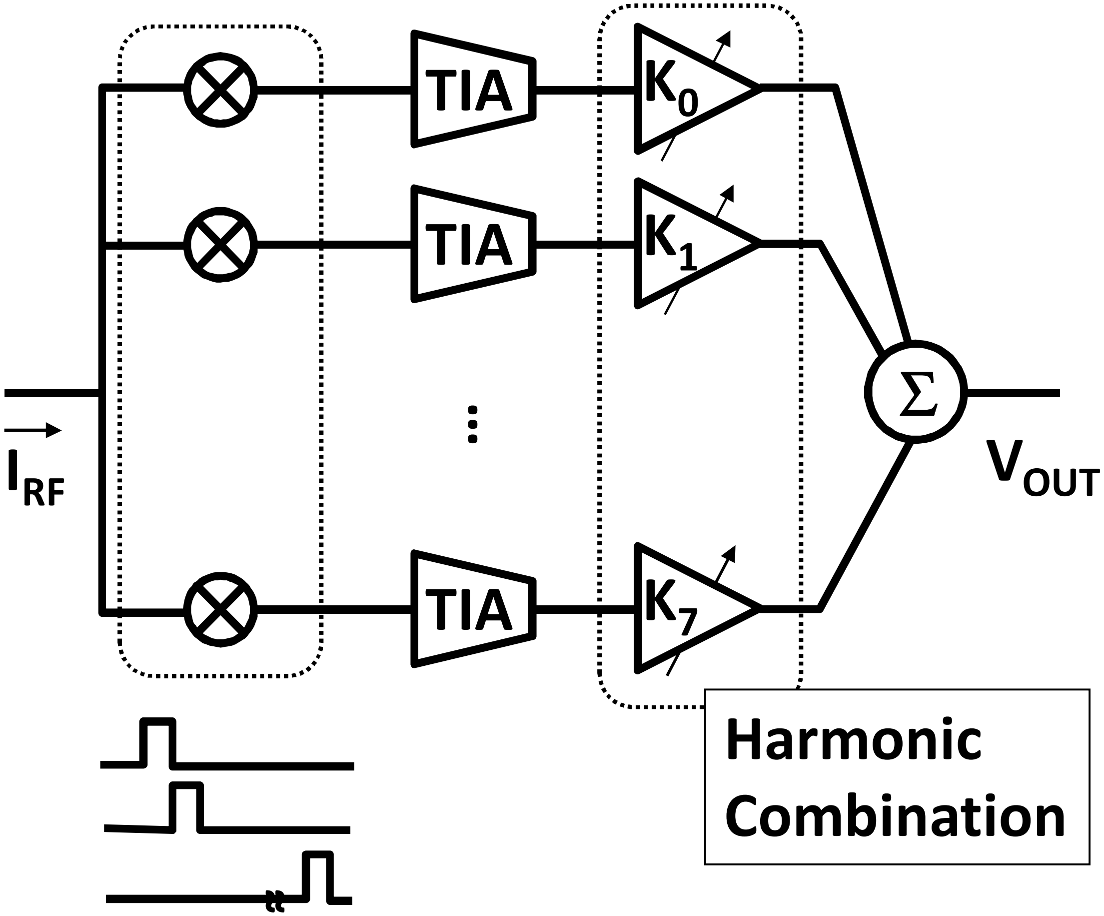
Noise Cancelling Receivers

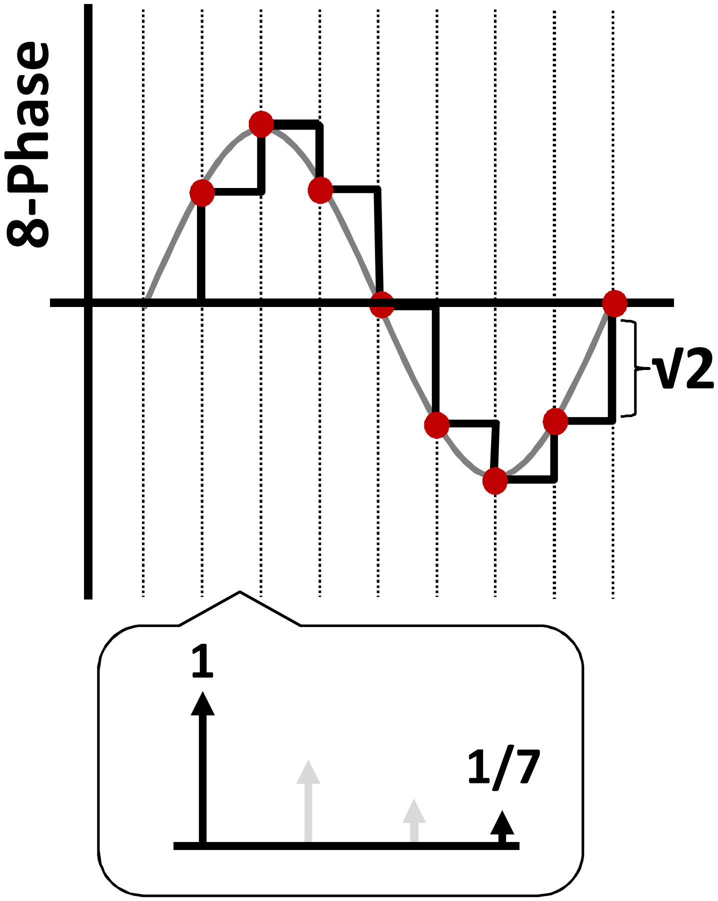


- **Low noise and linear**
- **No Balun required**

🗎 [26] Murphy, ISSCC 2012

Over-Sampling Mixer Architecture





- Square-wave LO harmonically rich
- Synthesizes arbitrary 8-phase LO:

$$V_{OUT} = i_{RF}(t)\sum_{x=0}^{7} K_x sw(t - \frac{x}{8T})$$

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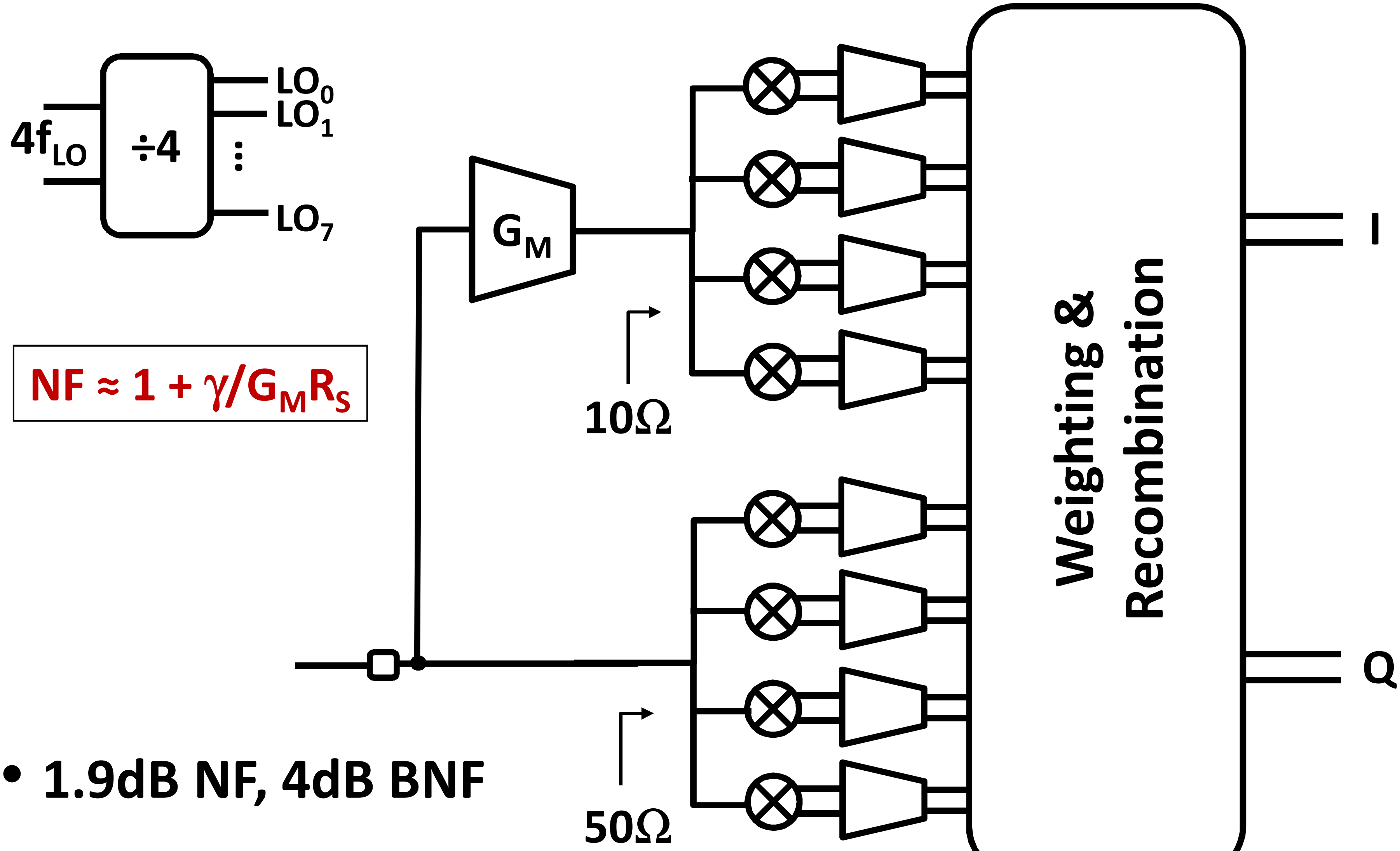
[17] Weldon, JSSC 2001

Case Study: NC SDR Receiver



$NF \approx 1 + \gamma/G_M R_S$

- 1.9dB NF, 4dB BNF

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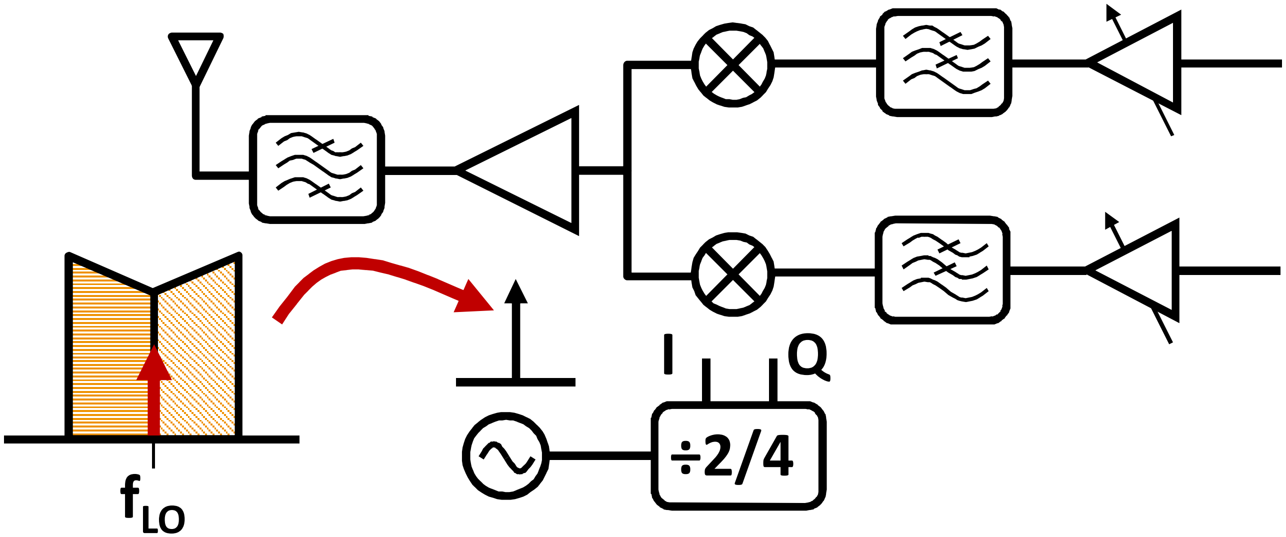
[26] Murphy, ISSCC 2012

Direct-Conversion Transmitters



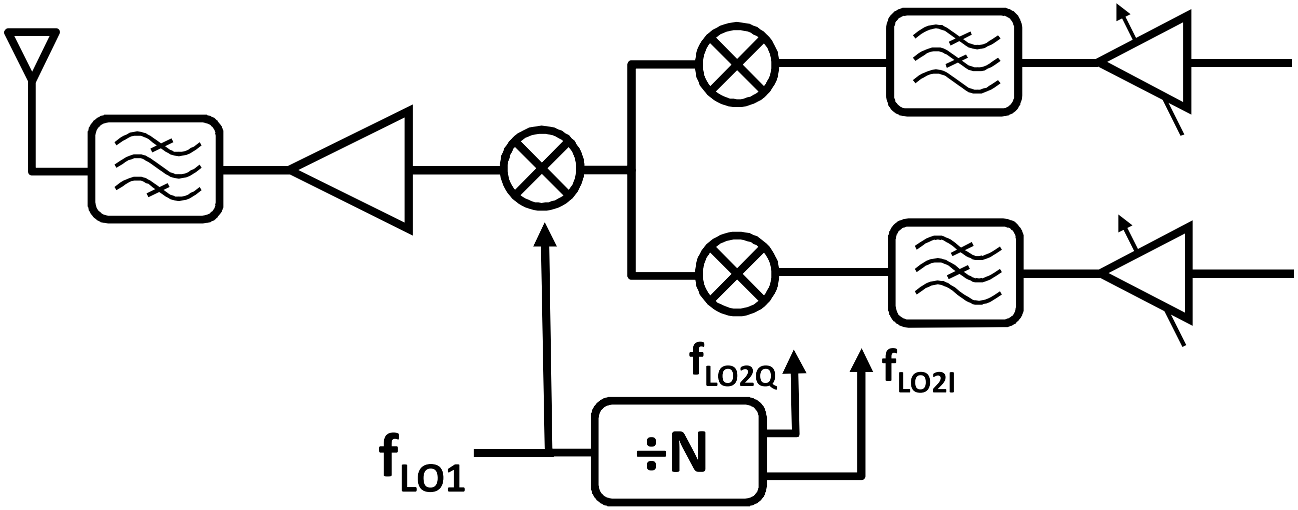
Pros

- Low power
- Versatile
- Highly integrated

Cons

- Suffers from pulling
- LOFT, IQ matching
- Far-out noise

Dual-Conversion Transmitters



Pros

- No pulling
- LOFT/IR less problematic
- Sliding IF

Cons

- Higher power
- More complex filtering needed

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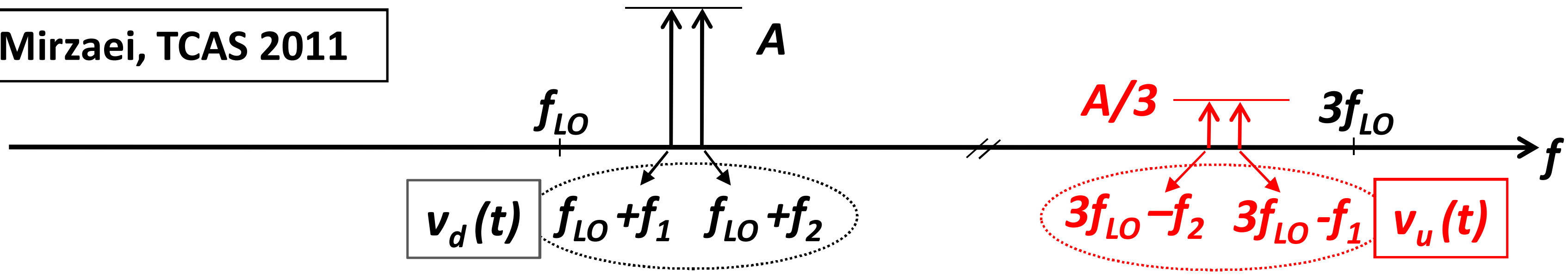
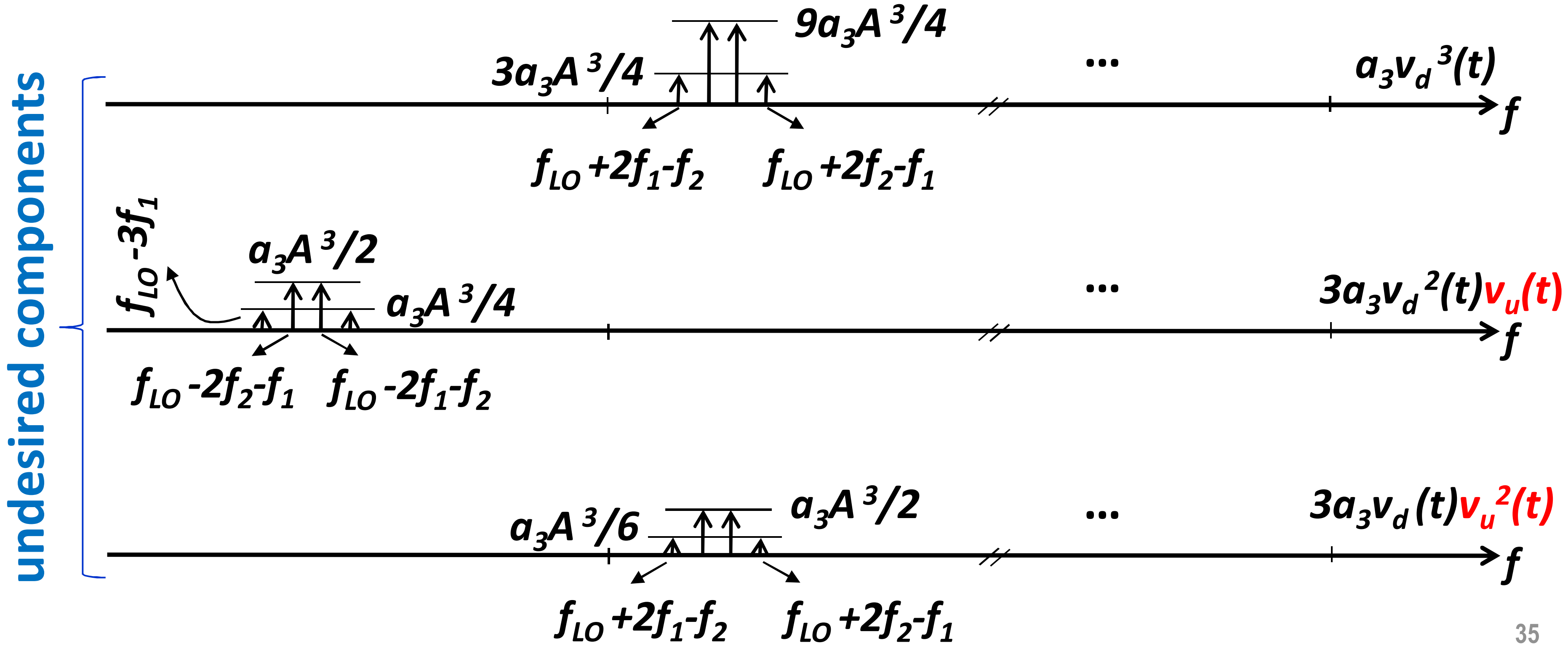
[13] Zargari, JSSC 2002

Third Harmonic Folding

🗎 [23] **Mirzaei, TCAS 2011**

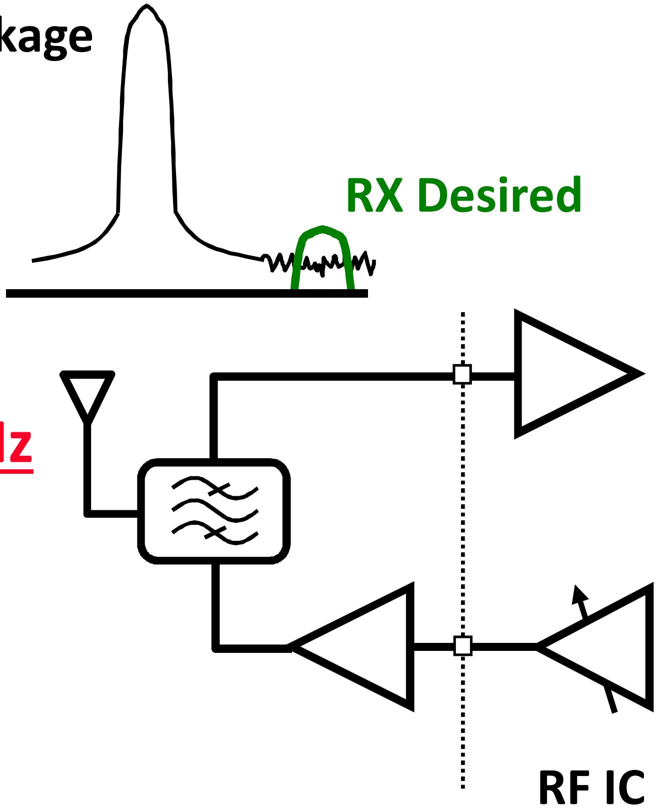


PA driver nonlinearity: $y=a_1x+a_3x^3$



WCDMA TX General Requirements

- -160dBc/Hz RX-band noise results in 0.5dB NF degradation

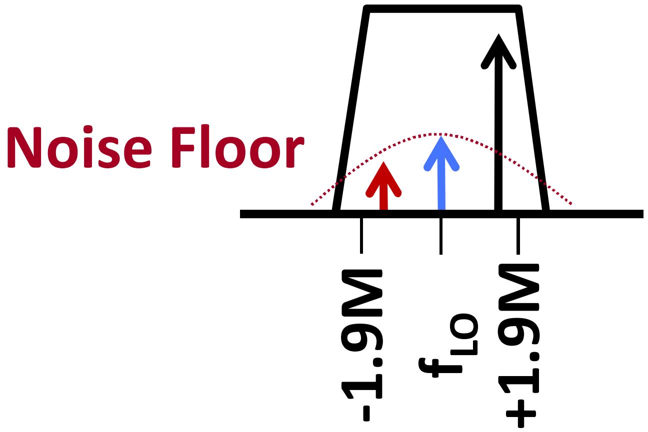


Noise Floor = 28-50-160 = -182dBm/Hz

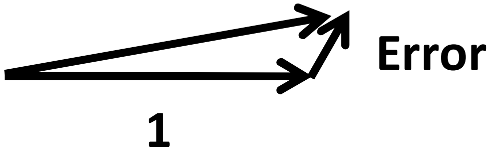
- ACLR1 at 5MHz: -33dBc
- ACLR2 at 10MHz: -43dBc
- EVM: 19%

WCDMA TX EVM

- In linear TX, IQ imbalance, LOFT & PN dominate



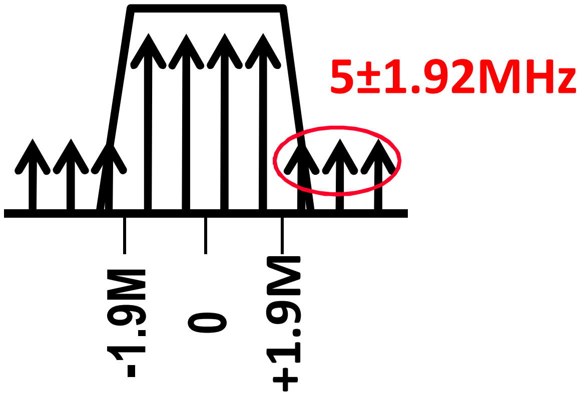
$$EVM\,(\%) = \sqrt{10^{\frac{IQ}{10}} + 10^{\frac{LOFT}{10}} + 10^{\frac{PN}{10}}}$$

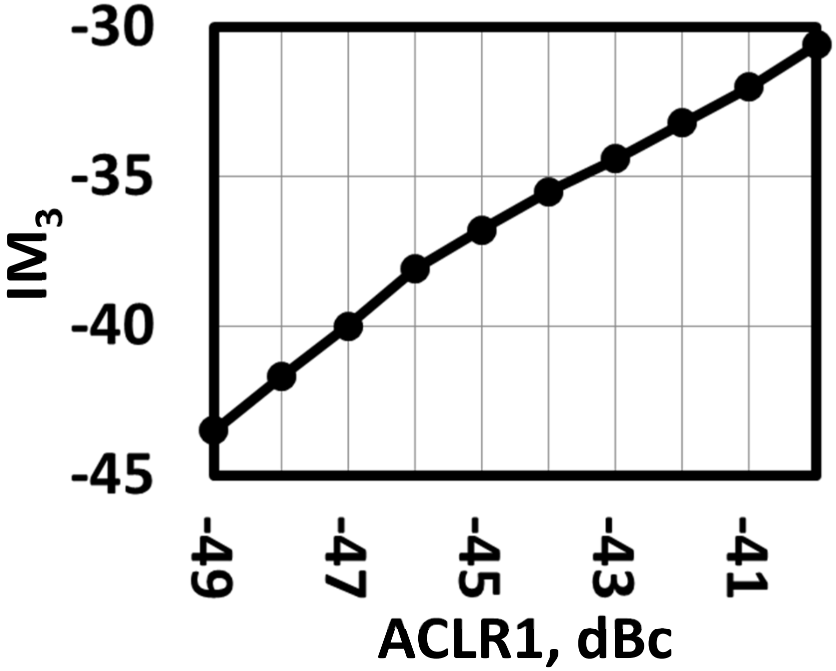


- 40dBc equal contribution results in √3 = 1.7% EVM
- Baseband filter ripple adds further
- Typical RF IC EVM around 3%

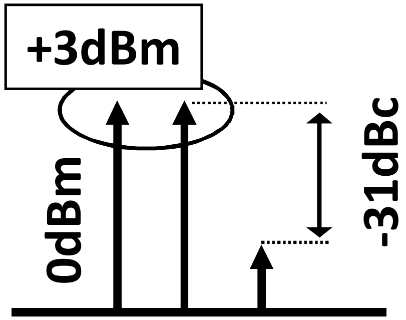
WCDMA TX ACLR

- Nonlinearity results in ACLR
  - Depends on PAR, modulation





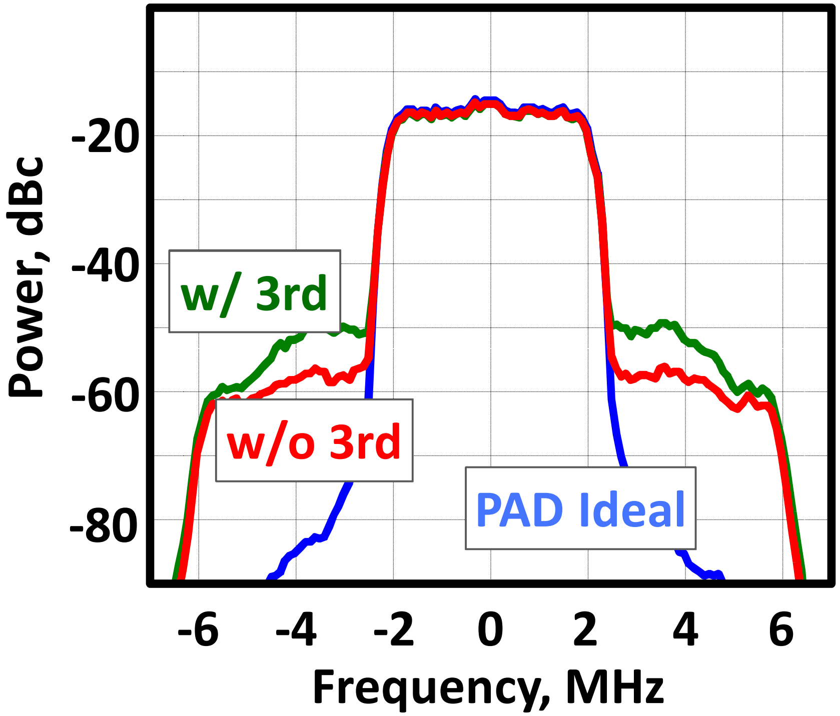
- ACLR1 requirement of -33dBc at the antenna
  - PA WC -37dBc (optimized for efficiency)
  - 2dB production margin
  - Leaves RFIC WC of -40dBc

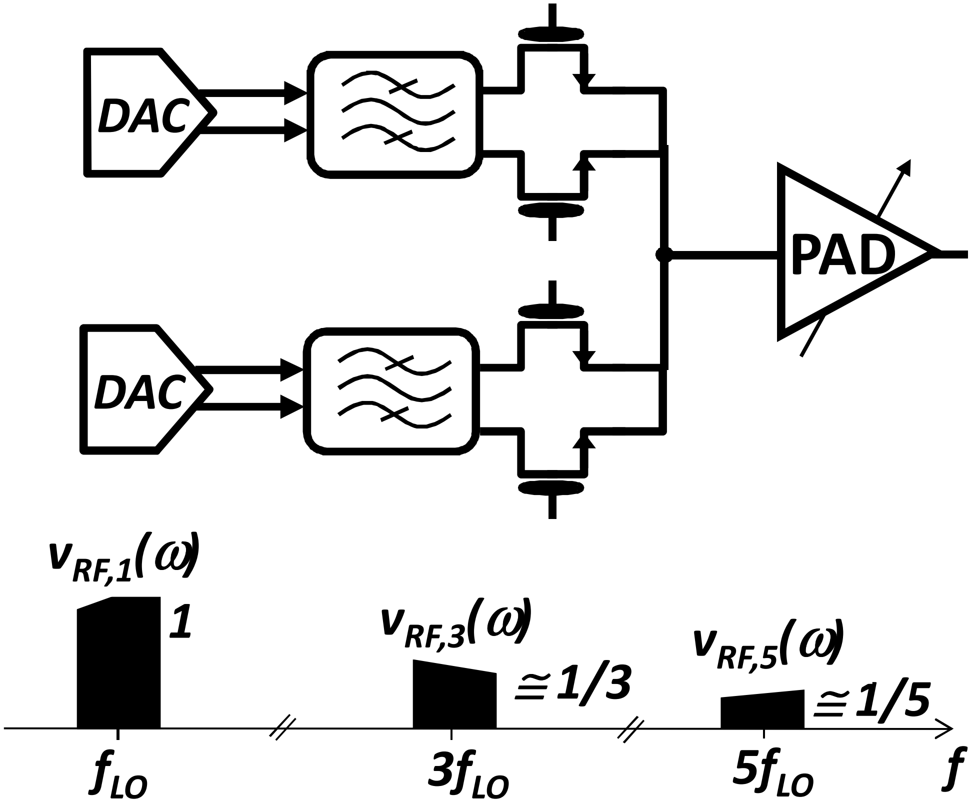


OIP_3 = 15.5dBm

Folding Impact on PAD Linearity

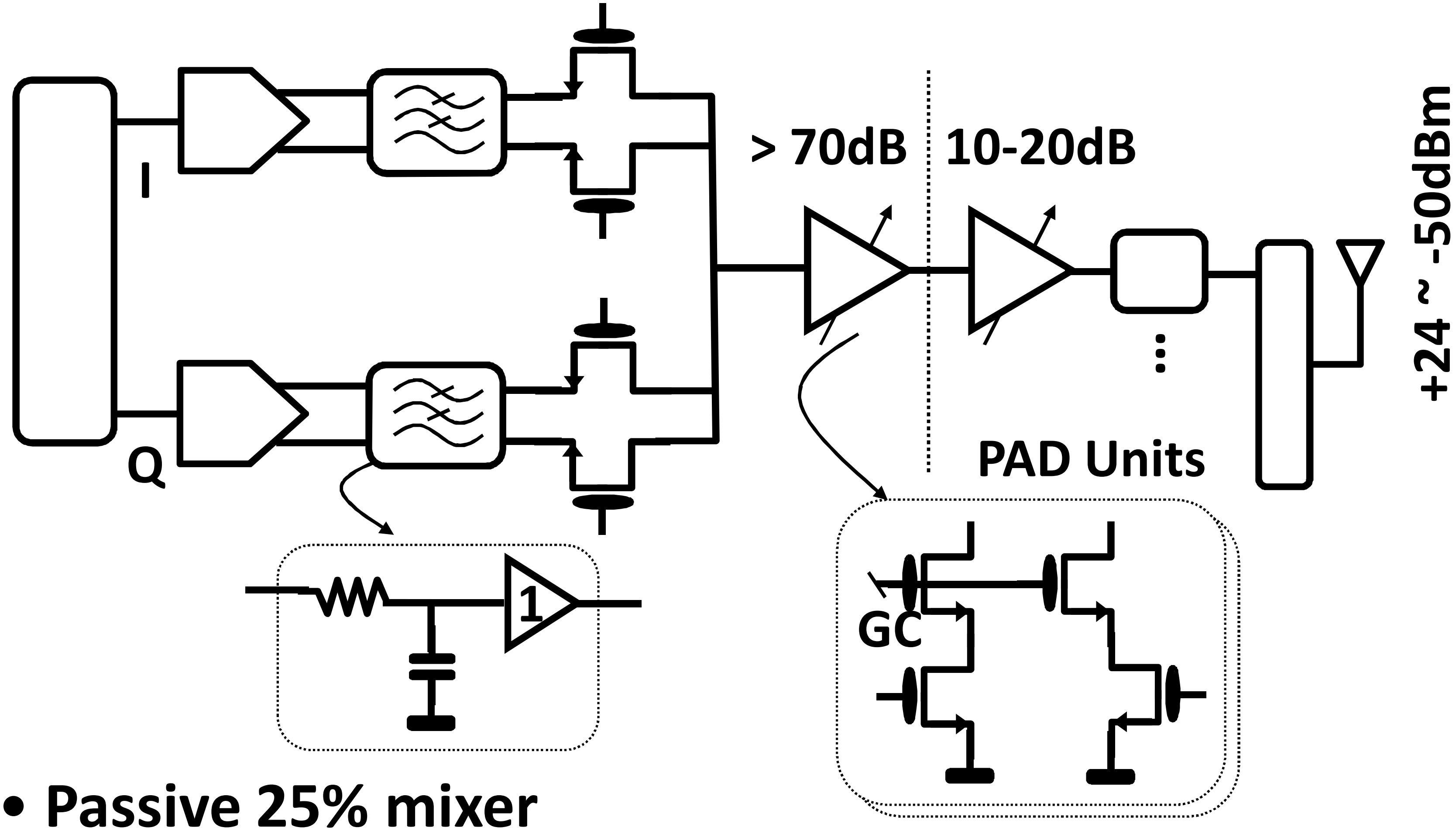
Output 3G Signal





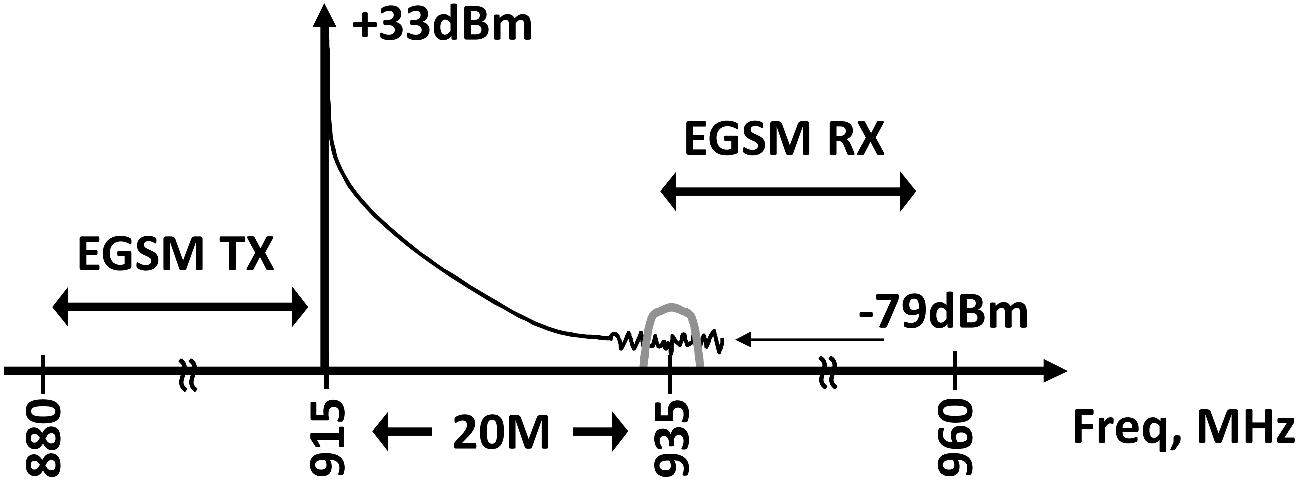
- With third harmonic present: ACLR = -38 dBc
- With third harmonic removed: ACLR = -44 dBc
- Makes the PAD linearity requirements more stringent

Case Study: Direct-Conversion 3G TX



- **Passive 25% mixer**
- **LOFT scales w/ RF gain**

GSM RX-Band Noise Requirements

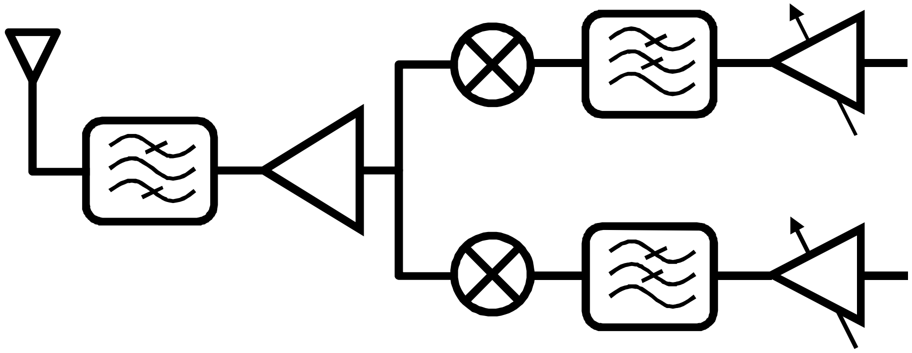


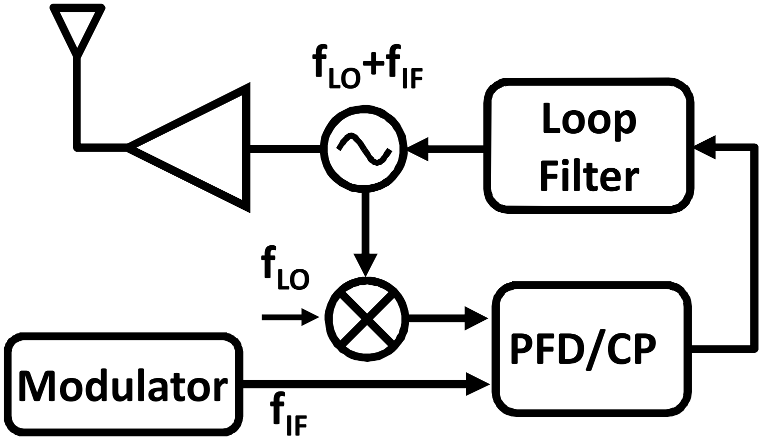
- TX noise in RX-band -79dBm not to mask adjacent RX
- Corresponds to a 20MHz phase noise of:

PN = -79dBm – 10Log(100kHz) – 33dBm = -162dBc/Hz

- Typical PA noise ≈ -83dBm, leaving -165dBc for RF IC
- -112dBc spur, five exceptions allowed

Linear TX vs. Translational Loop





- Sensitive to Pulling
- 20M noise an issue
- Simple
- Generic TX

- No pulling issue
- Relaxed filtering
- More complex
- Suitable for PM only

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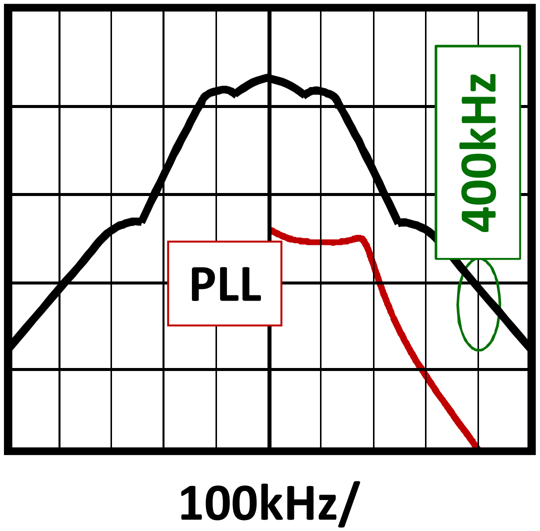
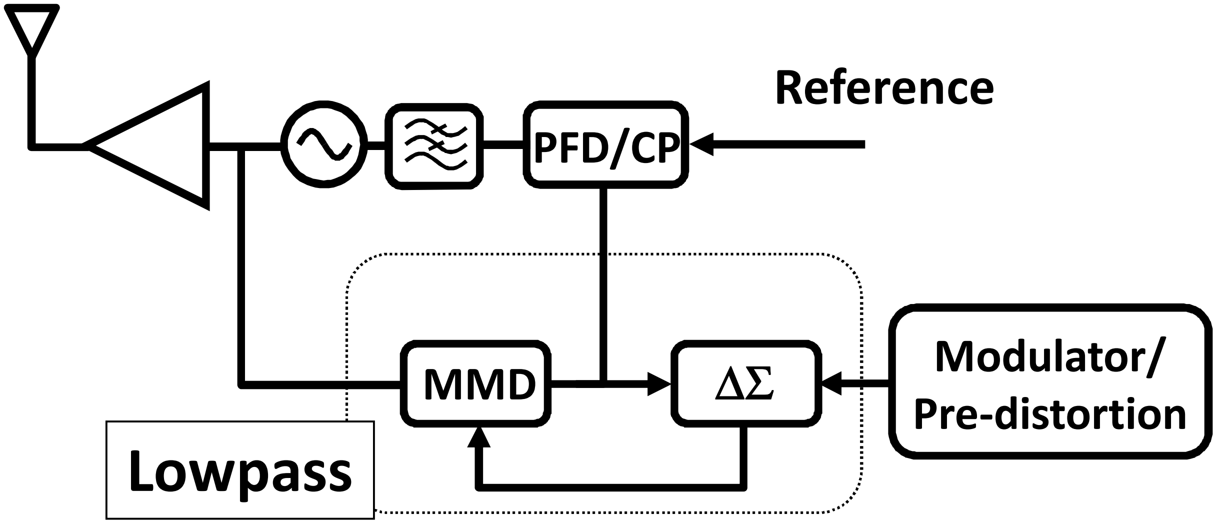
[2] Erdogan, ISSCC 2005

PLL-Based Transmitters





- Mixer/LO, analog modulator eliminated
- More sensitive to analog impairments
- Trade-off between BW and phase noise

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[3] Bonnaud, ISSCC 2006

GSM Mask & Phase Error Calculations

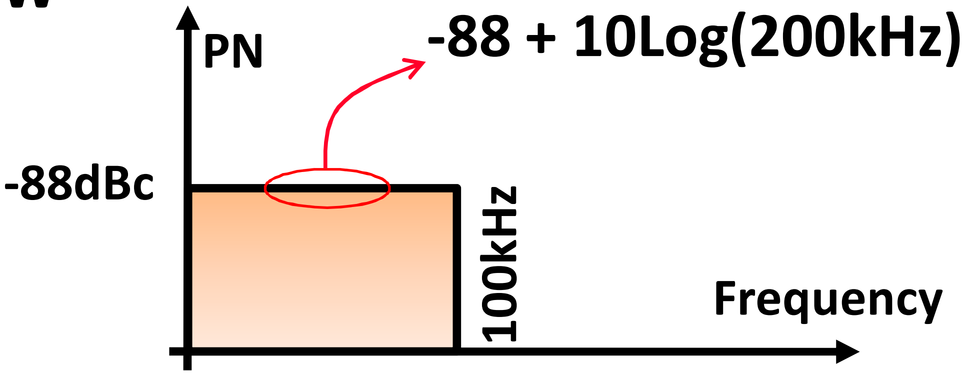
- -60dBc at 400kHz
  - 3dB production margin
  - 2dB PVT margin

Power integrated in 30kHz BW

≈ 10Log (200k/30k)

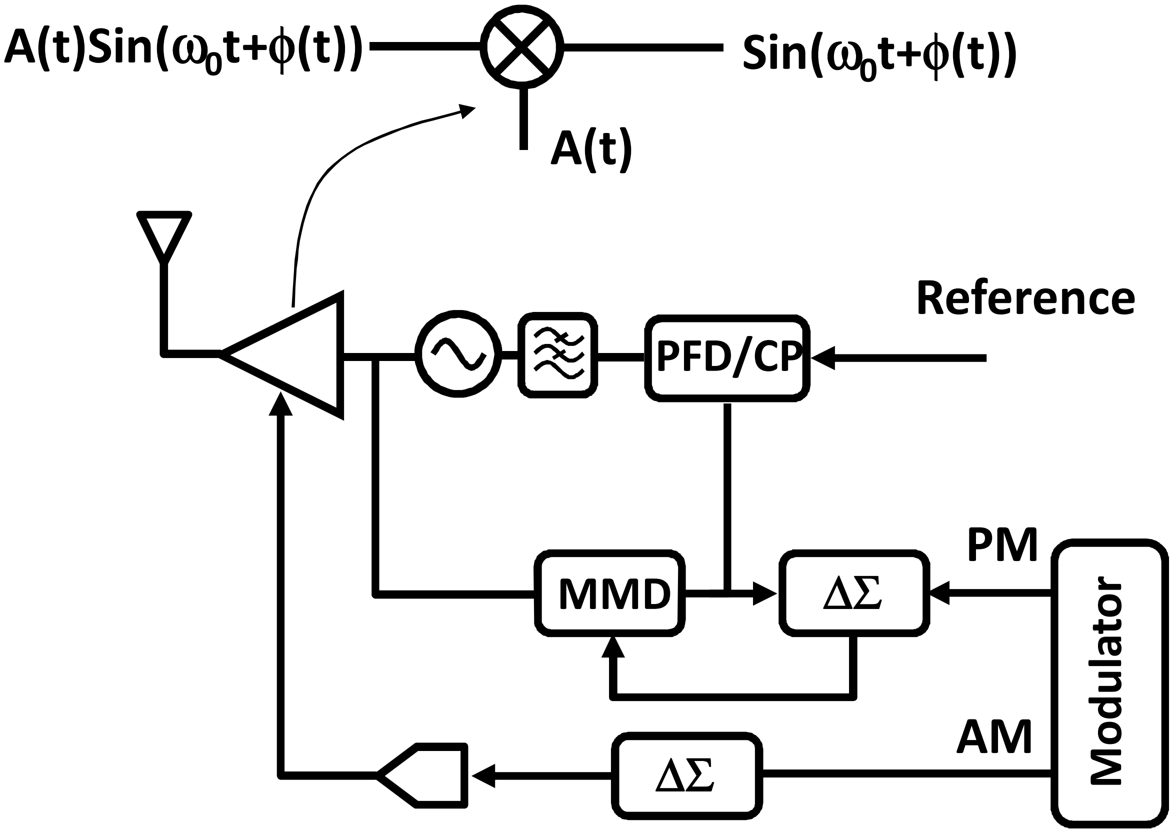
$$PN = -65 - 10\text{Log}(30\text{kHz}) - \boxed{9} = -118.8\text{dBc/Hz}$$

- 5° RMS phase error
  - 2° production margin
  - 2° PVT, BW



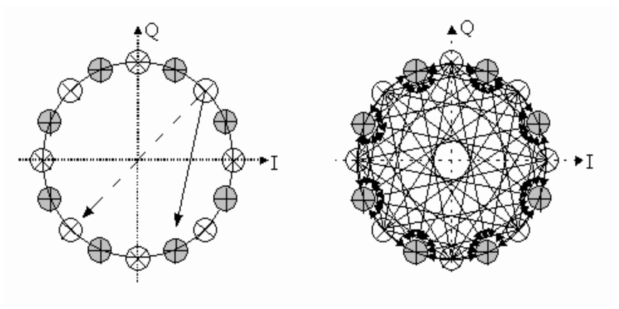
$$-88 + 10\text{Log}(200\text{kHz}) = \overbrace{-35\text{dBc}}^{0.0178\ \text{Radian}} = 1^{o}$$

Basics of Polar Transmitters



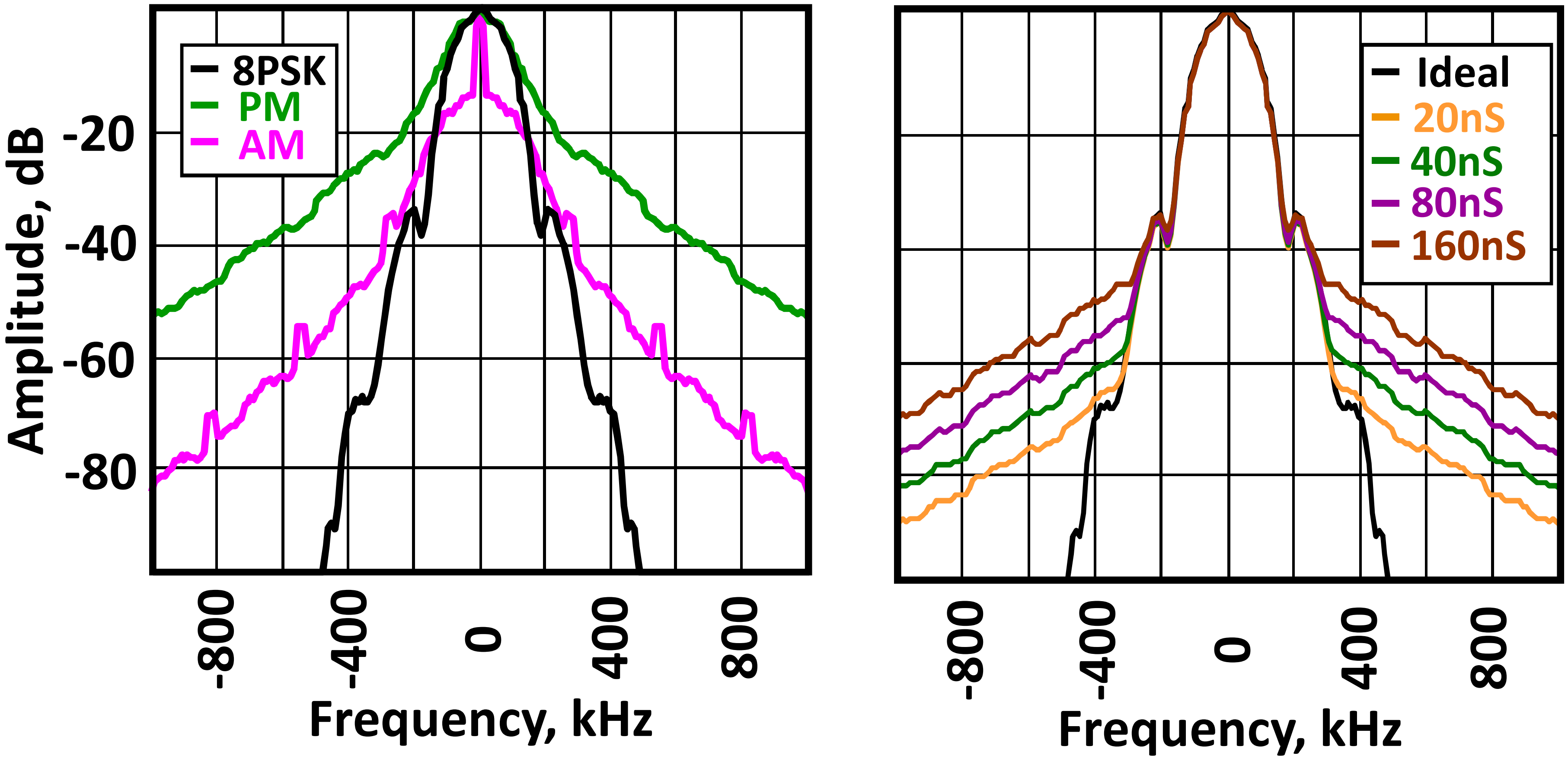
$$I + jQ = re^{j\theta}$$

EDGE Constellation



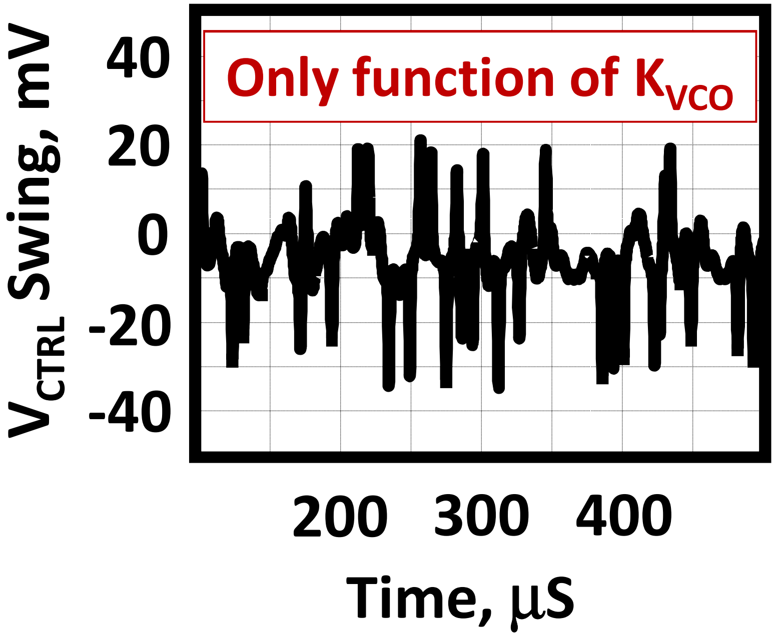
- Lower power consumption
- Compatible with GMSK TX
- Very sensitive to nonlinearities

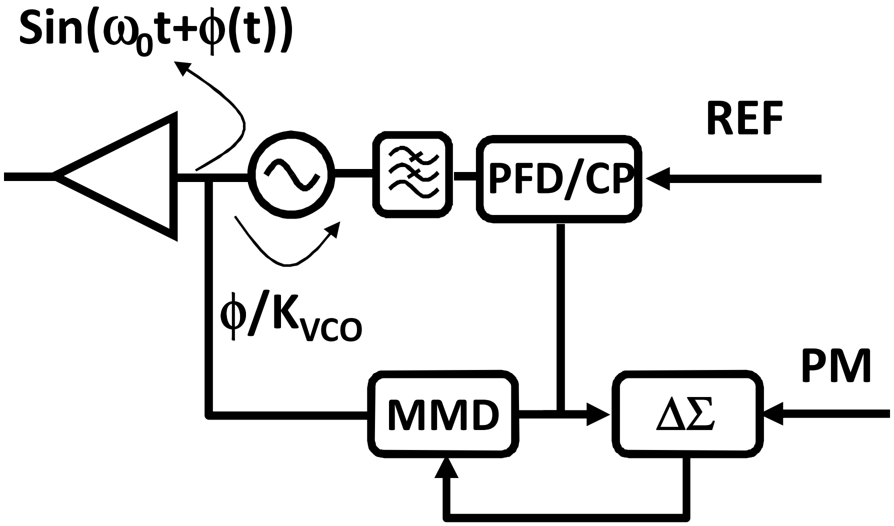
EDGE AM & PM Signals Spectrum



- AM & PM stand-alone signals much wider

PM Path Concerns

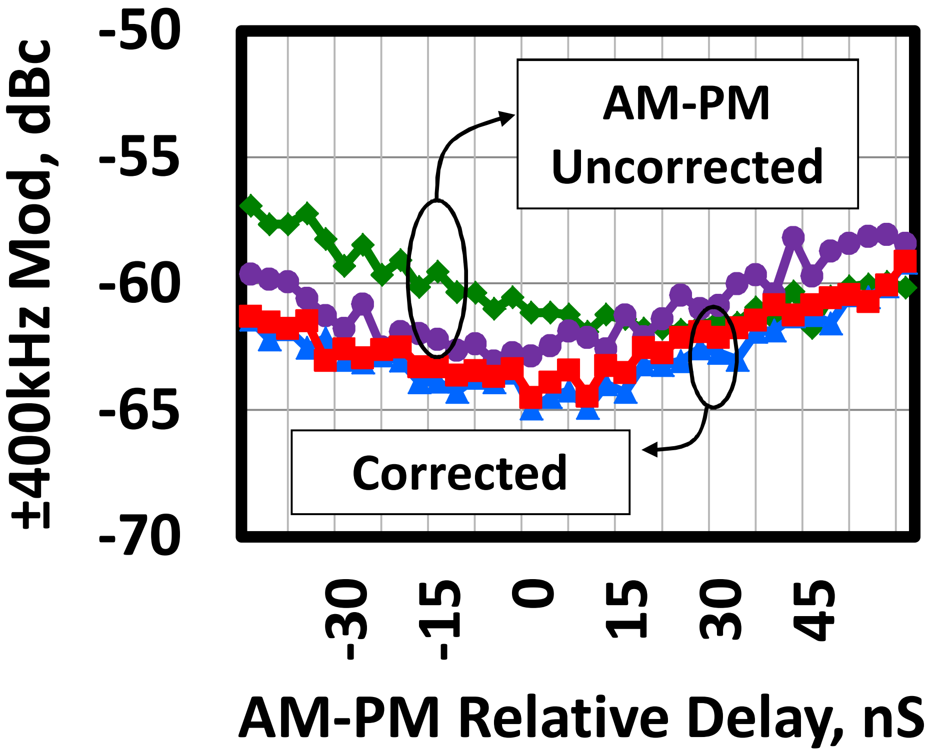


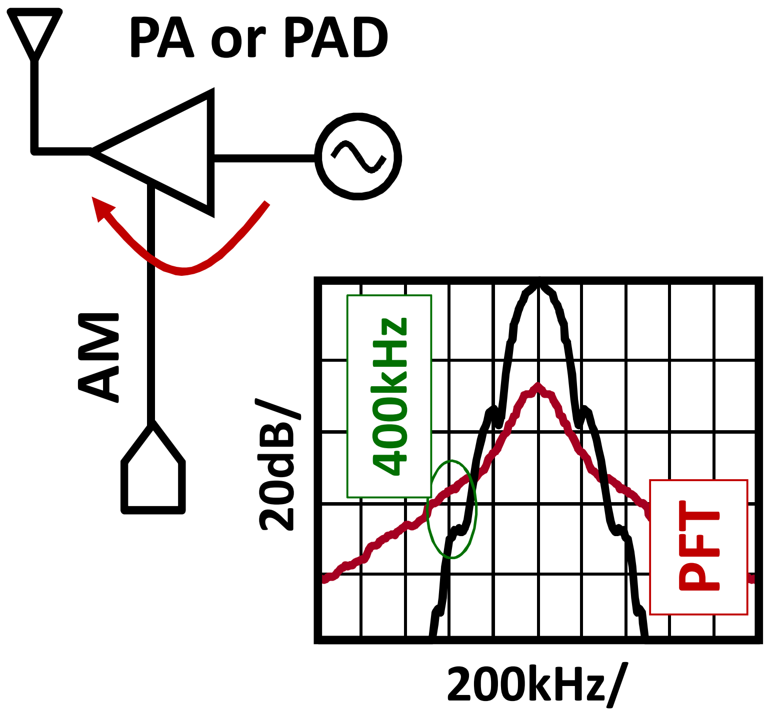


- Phase noise
- VCO & CP nonlinearity due to large swing, wide BW
- PLL BW needs to be accurately controlled
  - $BW \propto K_{VCO} \times R \times I_{CP}$: Measure K_{VCO} and adjust I_{CP}

[5,9] Darabi, JSSC 2011

AM Path Concerns

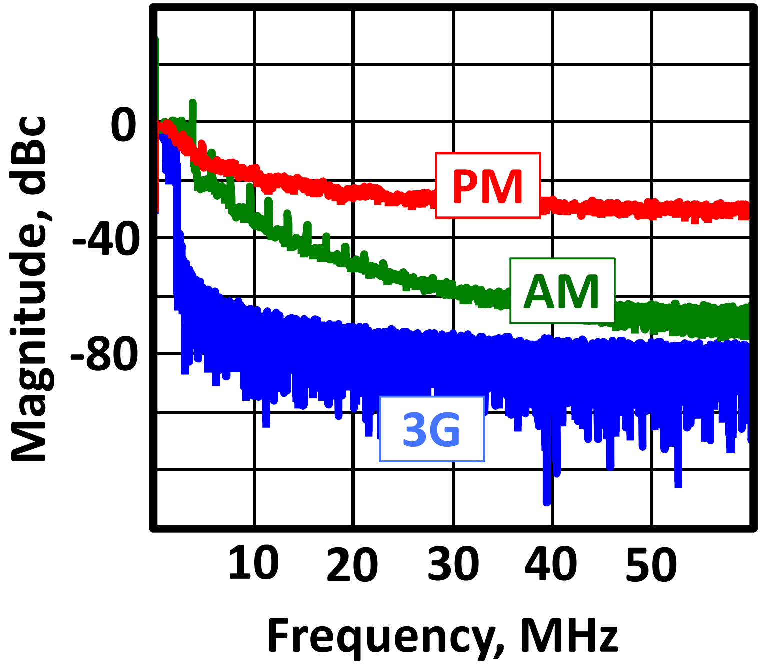


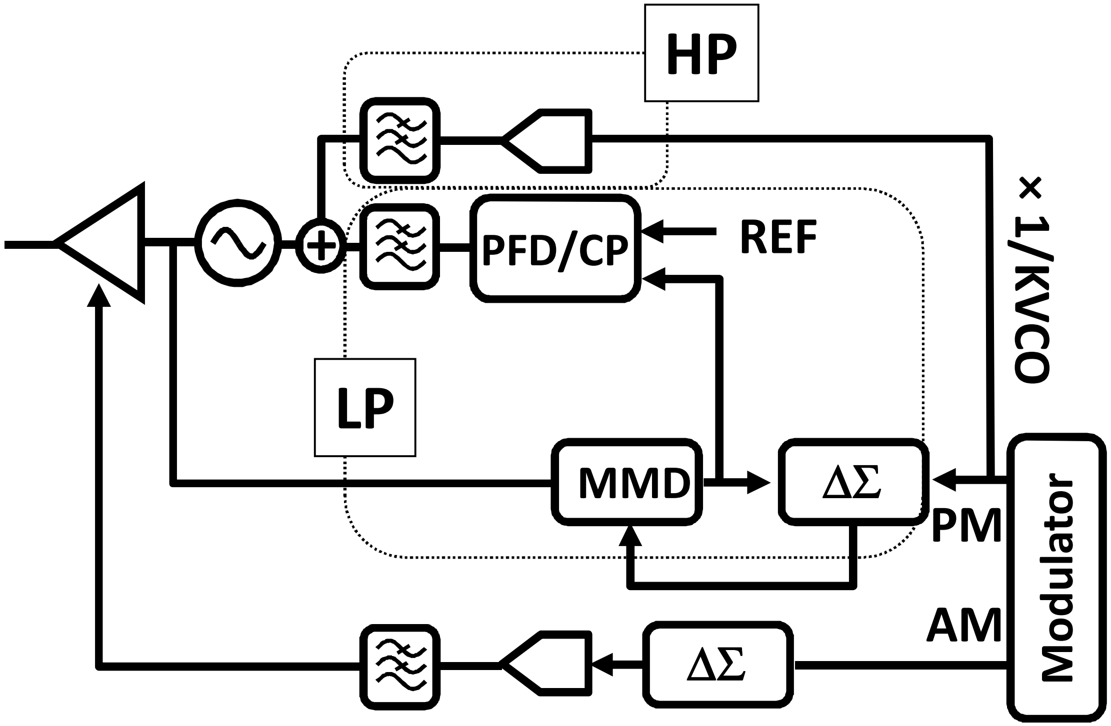


Mask Limiting Factors:

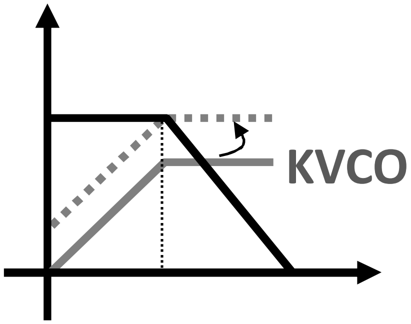
- AM-AM/PM distortion in PAD
  - Static: AM-AM
  - Dynamic: AM-PM
- Phase feed-through

2-Point PLL Based Polar Transmitters


3G AM & PM Signals



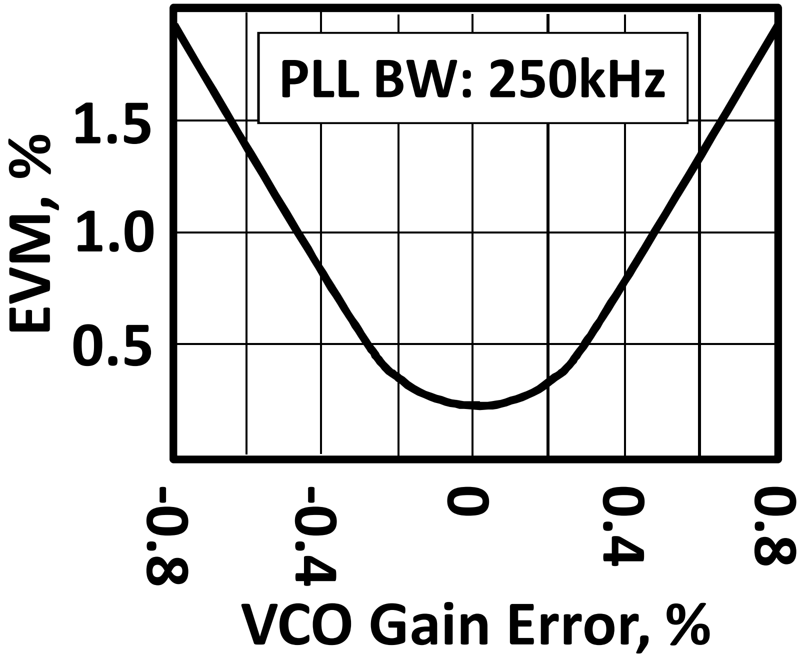
- HP path to give a flat response
- Accurate K_{VCO} needed
- Accurate AM-PM matching needed

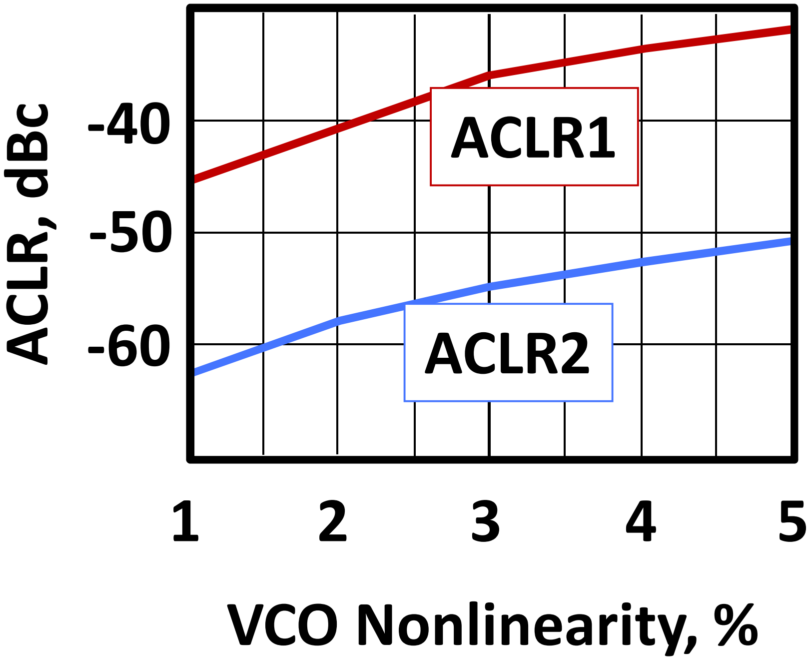


Impact of VCO Nonlinearity on 3G Signal

- $K_{VCO} = d\omega/dV = 0.5\times\omega_0^3\times L\times \underbrace{(dC_{VAR}/dV)}_{\text{PVT Dependent}}$

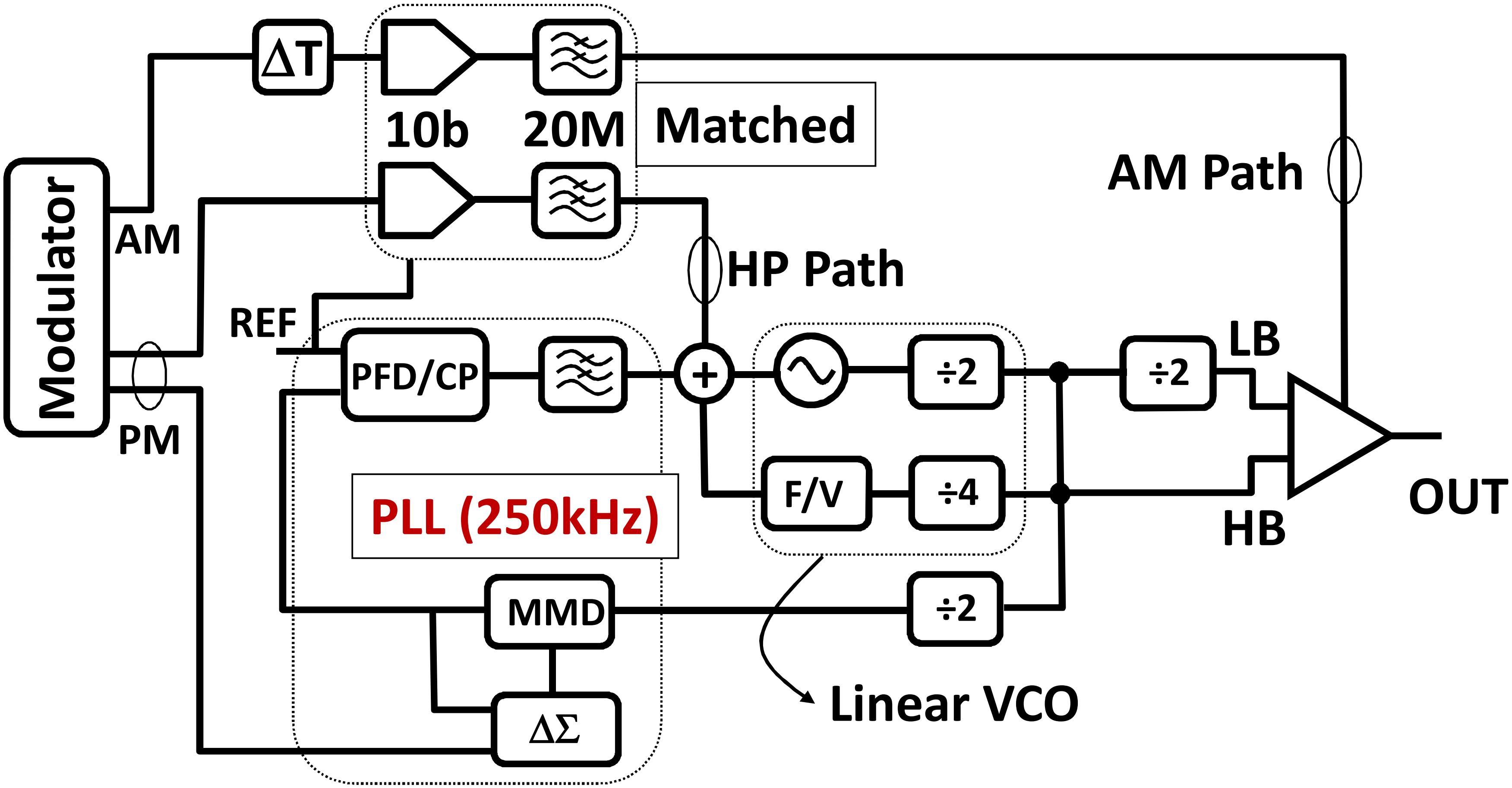
- LC and C_{VAR} not modeled accurately





- K_{VCO} accuracy/linearity of better than 2% needed

Case Study: 3G Polar TX



- < -40dBc ACLR, < 3% EVM

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6 Youssef, JSSC 2011

Summary & Conclusions

- Standards set design parameters, radio architecture
- On receiver side:

Architecture	1/f, IIP_2	IMR	Linearity	Limitations
Zero-IF	Poor	Self	Modest	WB
Low-IF	Modest	In-band	Modest	NB

- CM receivers improve linearity, relax filtering
- On transmitter side:

Architecture	Power	Noise	Pulling	Limitations
Direct	Modest	Poor	Poor	Generic
PLL	Lowest	Good	None	Only PM, NB
Polar	Lowest	Good	Good	Complex, NB

References

1. A. A. Abidi, “Direct-Conversion Radio Transceivers for Digital Communications,” IEEE J. of Solid-State Circuits, vol. 30, no. 12, pp. 1399-1410, 1995
2. O. Erdogan, et. al., “A single-chip quad-band GSM/GPRS transceiver in 0.18mm CMOS,” *ISSCC Digest of Technical Papers*, pp. 318-319, Feb. 2005.
3. O. Bonnaud, et. al., “A fully integrated SoC for GSM/GPRS in 0.13mm CMOS,” *ISSCC Digest of Technical Papers*, pp. 482-3, Feb. 2006.
4. L. Franks and I. Sandberg, “An alternative approach to the realizations of network functions: N-path filter,” in Bell Syst. Tech. J., 1960, pp. 1321–1350.
5. H. Darabi, at. el., “A Quad-Band GSM/GPRS/EDGE SoC in 65nm CMOS,” *IEEE J. of Solid-State Circuit*, no. 4, April 2011.
6. M. Youssef, et. al., “A Low-Power Wideband Polar Transmitter for 3G Applications,” *ISSCC Digest of Technical Papers*, Feb. 2011.
7. E. H. Armstrong, “The Super-Heterodyne-Its Origin, Development, and Some Recent Improvements ” Proc. of the Institute of Radio Engineers Volume: 12 , Issue: 5, 1924, pp. 539-552
8. Z. Boos, et. al., “A Fully Digital Multi-Mode Polar Transmitter Employing 17b RF DAC in 3G Mode,” *ISSCC Digest of Technical Papers*, Feb. 2011.
9. H. Darabi, et. al., “Analysis and Design of Small Signal Polar Transmitters for Cellular Applications,” *IEEE J. of Solid-State Circuit*, 2011.
10. J. Mitola, “The software radio architecture,” *IEEE Communications Magazine*, vol. 33, no. 5, pp. 26-38, May 1995.
11. A. Mirzaei, et. al., “Analysis and optimization of current-driven passive mixers in narrowband direct-conversion receivers,” *IEEE J. of Solid-State Circuit*, no. 10, pp. 2678-2688, October 2009.
12. D. Kaczman, et. al., “A single-chip 10-band WCDMA/HSDPA 4-band GSM/EDGE SAW-less CMOS receiver with DigRF 3G interface and 90dBm IIP3”, *IEEE J. of Solid-State Circuit*, no. 3, pp. 718-739, 2009.
13. M. Zargari, et. al., “A 5-GHz CMOS transceiver for IEEE 802.11a wireless LAN systems”, *IEEE J. of Solid-State Circuit*, no. 12, pp. 1688-1694, 2002.
14. A. Mirzaei, et. al, “Analysis and optimization of direct-conversion receivers With 25% duty-cycle current-driven passive mixers ,” *IEEE Trans Circuits & Systems I*, No. 9, Vo. 47, 2010, pp. 23530-2366.
15. E. Cijvat, et. al, “Spurious mixing of off-channel signals in a wireless receiver,” *IEEE Trans Circuits & Systems II*, No. 8, Vo. 49, 2002, pp. 539-544.
16. A. Mirzaei, et. al., “A 65nm CMOS quad-band SAW-less receiver for GSM/GPRS/EDGE,” *IEEE J. of Solid-State Circuit*, no. 4, April 2011.
17. J. Weldon, et. al., “A 1.75-GHz highly integrated narrow-band CMOS transmitter with harmonic-rejection mixers ,” *IEEE J. of Solid-State Circuit*, no. 12, pp. 2003-2015, Dec 2001
18. C. Andrews, et. al., “A passive-mixer-first receiver with Digitally Controlled and Widely Tunable RF Interface,” *IEEE J. of Solid-State Circuit*, Vol. 45, no. 12, pp. 2696-2708, Dec 2010
19. M. Soer, et. al., “A 0.2-to-2GHz 65nm CMOS receiver w/o LNA achieving >11dBm IIP3 and <6.5dB NF,” *ISSCC Digest of Tech. Papers*, pp. 222-3, Feb. 09
20. X. He, et. al, “A Low-Power, Low-EVM, SAW-Less WCDMA Transmitter Using Direct Quadrature Voltage Modulation,” *IEEE J. of Solid-State Circuit*, vol. 44, no. 12, pp. 3448–3458, 2009.
21. A. Mirzaei, et. al., “A Frequency Translation Technique for SAW-Less 3G Receivers,” Proc. of IEEE Symp. VLSI Circuits, pp. 280-281, 2009.
22. M. Mikhemar, et. al., “A 13.5mA Sub-2.5dB NF Multi-Band Receiver,” Proc. of IEEE Symp. VLSI Circuits, 2012.
23. A. Mirzaei, et. al, “Analysis of Direct-Conversion IQ Transmitters With 25% Duty-Cycle Passive Mixers,” *IEEE Trans Circuits & Systems*, No. 10, Vo. 58, pp. 2318-2331, 2011.
24. A. Abidi, “Linearization of Voltage-Controlled Oscillators using Switched Capacitor Feedback,” *IEEE J. of Solid-State Circuits*, vol. 22, no. 3, pp. 494–496, June 1987.
25. F. Broccoleri, et. al., “Wide-band CMOS low-noise amplifier exploiting thermal noise canceling,” *IEEE J. Solid-State Circuits*, vol. 39, no. 2, pp. 275–282, Feb. 2004.
26. D. Murphy, et. Al., “A blocker-tolerant wideband noise-cancelling receiver with a 2dB noise figure ” *ISSCC Digest of Tech. Papers*, pp. 74-6, Feb. 12.