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Time-Varying Filtering Techniques for RF Front-Ends

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Acknowledgements

Research done by several graduate students…

- Dr. Mansour Rachid
- Dr. Sameed Hameed
- Dr. Neha Sinha
- (soon to be Dr.) Shi Bu

Research sponsored by…

- National Science Foundation

Outline

- Problem and prior art

- Filtering-by-Aliasing
  - Concept of using sampling aliases for sharp filtering
  - Designing FA filters: some examples

- Example applications
  - Agile RF front ends
  - Spectrum scanners

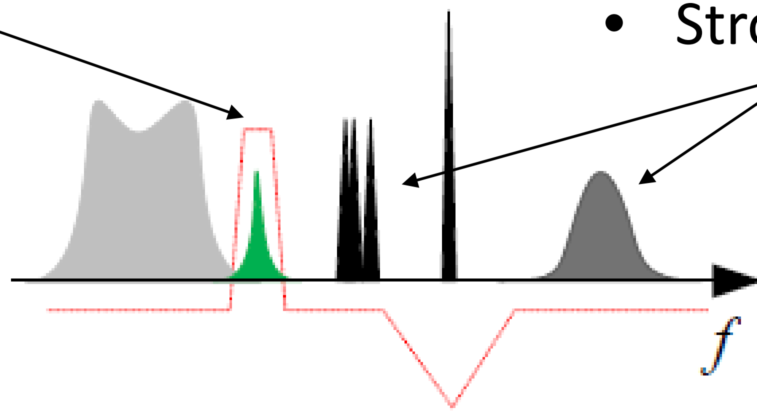
The RF Front End Problem

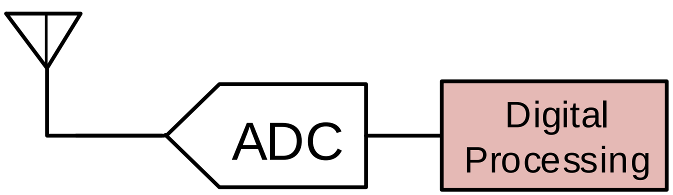
<u>Desired signal</u>:

- Varying freq. location
- Weak

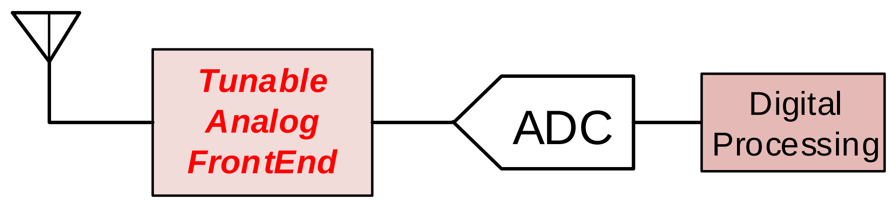
<u>Interferers</u>:

- Varying freq. location
- Strong



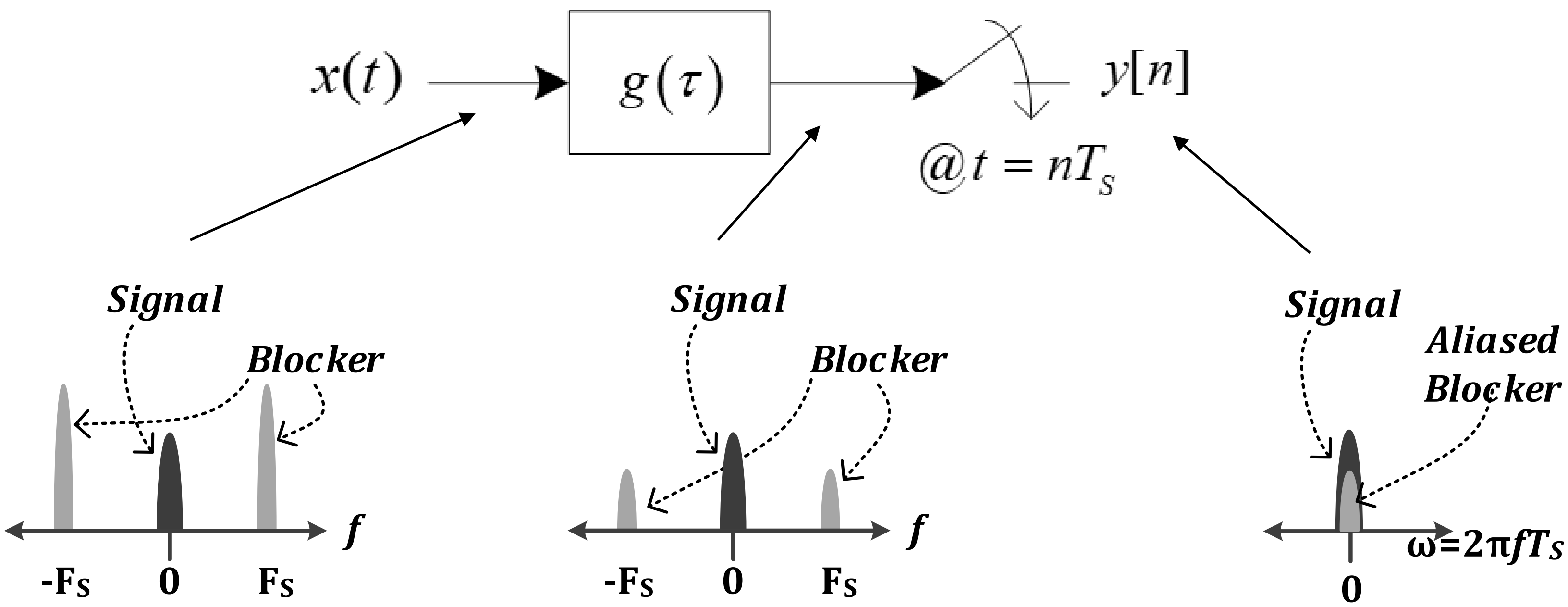


Feasible only in measurement equipment!



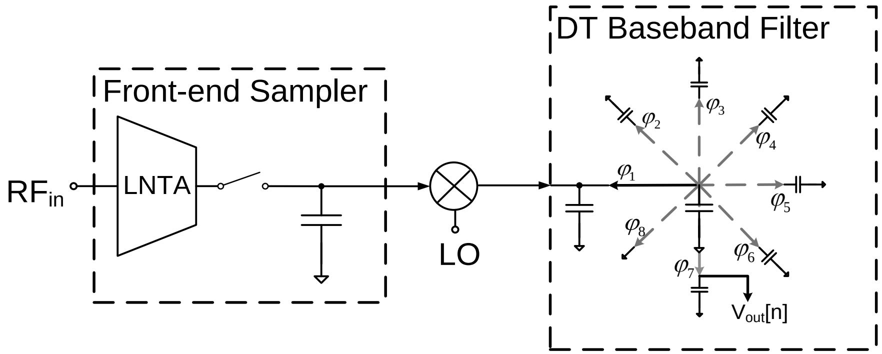
Sharpness vs tunability vs linearity tradeoffs!

Aliasing Is The Problem



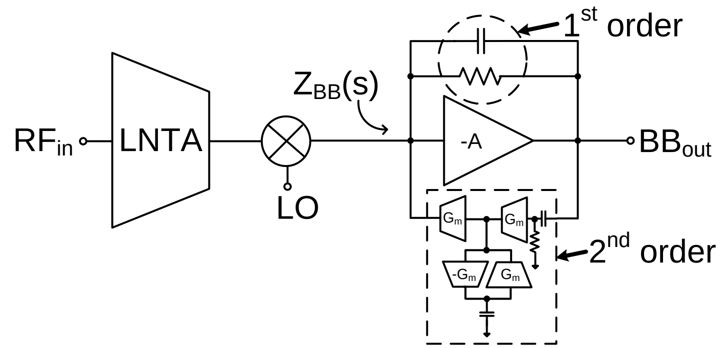
- Blockers alias upon sampling & corrupt the desired signal
- Age-old wisdom: <u>sharp filtering prior to sampling to avoid aliases</u>!
- Filtering is difficult
  - Passive filters (SAW/BAW/MEMS…) are linear but bulky, not programmable
  - Active filters are programmable, but not linear enough

Active RF Front-End Prior Art



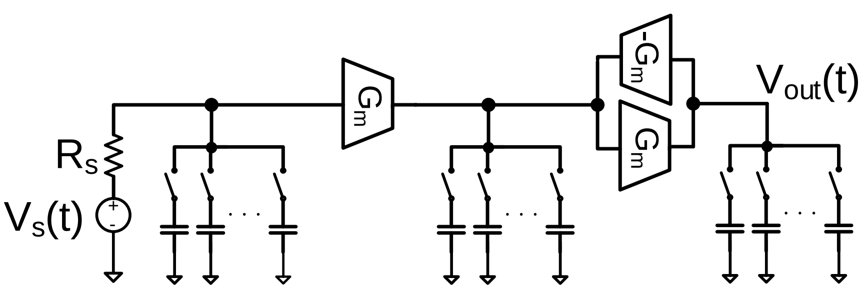
Charge-domain filtering

[Tohidian, et.al. ISSCC ’14]



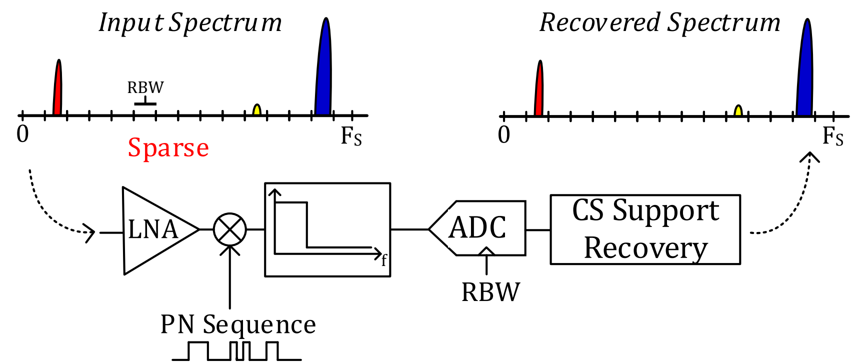
Mixer-first receivers

[Chen, ISSCC ’15, Murphy JSSC’12]



N-path Circuits

[Darvishi ISSCC’13, Lien ISSCC’17, …]



Compressive Sampling

[Mishali IET CDS’11, Yazicigil ISSCC’15]

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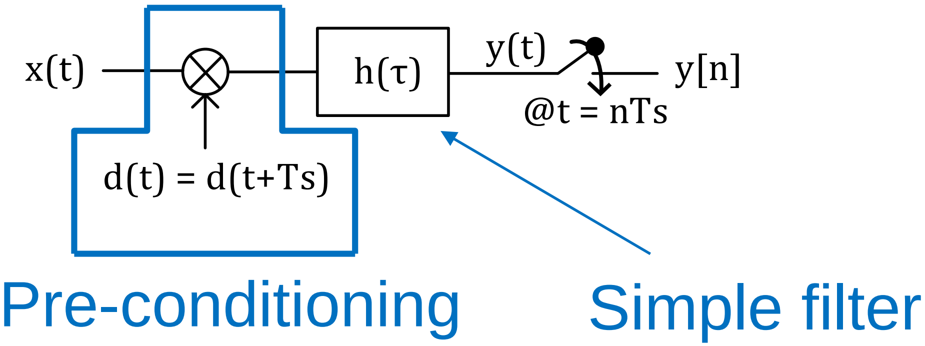
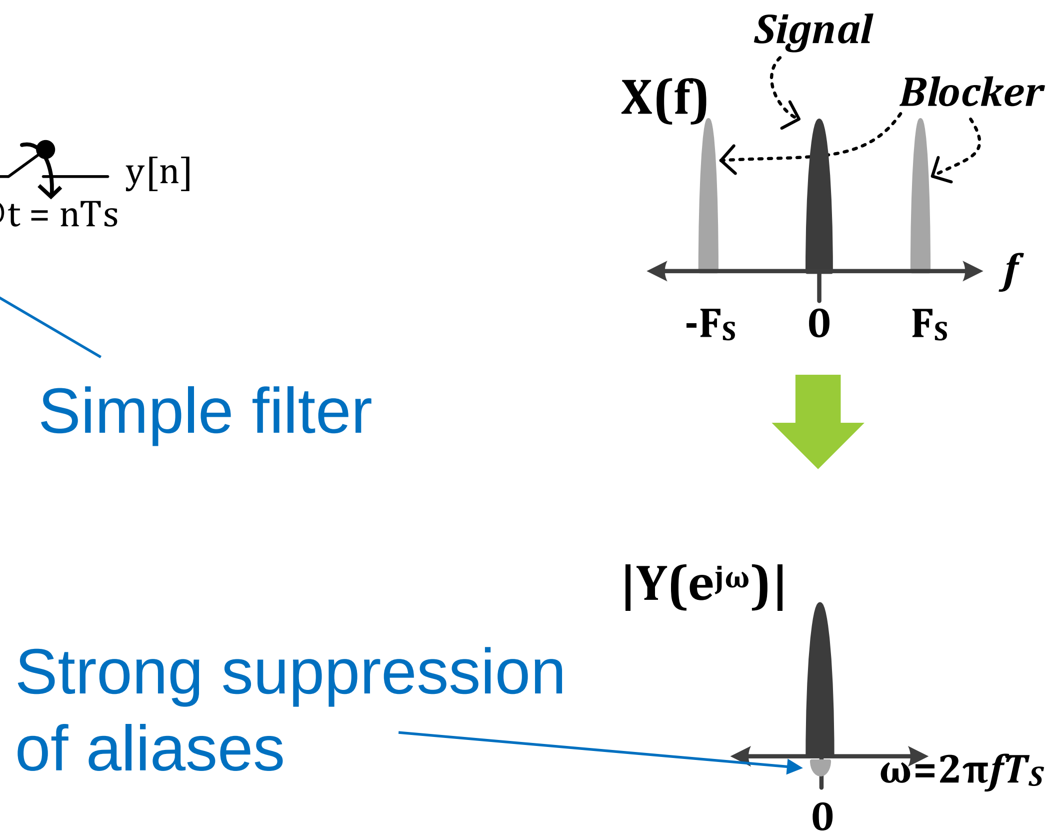
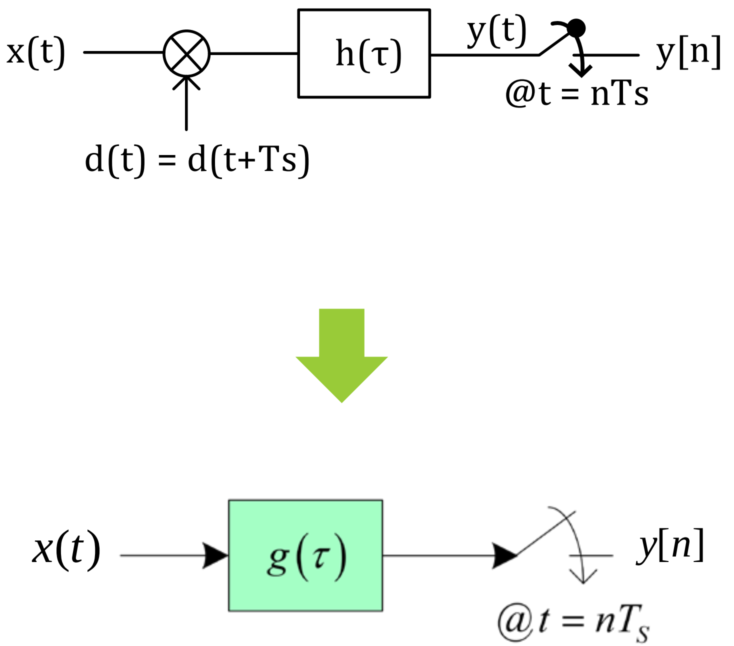
Filtering by Aliasing (FA)

Pre-condition signal such that sampling aliases combine destructively!





Filtering by Aliasing: Time-Domain



$$y[n] = \int_0^{\infty} h(\tau) \cdot d(t-\tau) \cdot x(t-\tau) \cdot d\tau \Big|_{t=nT_S}$$

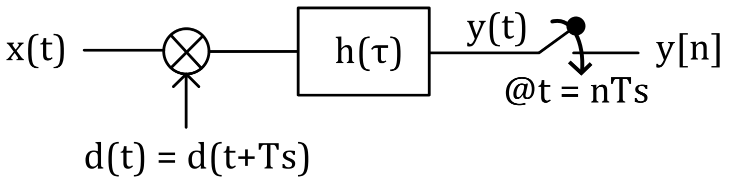
$$d(nT_S - \tau) = d(-\tau) \Rightarrow$$

$$y[n] = \int_0^{\infty} \underbrace{h(\tau) \cdot d(-\tau)}_{\triangleq g(\tau)} \cdot x(t-\tau) \cdot d\tau \Big|_{t=nT_S}$$

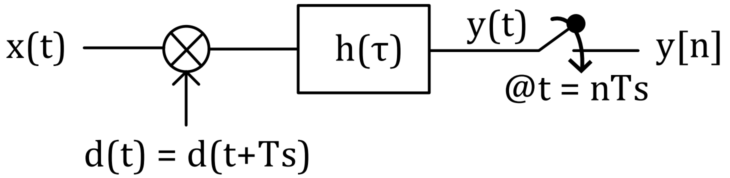
<u>Effective impulse response, g(t), can be precisely engineered:</u>

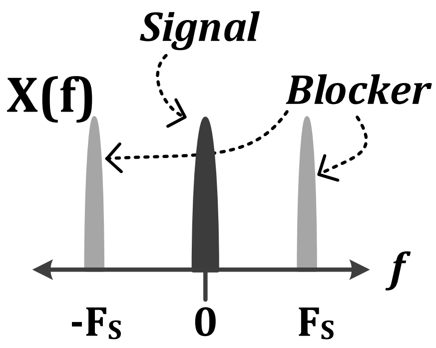
- Use a simple filter, h(t), with good linearity and low power consumption
- Use advanced D/A converter techniques to realize d(t) precisely

FA: Frequency Domain

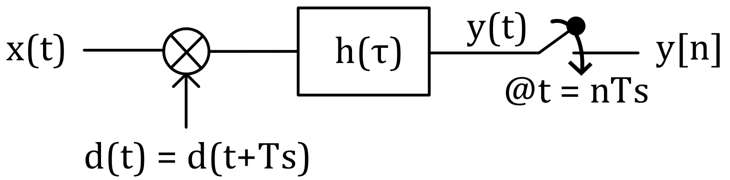


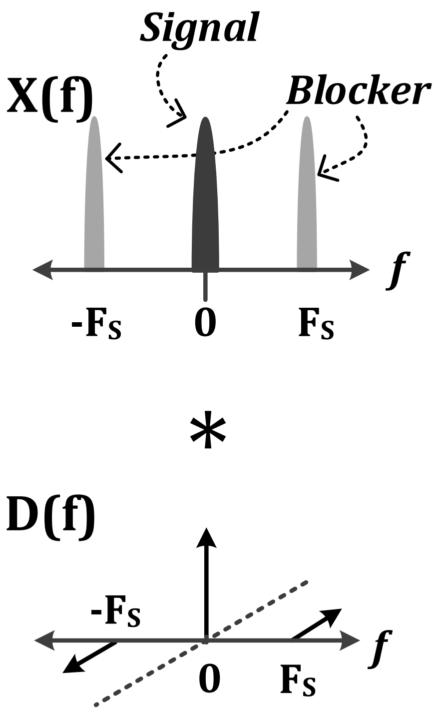
FA: Frequency Domain



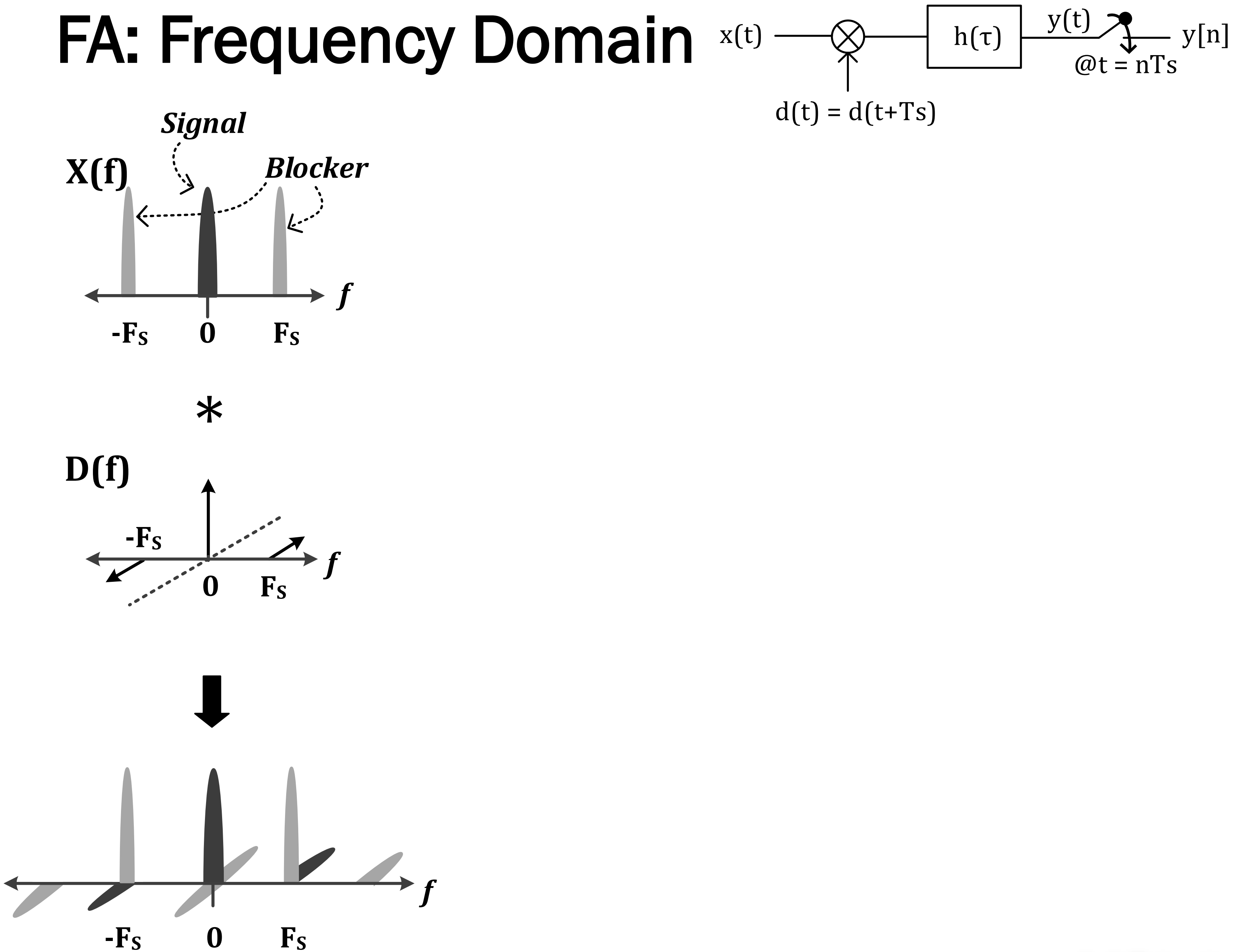


FA: Frequency Domain

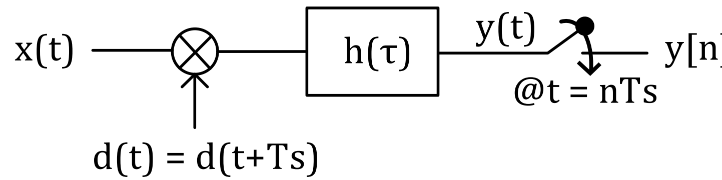


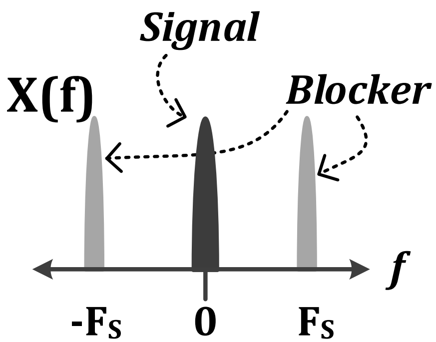


FA: Frequency Domain



FA: Frequency Domain





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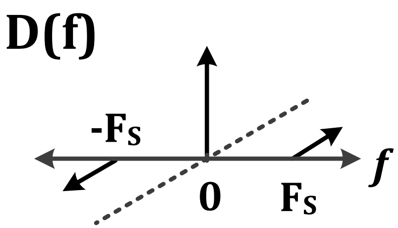

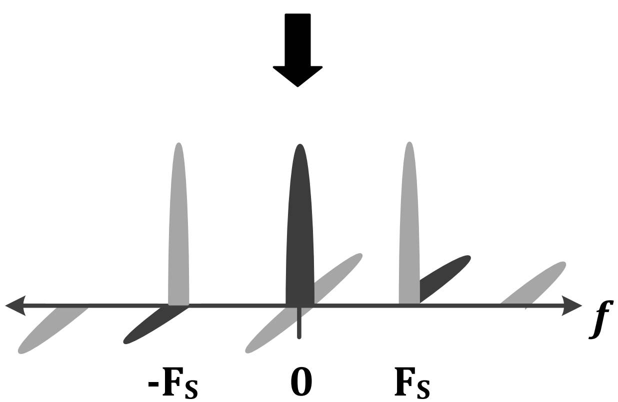

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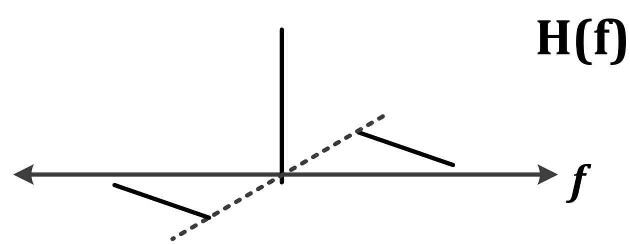
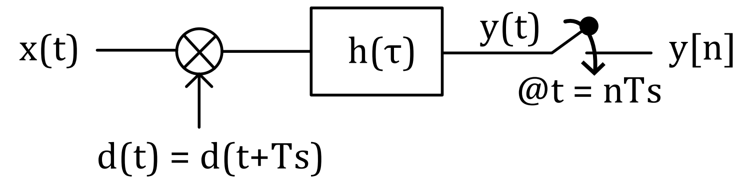
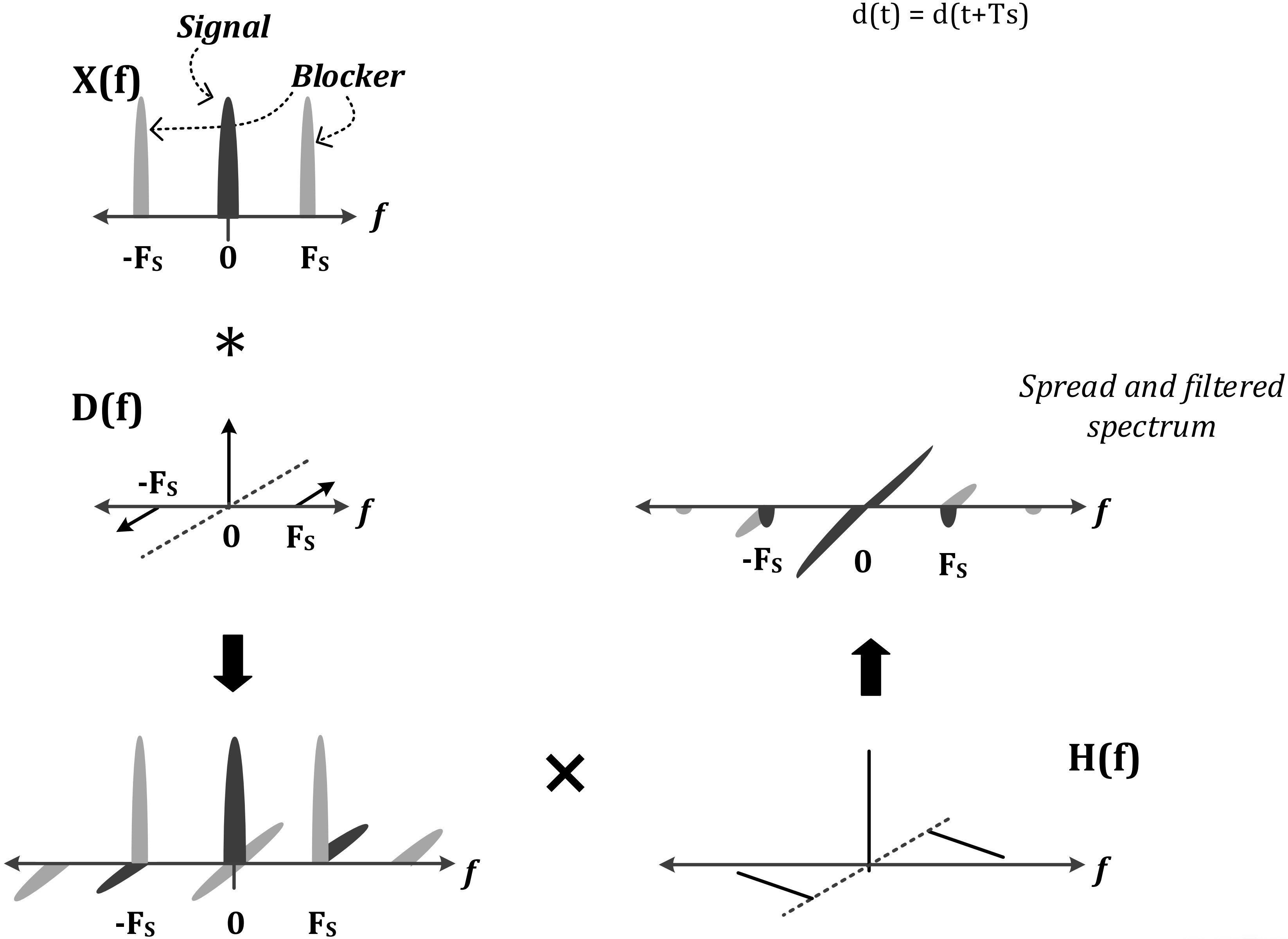
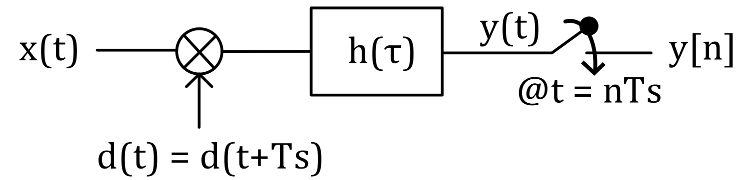


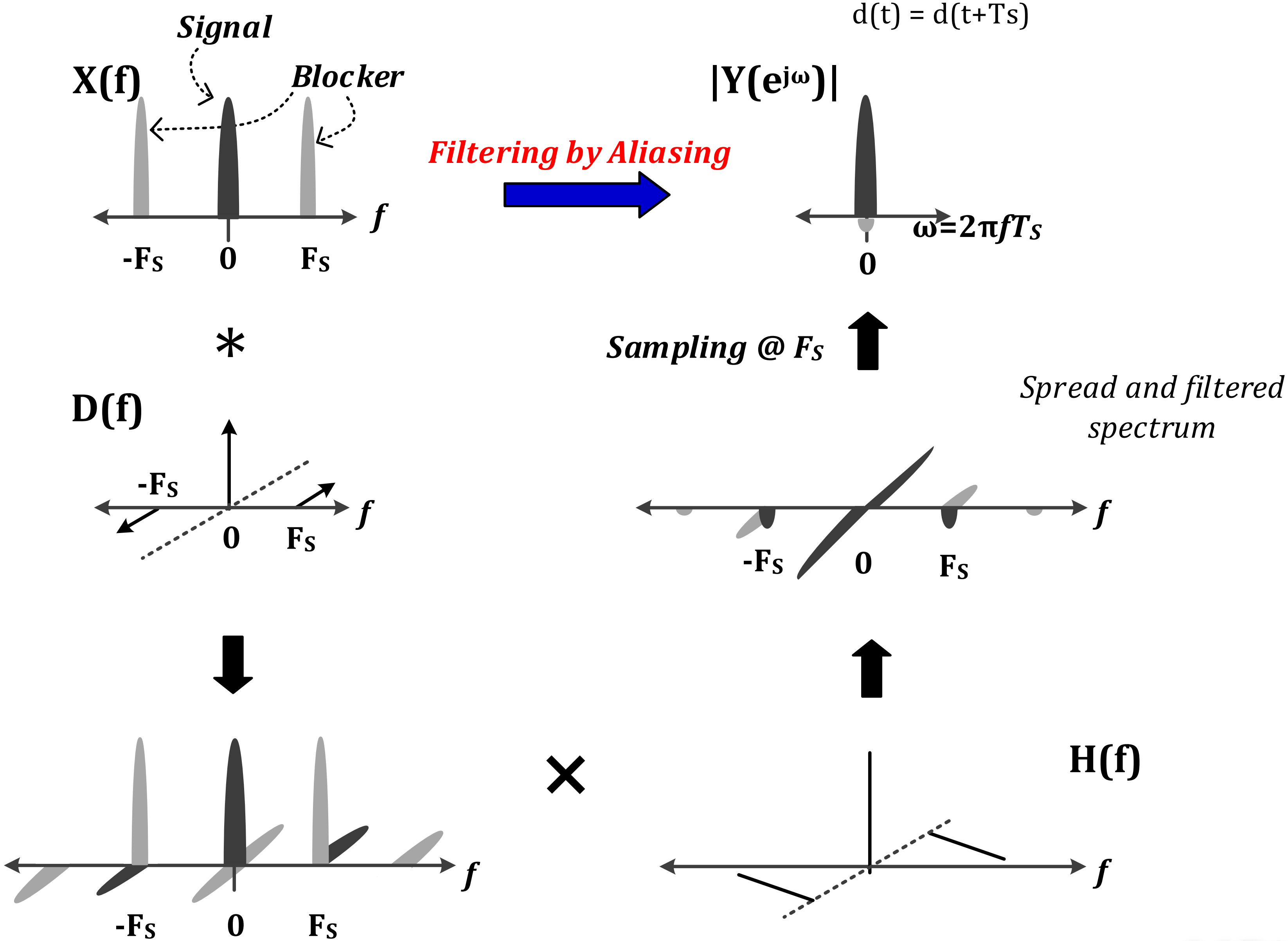
FA: Frequency Domain



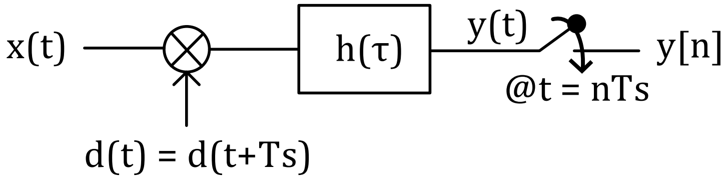


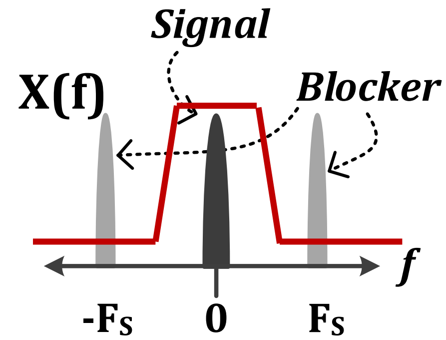
FA: Frequency Domain

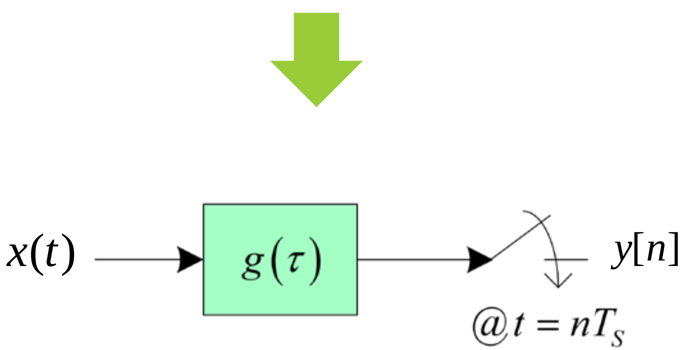


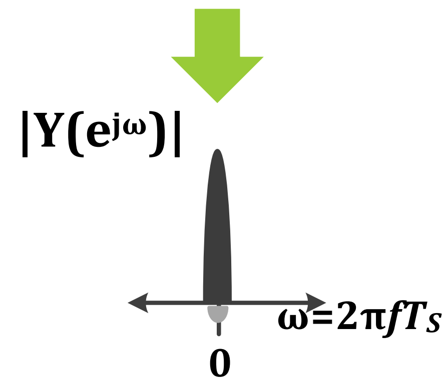


Filtering by Aliasing: Summary









$$g(\tau) = h(\tau)\, d(-\tau)$$

Effective impulse response, g(t), can be precisely engineered:

- Use a simple filter, h(t), with good linearity and low power consumption
- Use advanced D/A converter techniques to realize d(t) precisely

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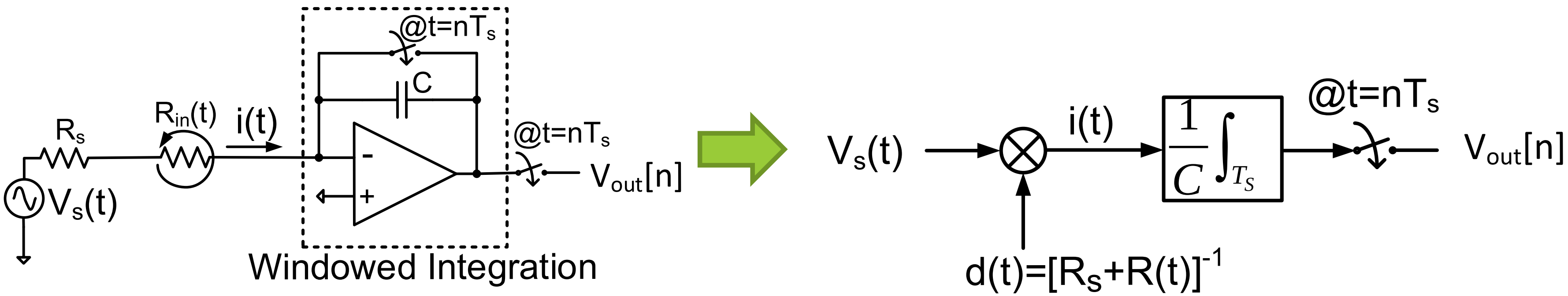
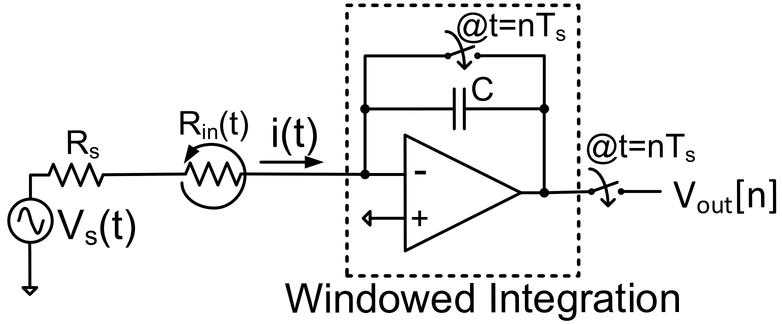
FA Example #1: Active RC

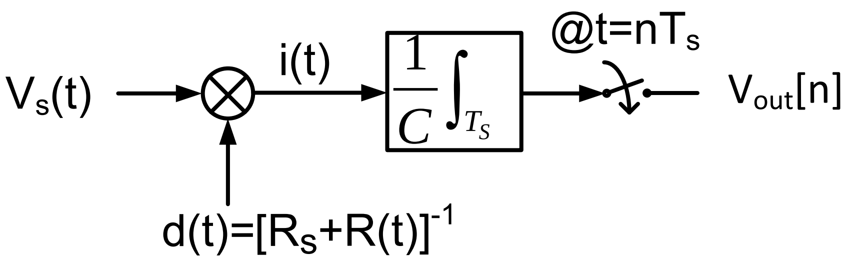


$$g(\tau) = d(-\tau) \cdot h(\tau) = \frac{1}{C\left[R_s + R(-\tau)\right]} \quad 0 \le \tau < T_s$$

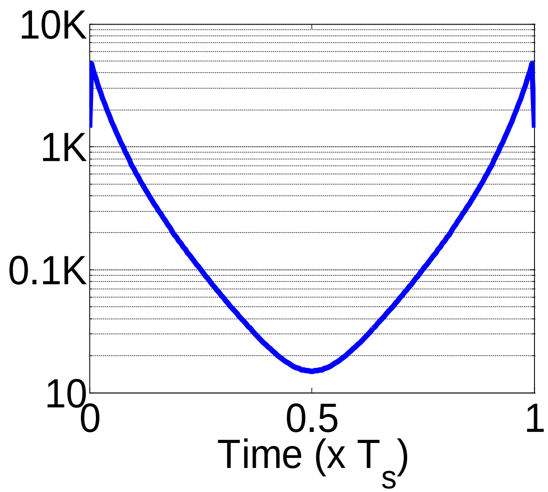
- Equivalent filter, *g(τ),* is simply an analog FIR filter
- Standard discrete-time FIR design methods apply, after discretization

FA Example #1: Active RC

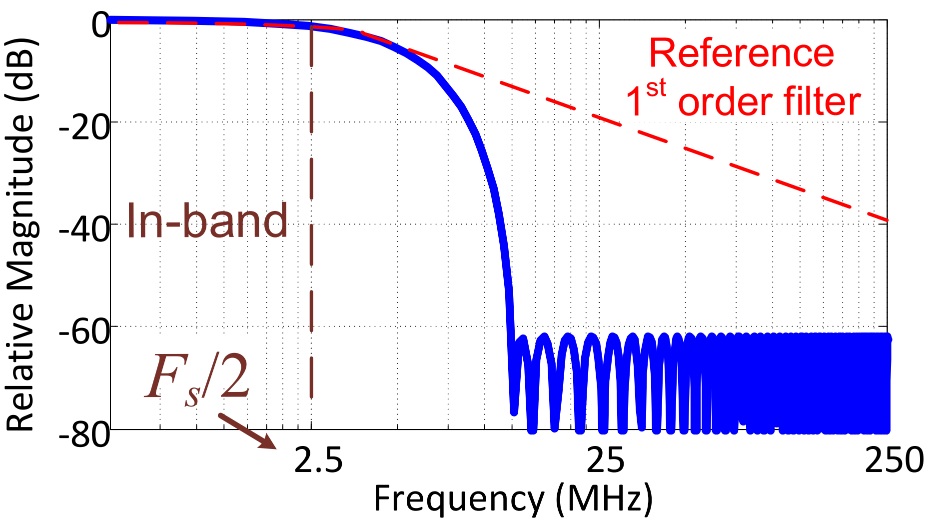




Periodic R(t) with T_s=0.2μs

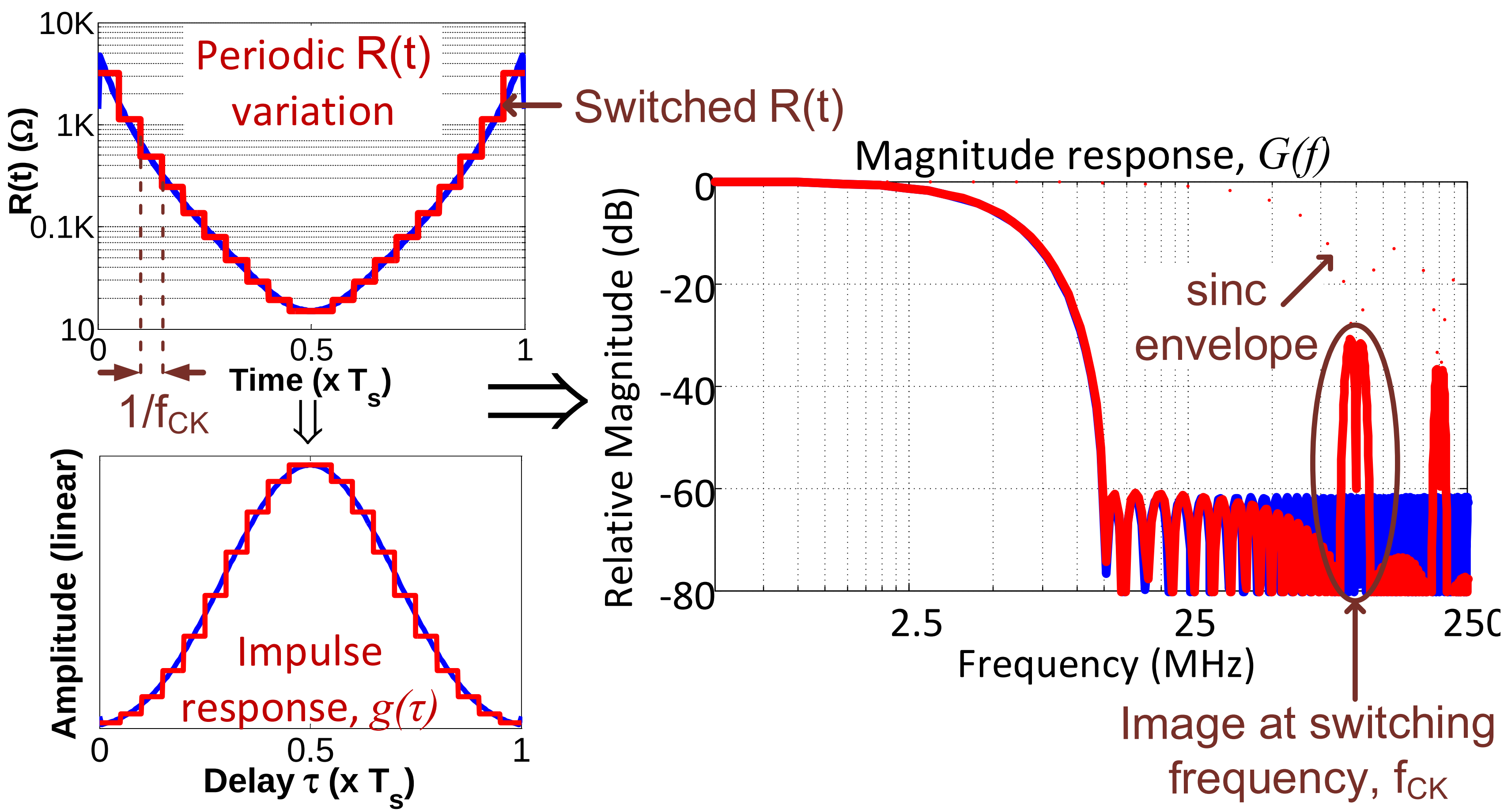


Effective filter at sampled output



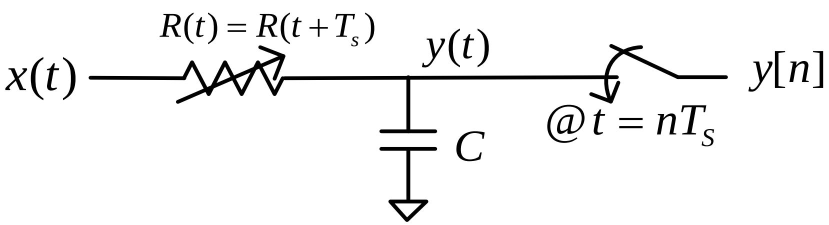
Time-Varying Resistor Implementation

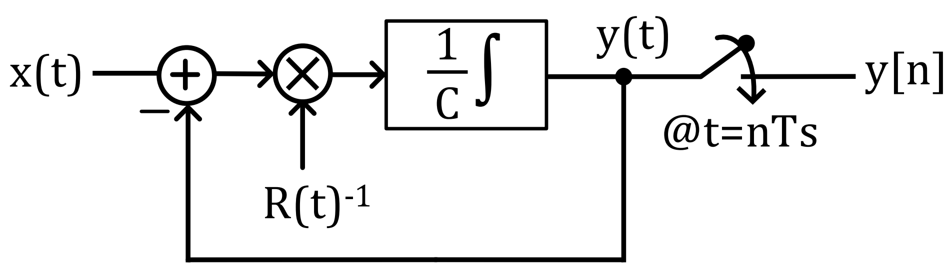
- R(t) is switched in steps → Images in freq response
  - High enough switching rate → Images below filter floor



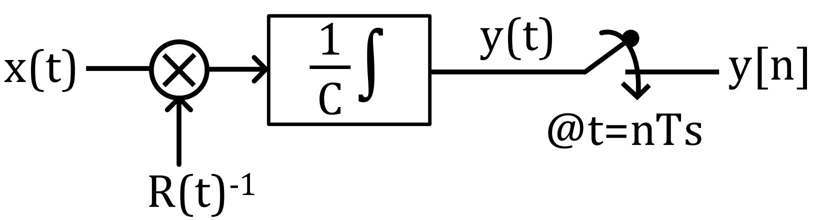
UCLA

FA Filter Example #2: Passive RC





Good approximation for out-of-band signals



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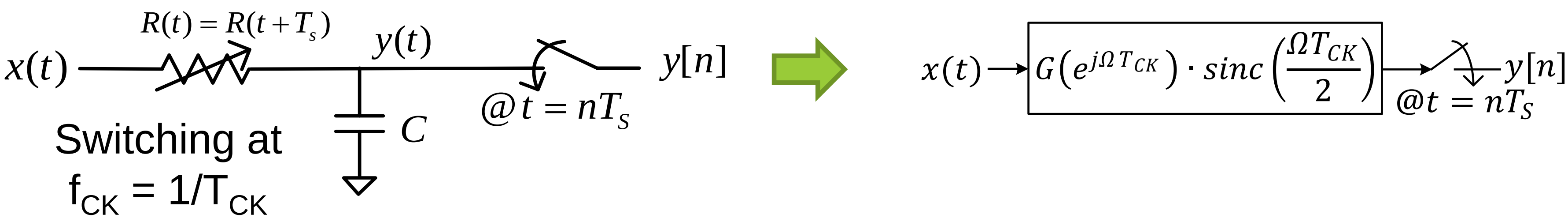
FA Filter Example #2: Passive RC

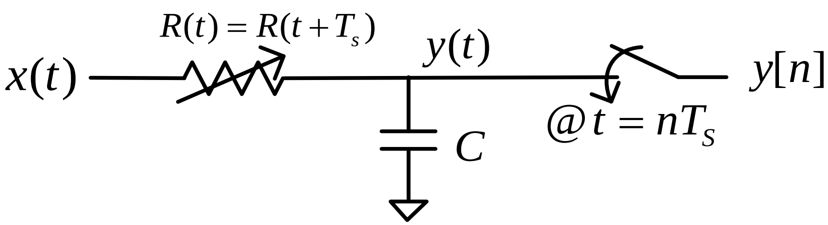


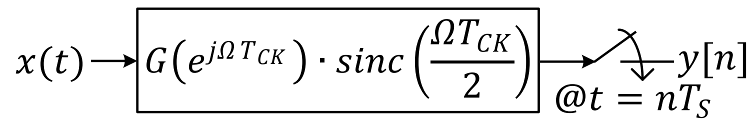
$$G(z)=\frac{\alpha_0+\alpha_1\beta_0 z^{-1}+\alpha_2\beta_1\beta_0 z^{-2}+\ldots+\alpha_{K-1}\beta_{K-2}\cdots\beta_0 z^{-(K-1)}}{1-\beta_{K-1}\cdots\beta_0 z^{-K}}$$

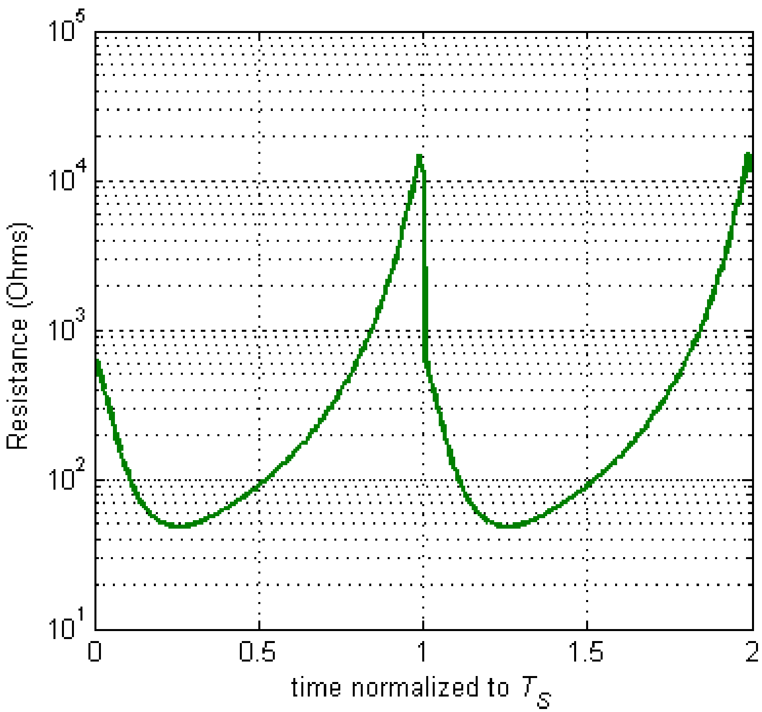
$$\text{where } \alpha_\eta=\frac{T_{CK}}{R(-\eta T_{CK})C},\ \beta_\eta=1-\alpha_\eta,\ \text{and } K=\frac{T_S}{T_{CK}}$$

- Discrete-time filter design techniques can be used to chose R(t) to achieve desired filter response

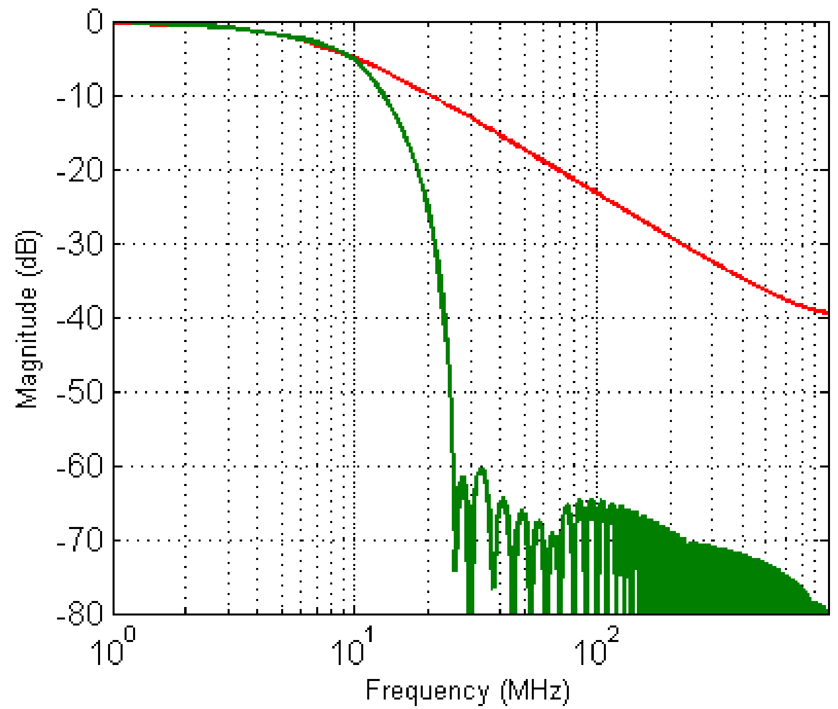
FA Filter Example #2: Passive RC







Example resistor variation



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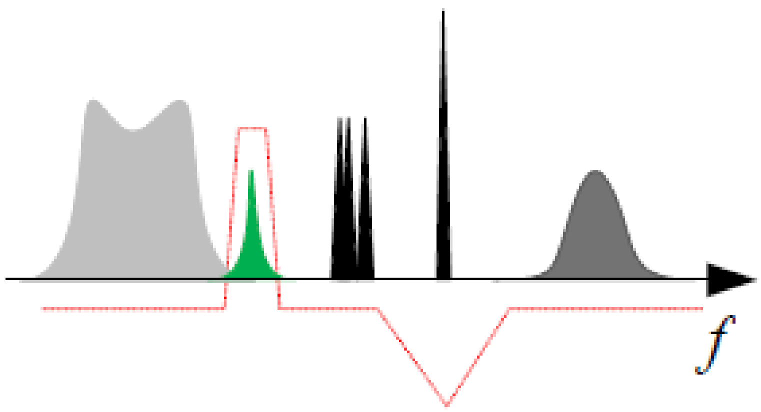
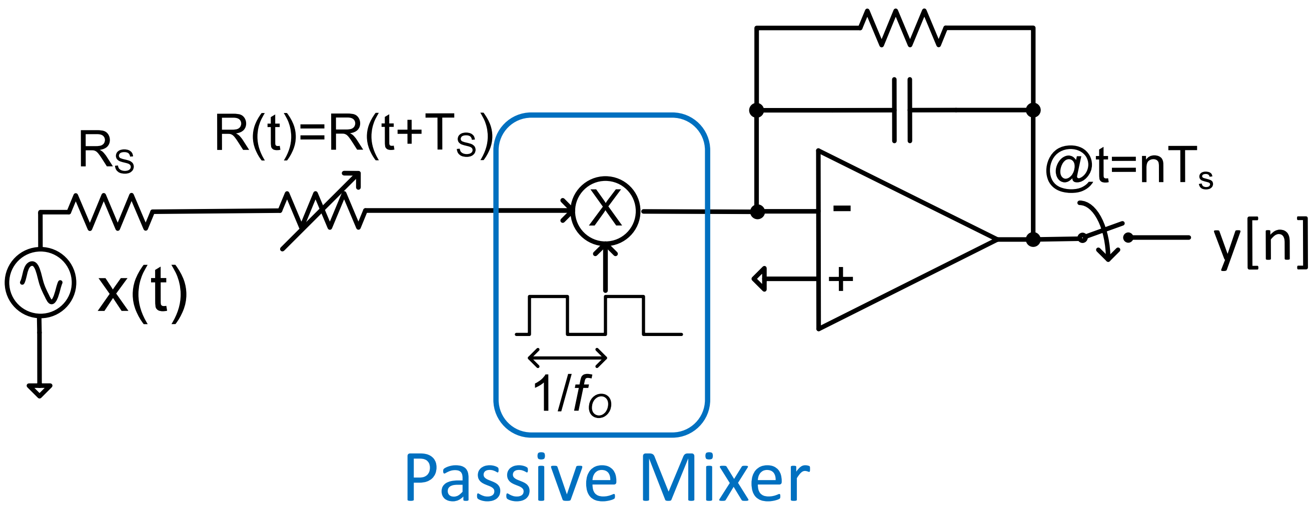
Agile RF Front-End: Requirements



- BPFs with programmable center frequency, BW
- Antenna impedance matching
- Blocker suppression/tolerance
  - Sharp filtering, good linearity, and low noise figure

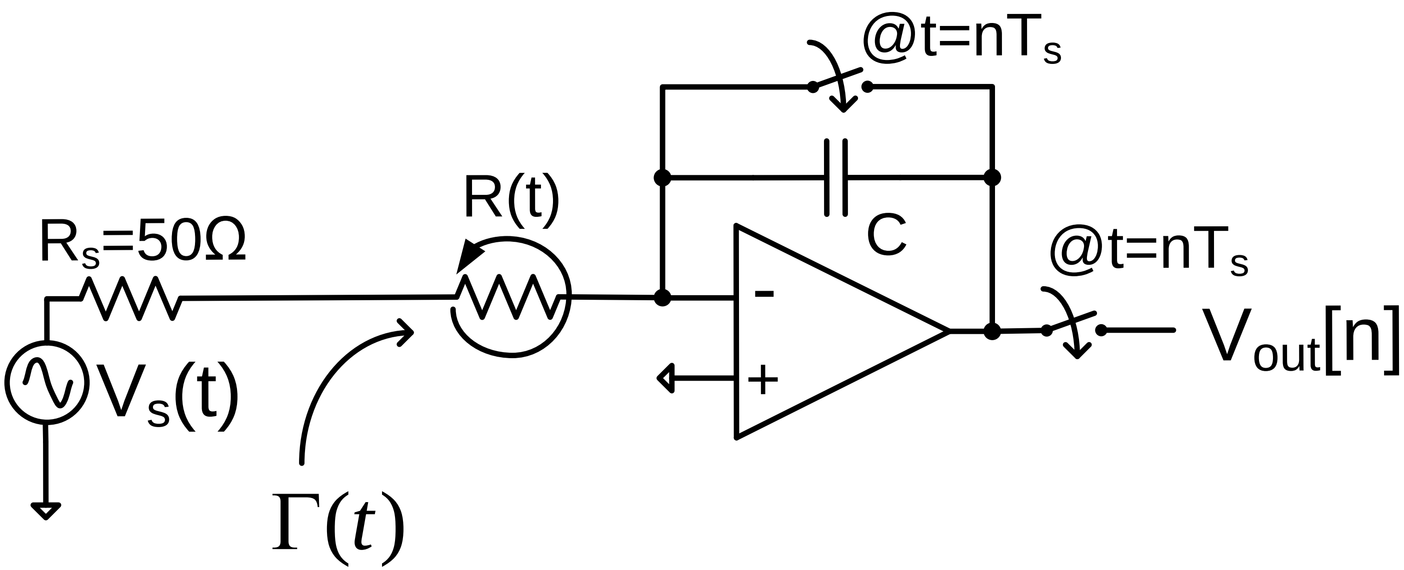
FA Bandpass Filter

[Hameed ISSCC 2016]



- LO mixing converts sharp FA LPF to a sharp FA BPF

Achieving Input Match



Reflection Coefficient

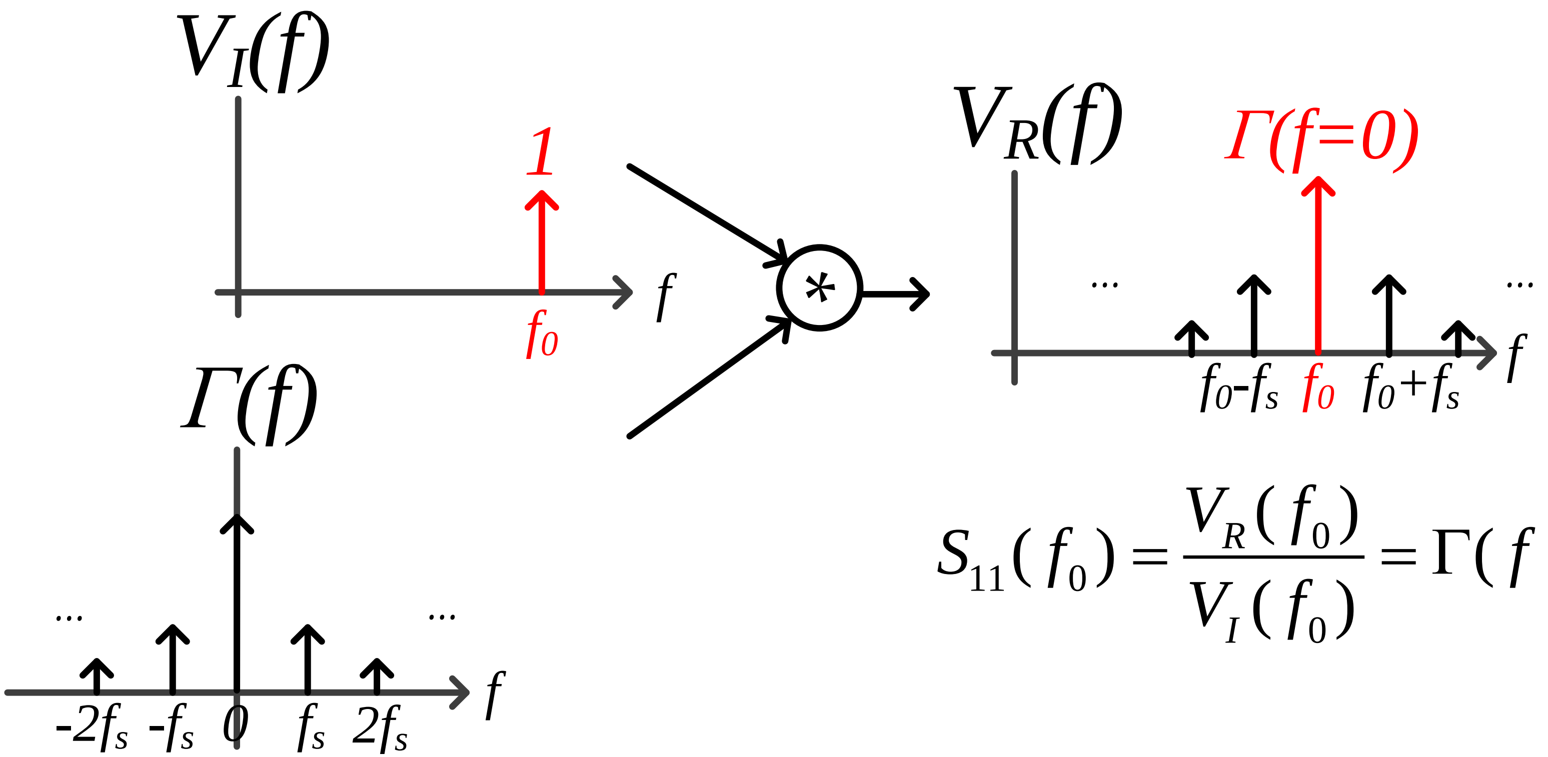
$$\Gamma(t) = \frac{V_R(t)}{V_I(t)} = \frac{R(t) - R_s}{R(t) + R_s}$$

Achieving Input Match

$$V_I(t) = \sin(2\pi f_0 t) \Rightarrow V_R(t) = \Gamma(t)\sin(2\pi f_0 t)$$

Achieving Input Match

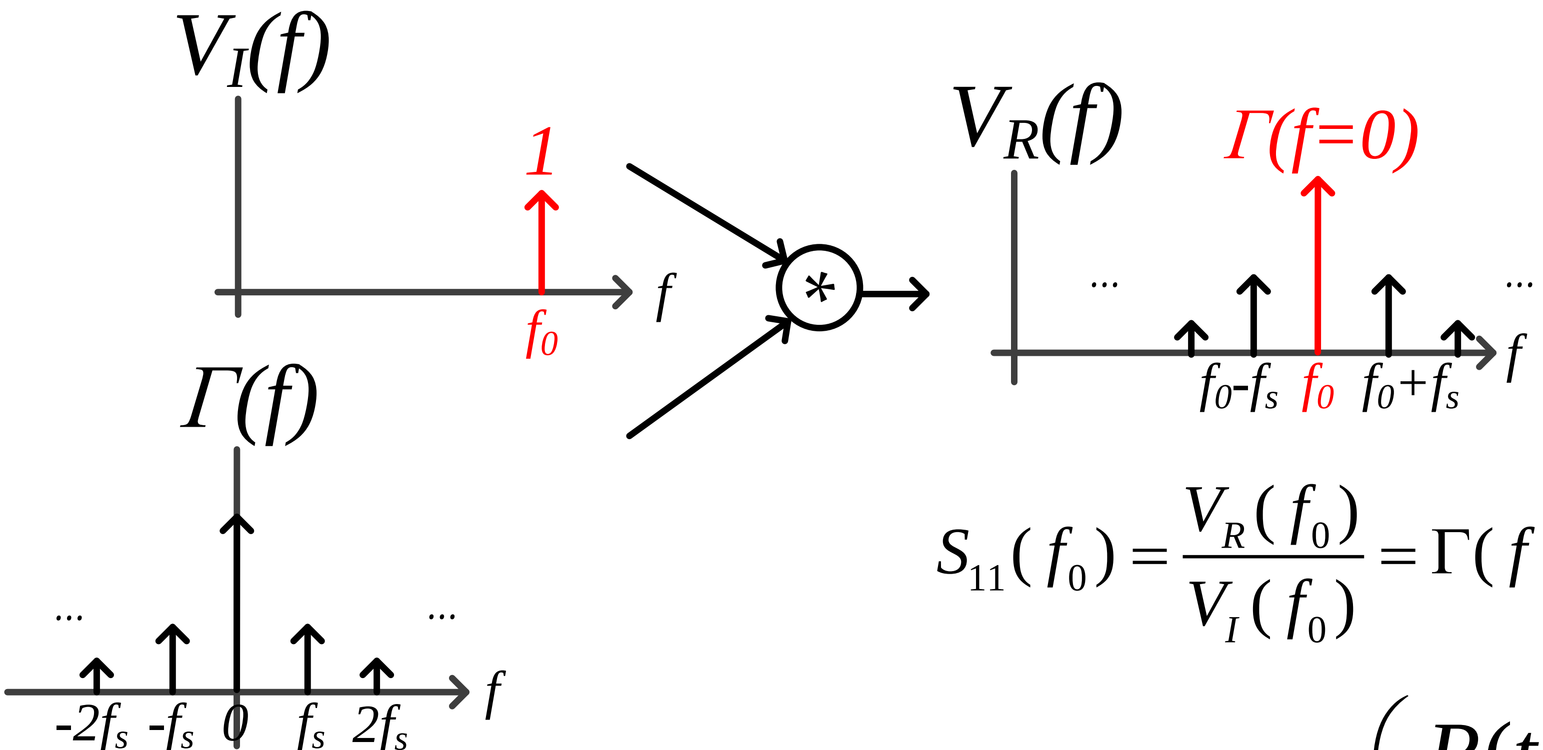
$$V_I(t) = \sin(2\pi f_0 t) \Rightarrow V_R(t) = \Gamma(t)\sin(2\pi f_0 t)$$



$$S_{11}(f_0) = \frac{V_R(f_0)}{V_I(f_0)} = \Gamma(f=0)$$

Achieving Input Match

$$V_I(t) = \sin(2\pi f_0 t) \Rightarrow V_R(t) = \Gamma(t)\sin(2\pi f_0 t)$$



$$S_{11}(f_0) = \frac{V_R(f_0)}{V_I(f_0)} = \Gamma(f=0)$$

$$\Rightarrow S_{11}(f_0) = mean\left(\frac{R(t) - R_s}{R(t) + R_s}\right)$$

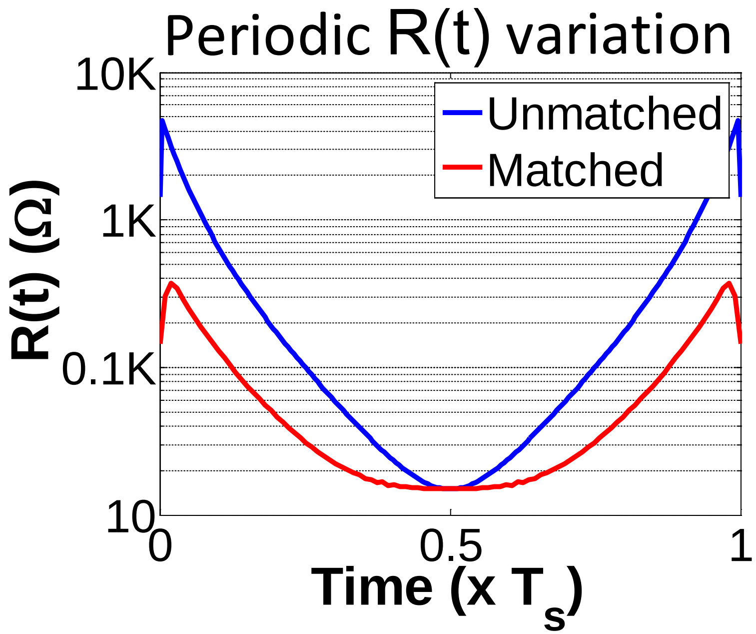
Achieving Input Match

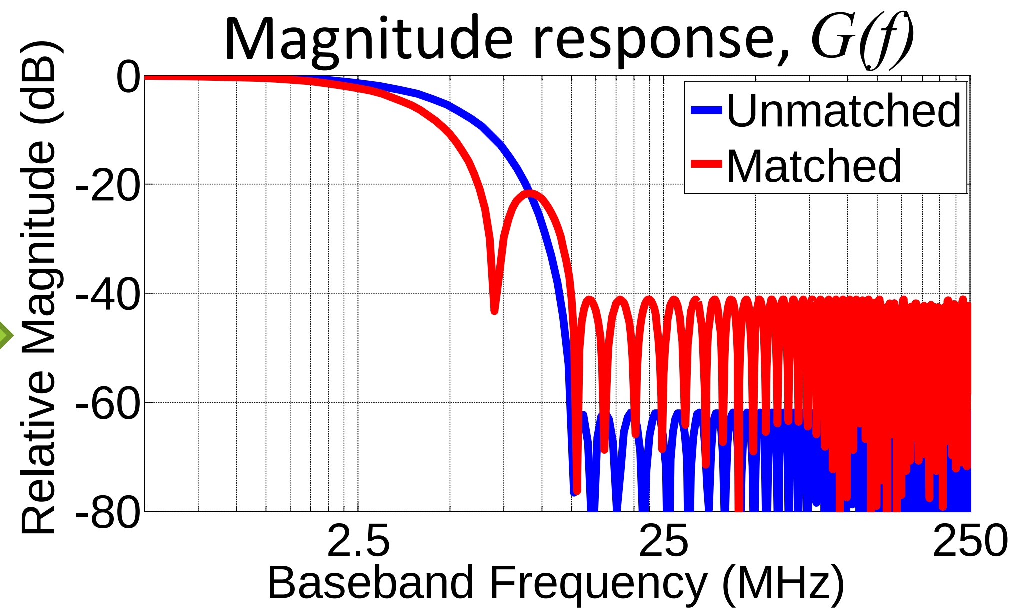
Matching Constraints

$$\begin{cases} R(\tau) > R_S \\ S_{11} = mean\left[\dfrac{R(\tau) - R_S}{R(\tau) + R_S}\right] < \alpha \end{cases}$$

↓

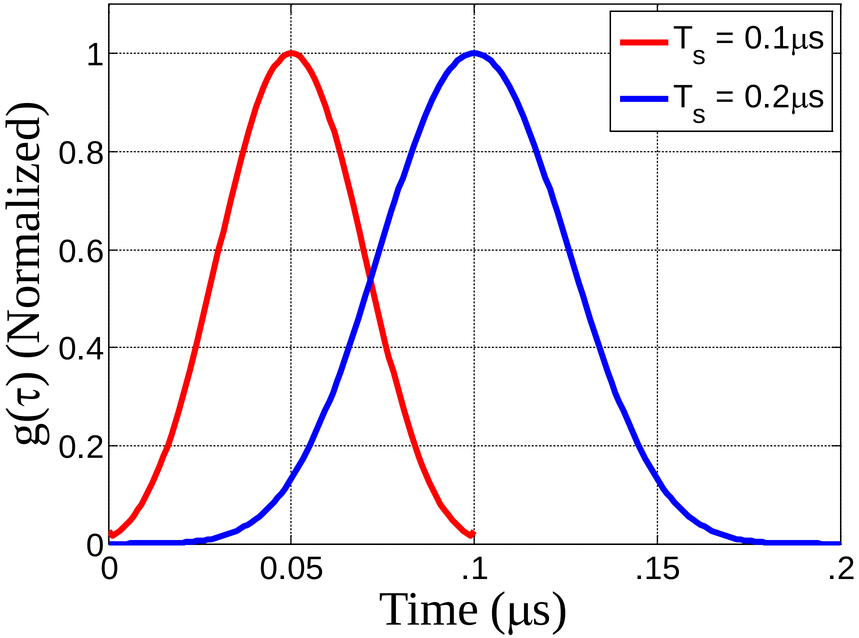
T_s, Filter BW, Transition BW → **Optimization** → Optimal $R(\tau)$





Improving Stop-band Attenuation

- Increase A_{stop} with longer $g(\tau)$?



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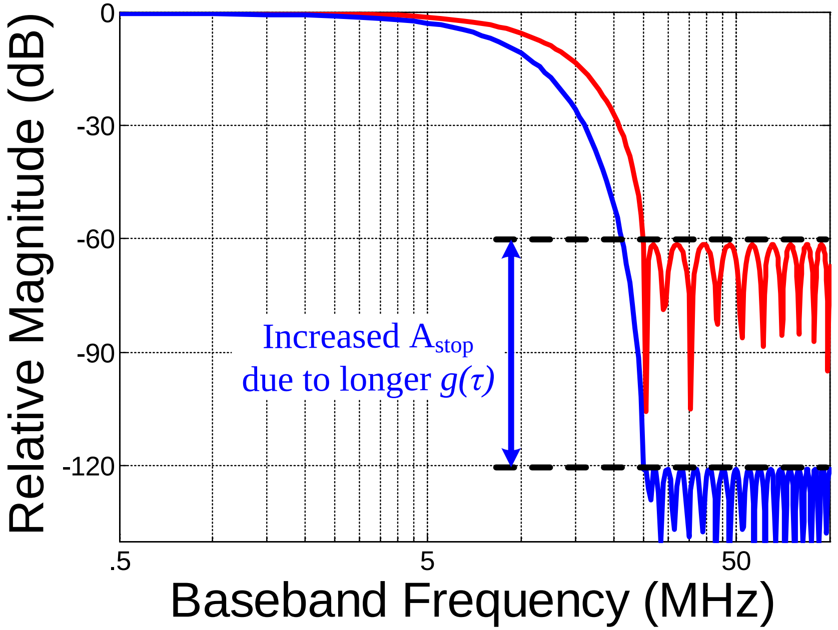
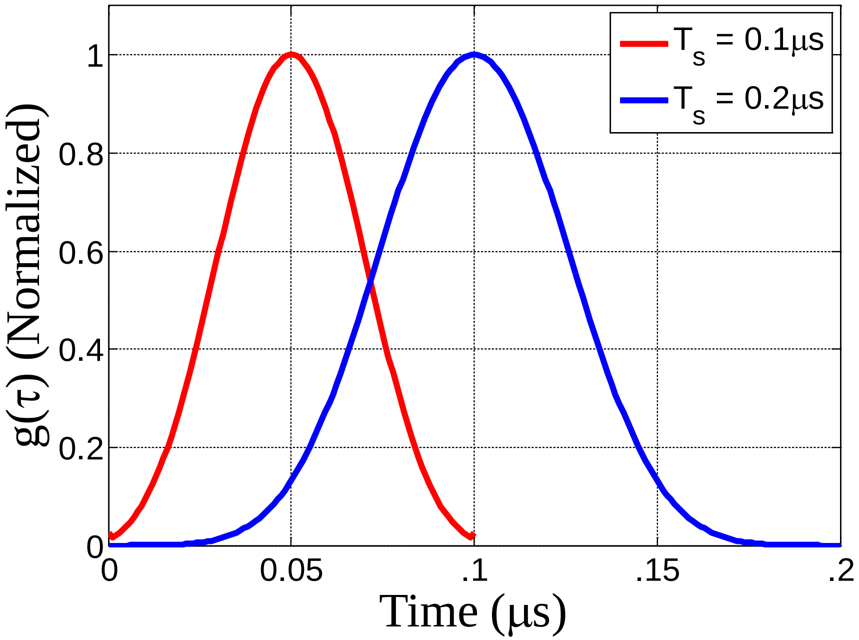


Improving Stop-band Attenuation

- Increase A_{stop} with longer $g(\tau)$?
  - Unfiltered aliasing frequency bins
  - Sampling period same as length of $g(\tau)$



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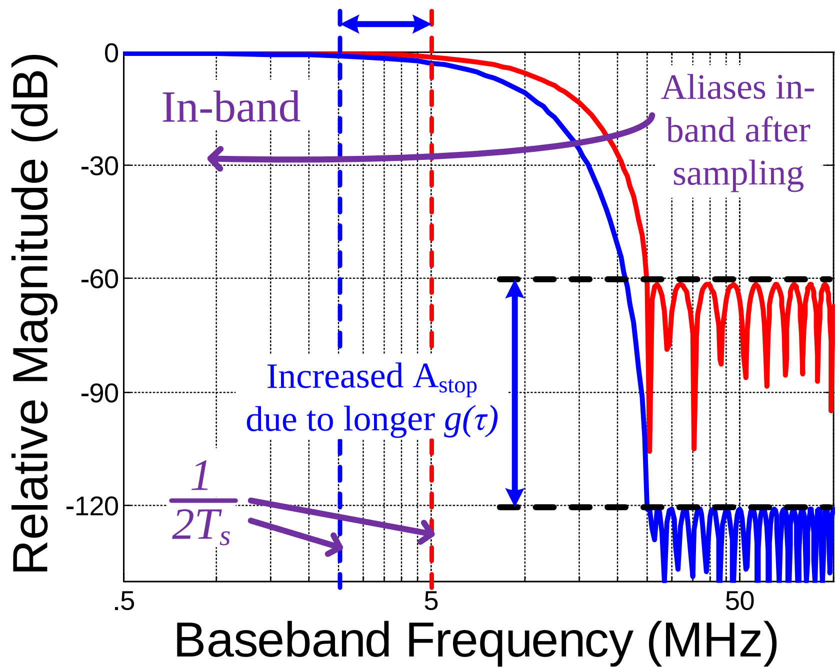
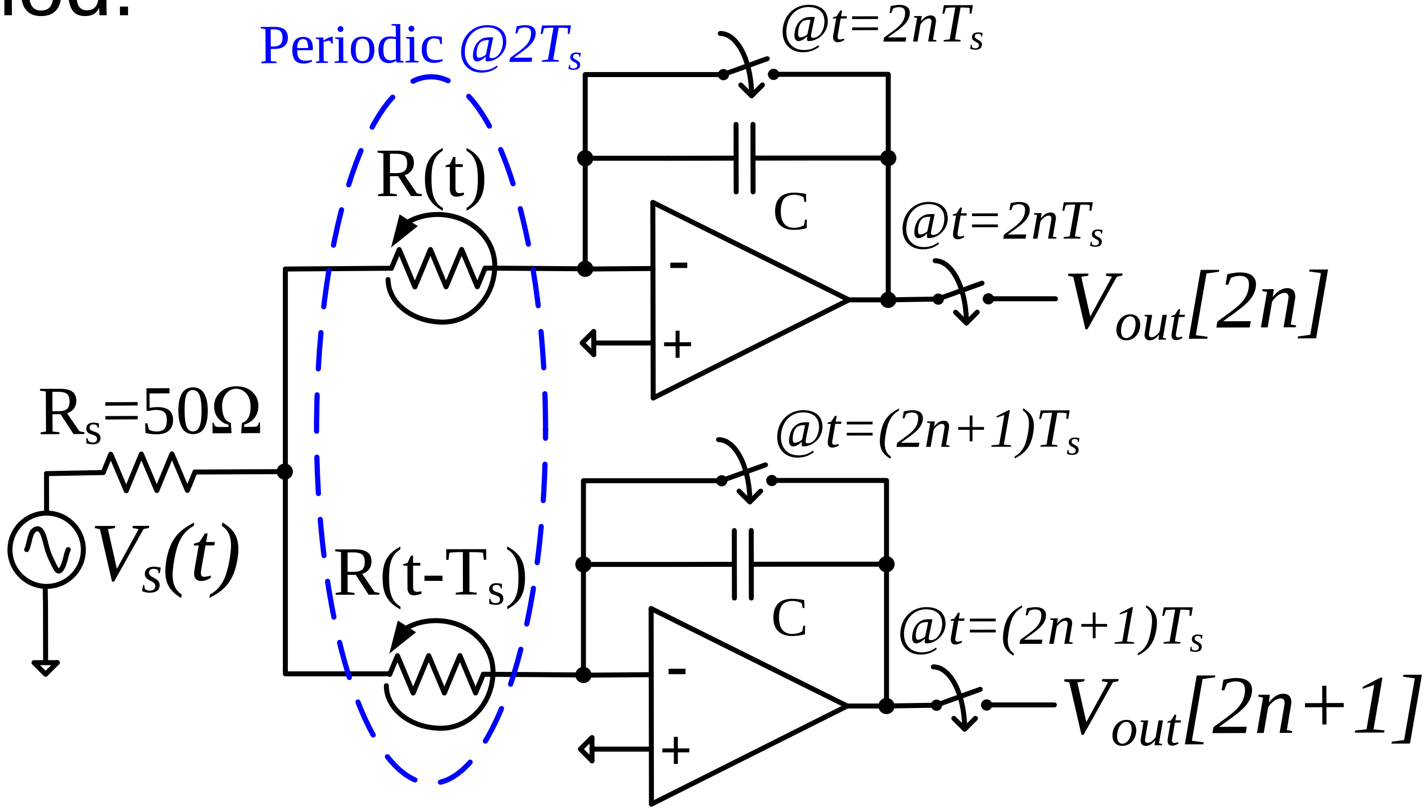


Time-Interleaved FA

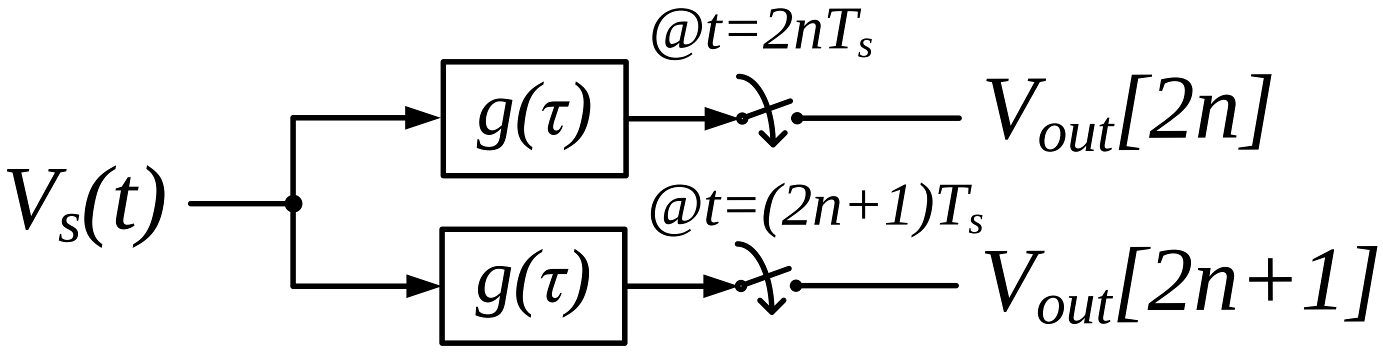
[Hameed ISSCC 2017]

Use time-interleaving to maintain sampling period:



Time-Interleaved FA

Sampling period is T_s:



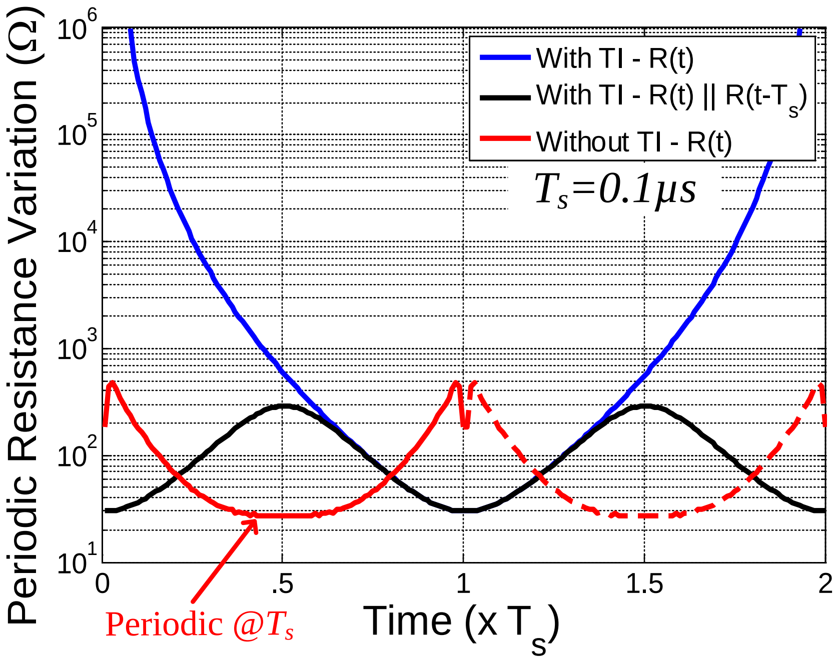
But $g(\tau)$ length is $2T_s$:

$$g(\tau) = \frac{R(T_s-\tau)}{\left[R(-\tau)+R(T_s-\tau)\right]} \frac{1}{\left[R_s + R(-\tau) \parallel R(T_s-\tau)\right]C}$$

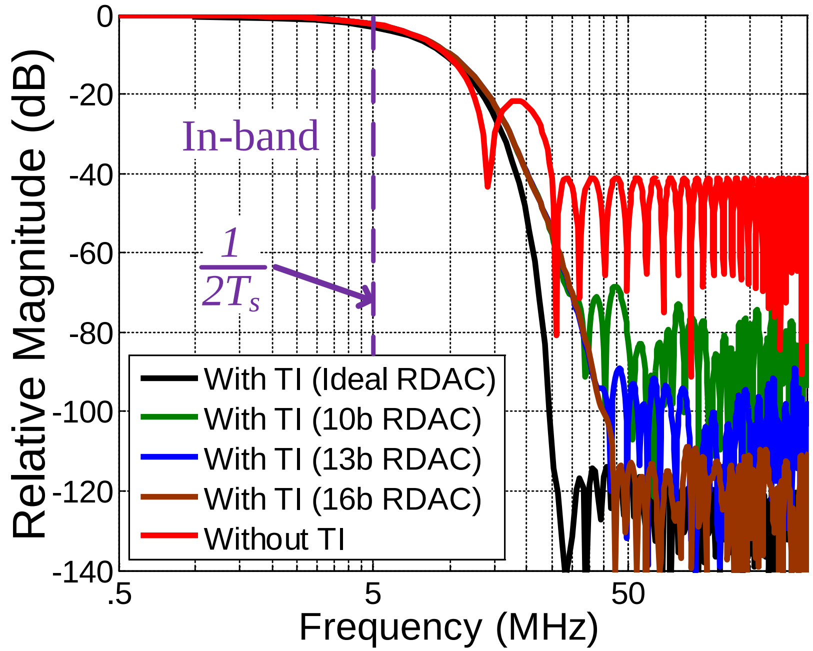
$$0 \leq \tau \leq 2T_s$$

Time-Interleaved FA

- Matching is easier
  - $S_{11} \sim f(R(t) \,//\, R(t-T_s))$
- Much higher A_{stop}
  - 70dB A_{stop} with 10b RDAC dynamic range

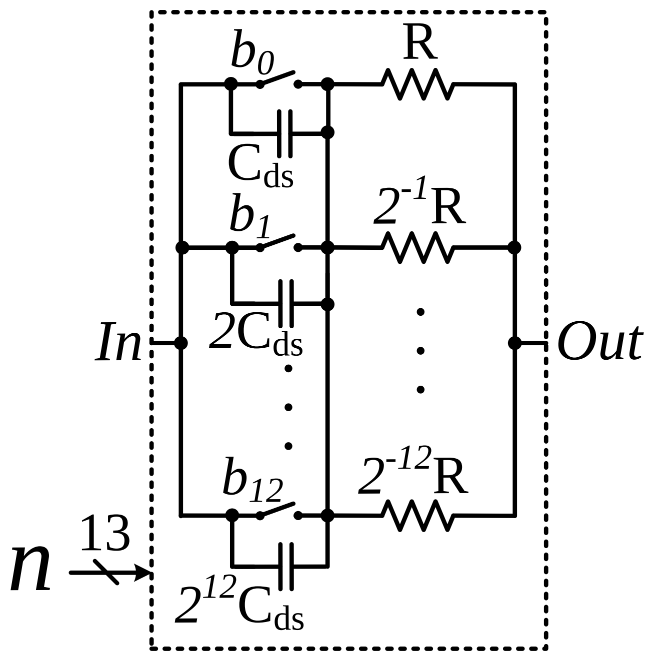


⇒

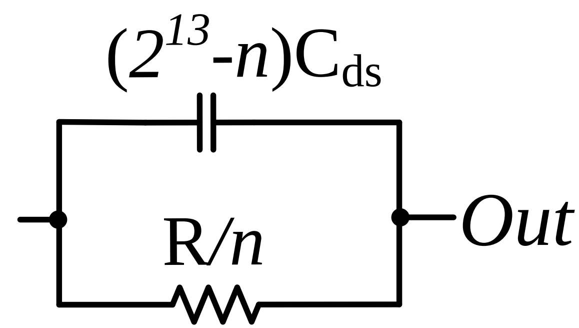


LPTV Resistor

- Built as 13b binary scaled resistor DAC
  - Switch resistance : Poly resistance set to 1:4
- Circuit parasitics limit dynamic range
  - e.g., C_{ds} across switches



$\approx$



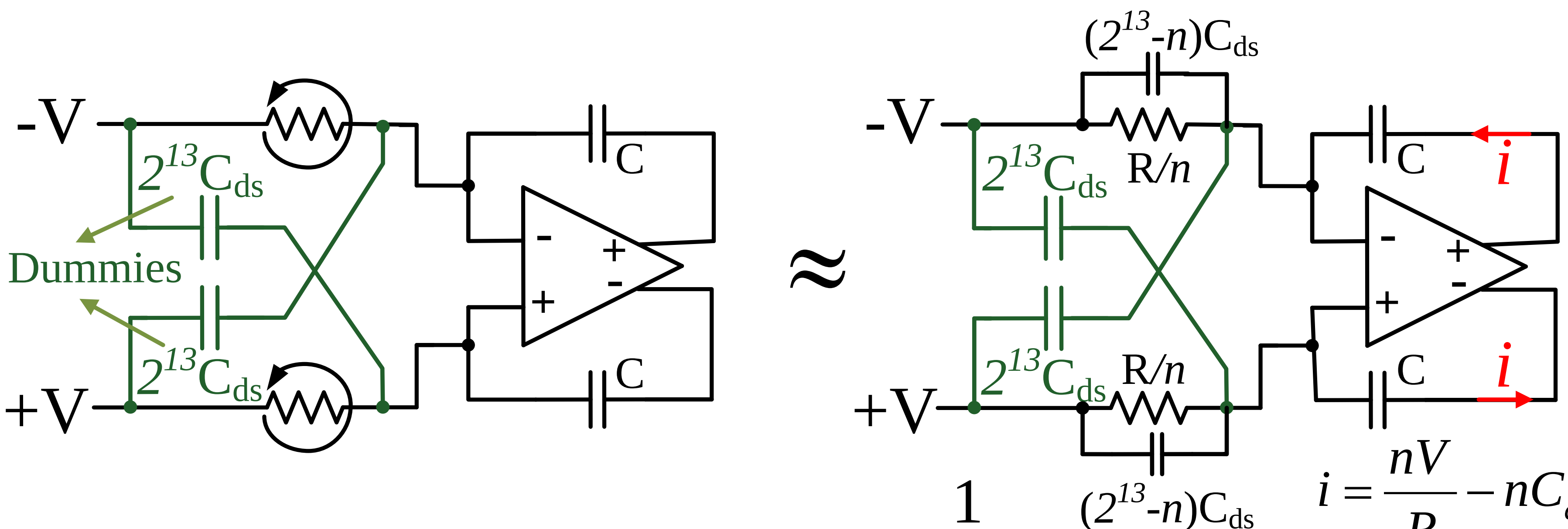
$$\omega_{corner} = \frac{n}{2^{13} - n} \frac{1}{RC_{ds}}$$

$\omega_{corner}\downarrow$ for small n!

UCLA

LPTV Resistor

- Alleviated in differential configuration
  - Corner freq. constant with addition of dummies

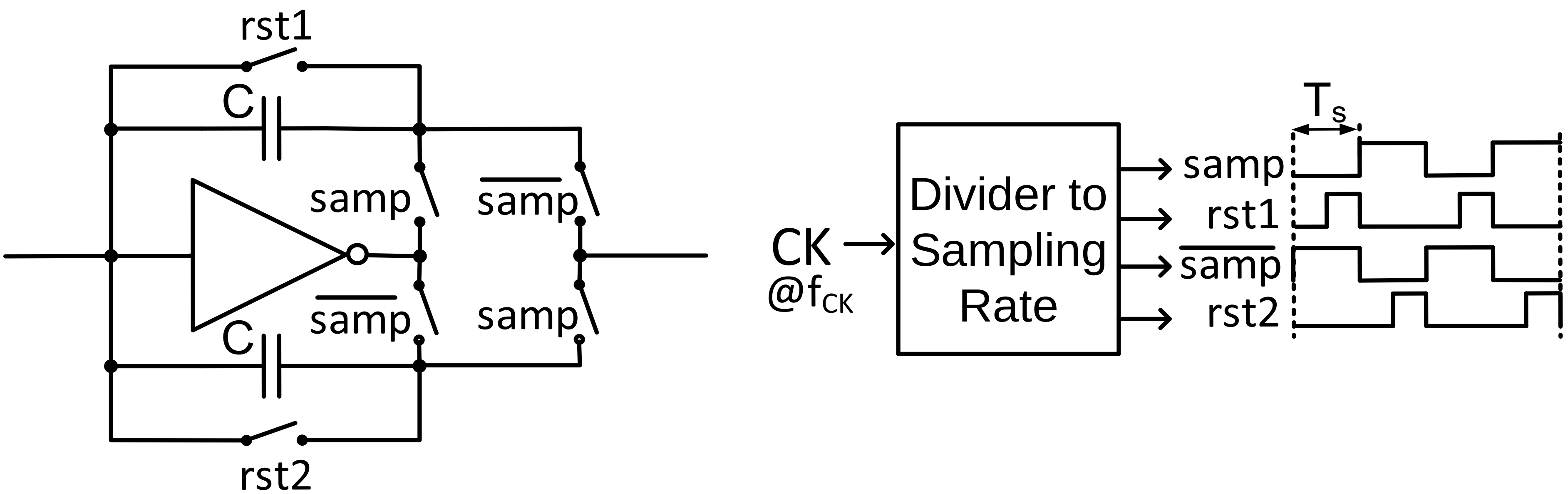


$$i = \frac{nV}{R} - nC_{ds}\frac{dV}{dt}$$

$$\omega_{corner} = \frac{1}{RC_{ds}}$$

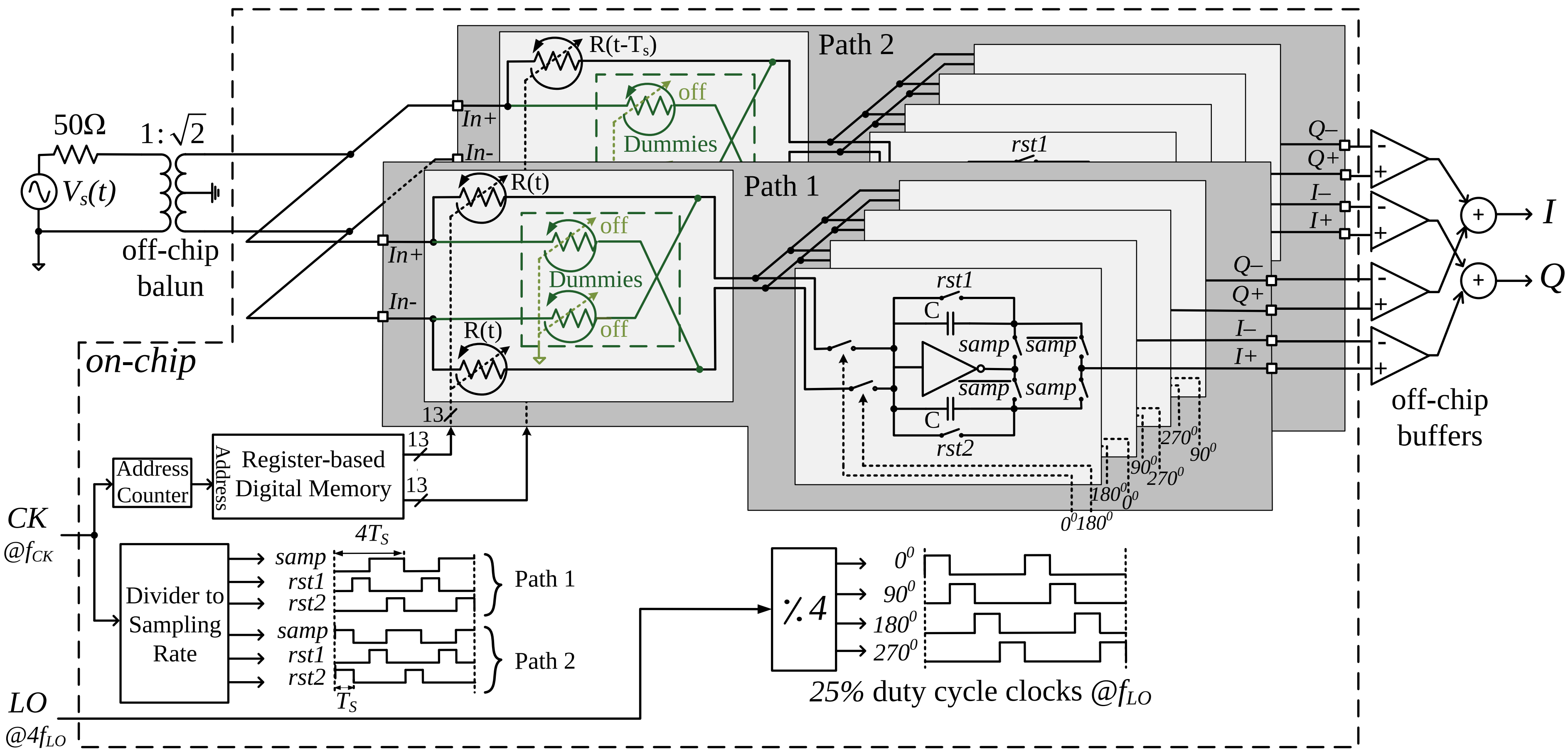
ω_{corner} independent of n!

Baseband Integrator

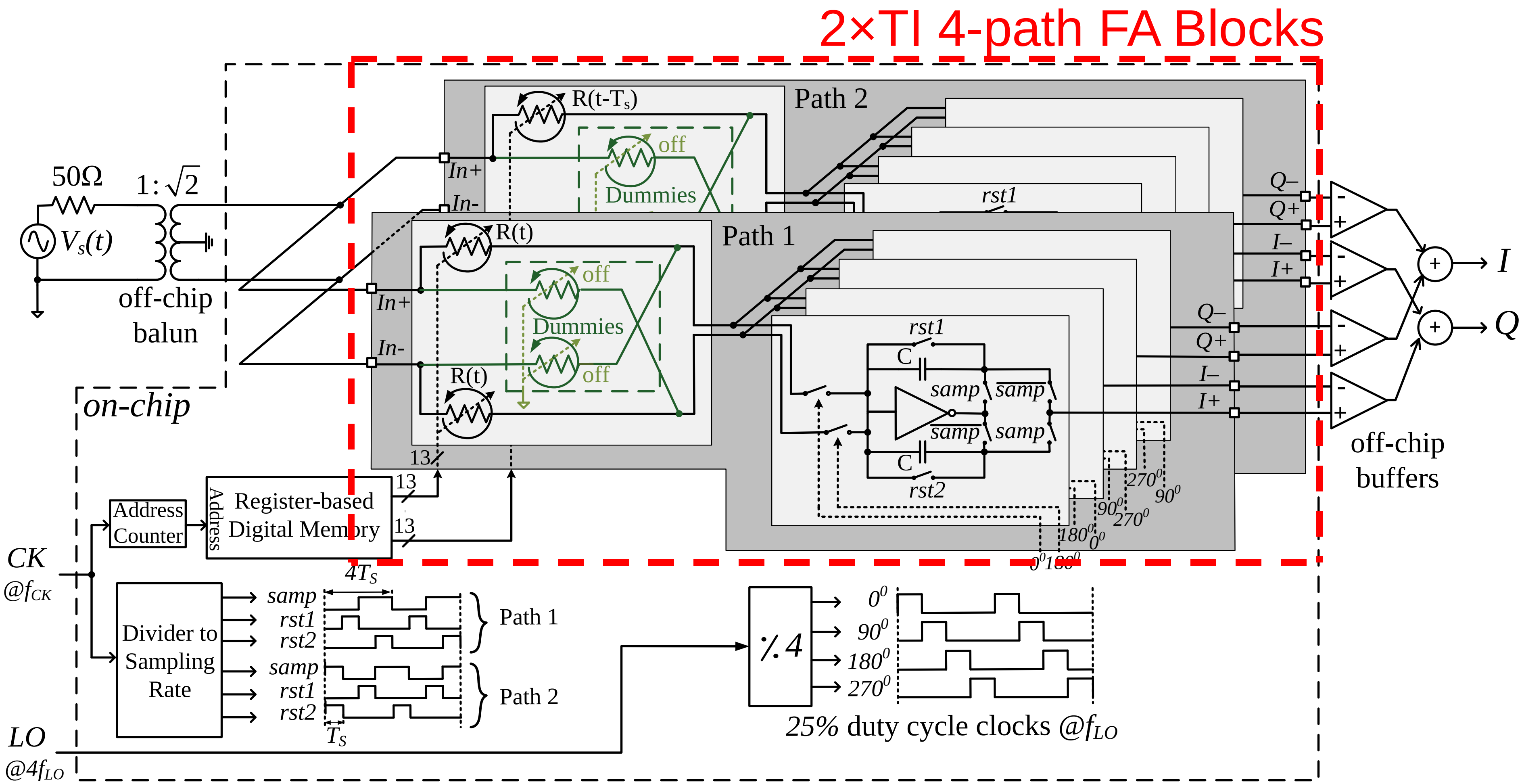


- Inverter-based op-amp
  - Self-biased due to periodic reset
- Feedback caps implemented as ping-pong structures
  - Capacitors implemented using MIM caps

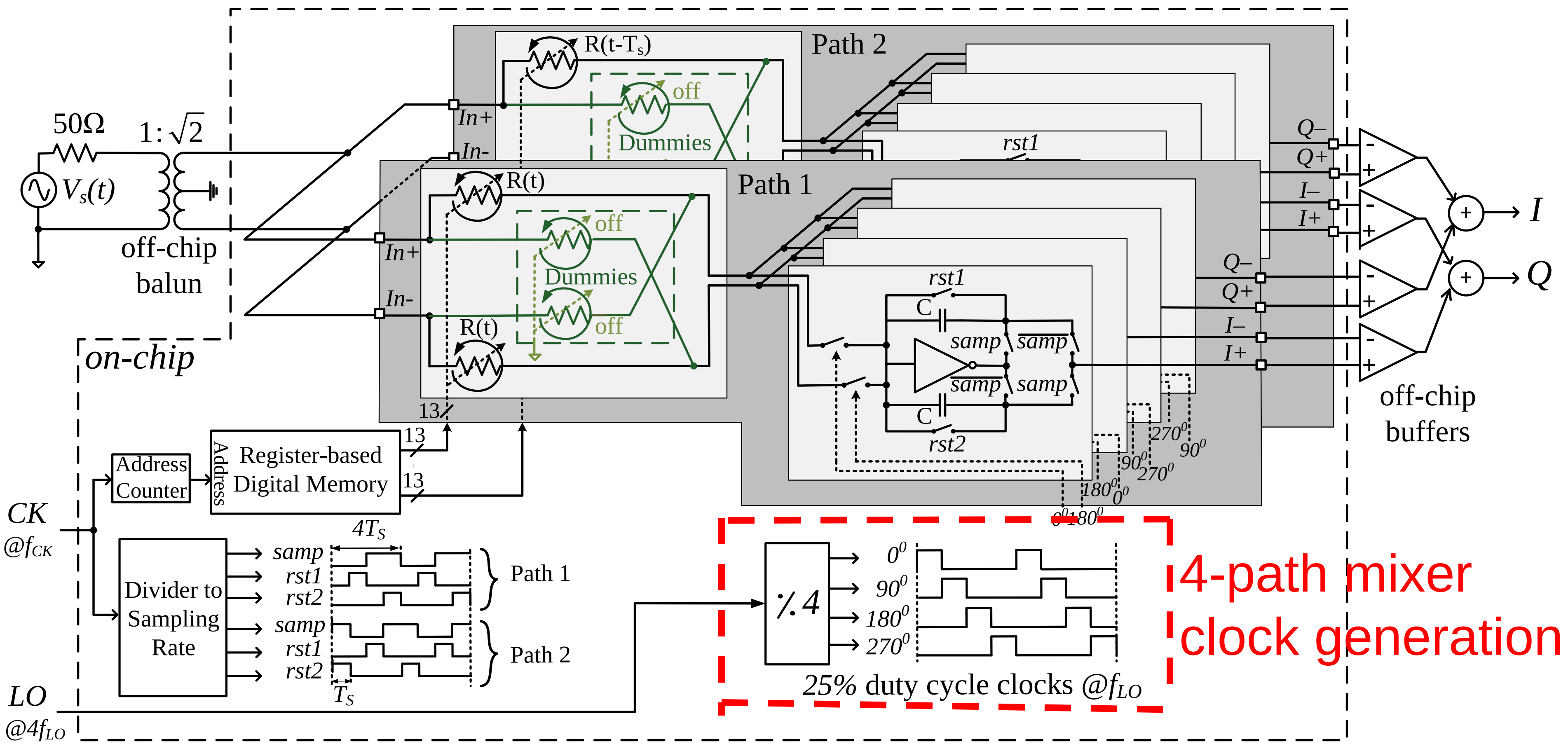
System Block Diagram



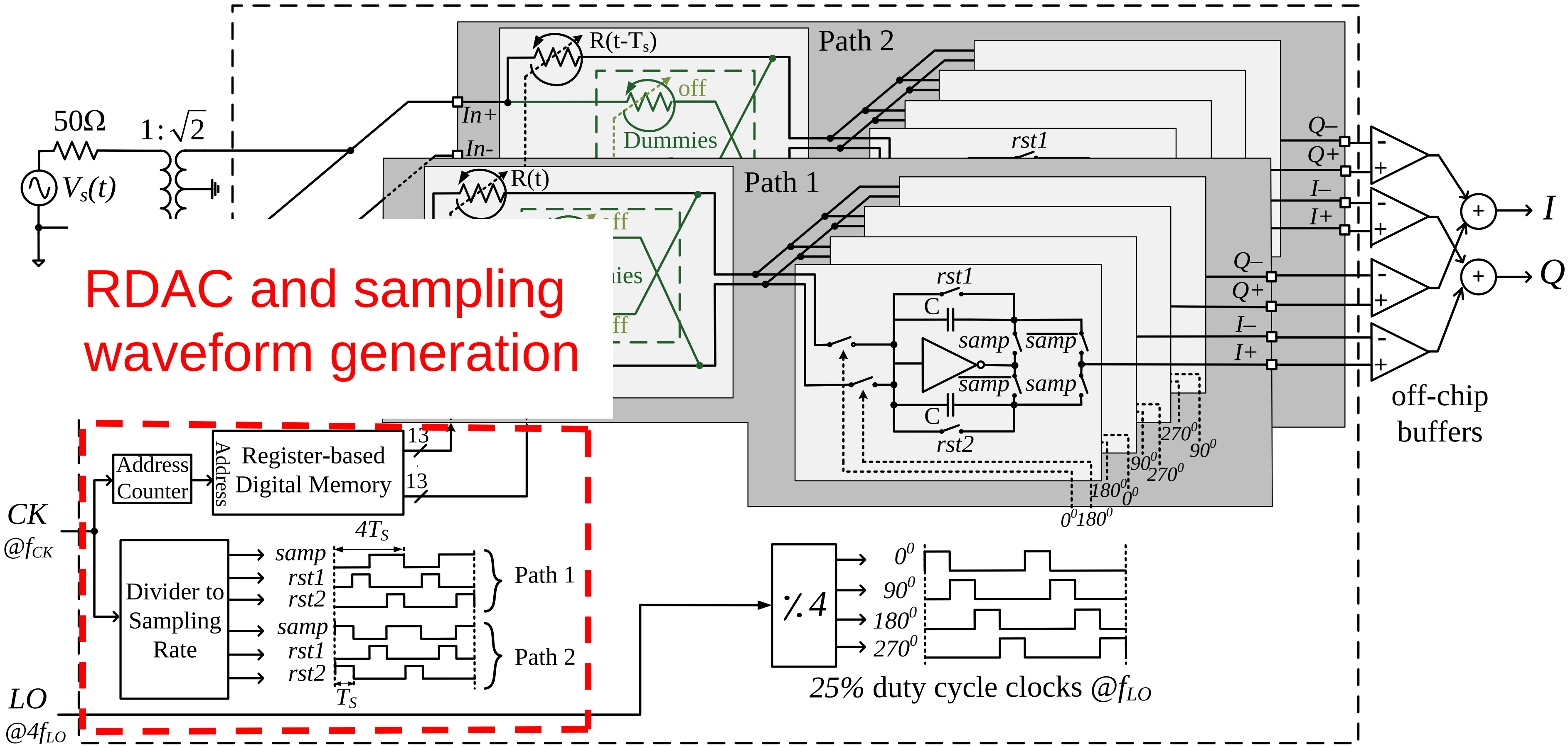
System Block Diagram



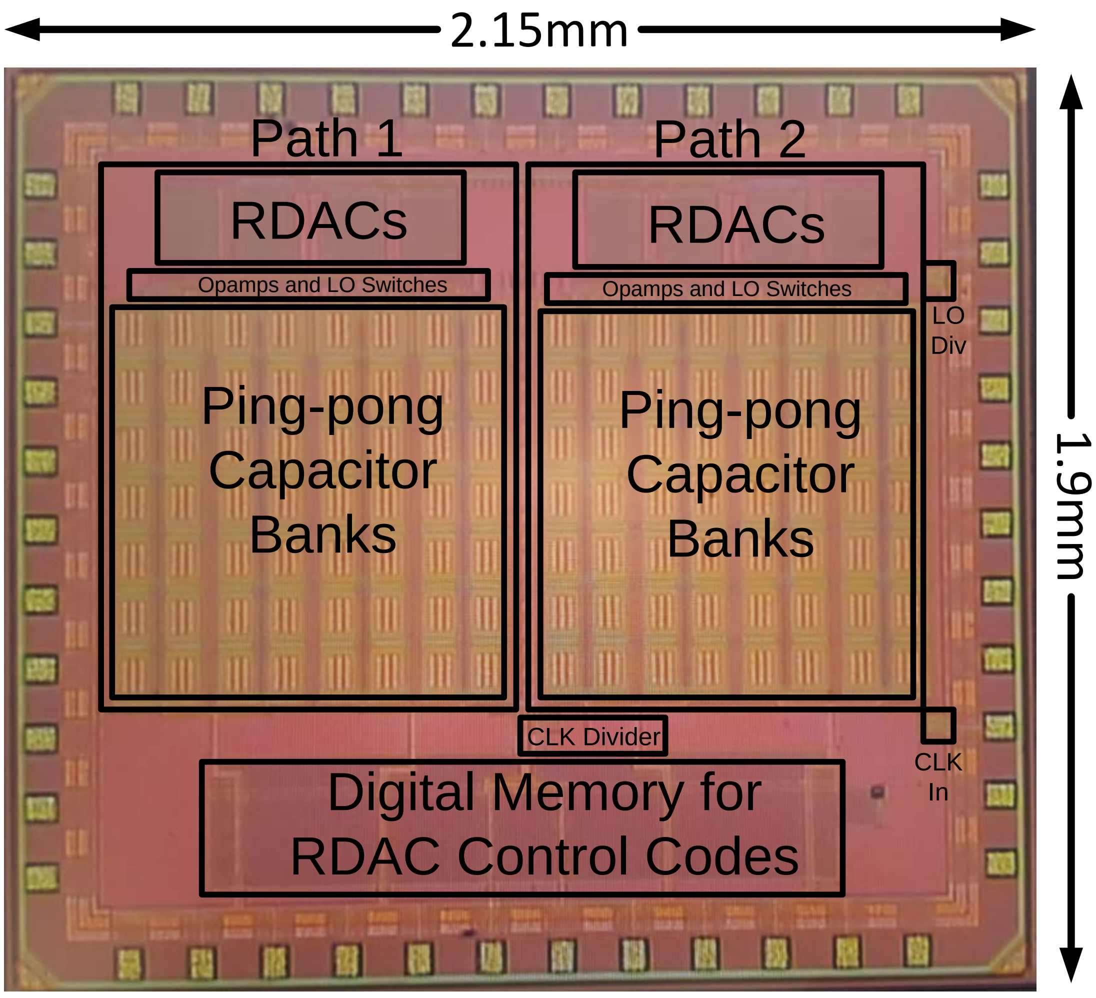
System Block Diagram



System Block Diagram

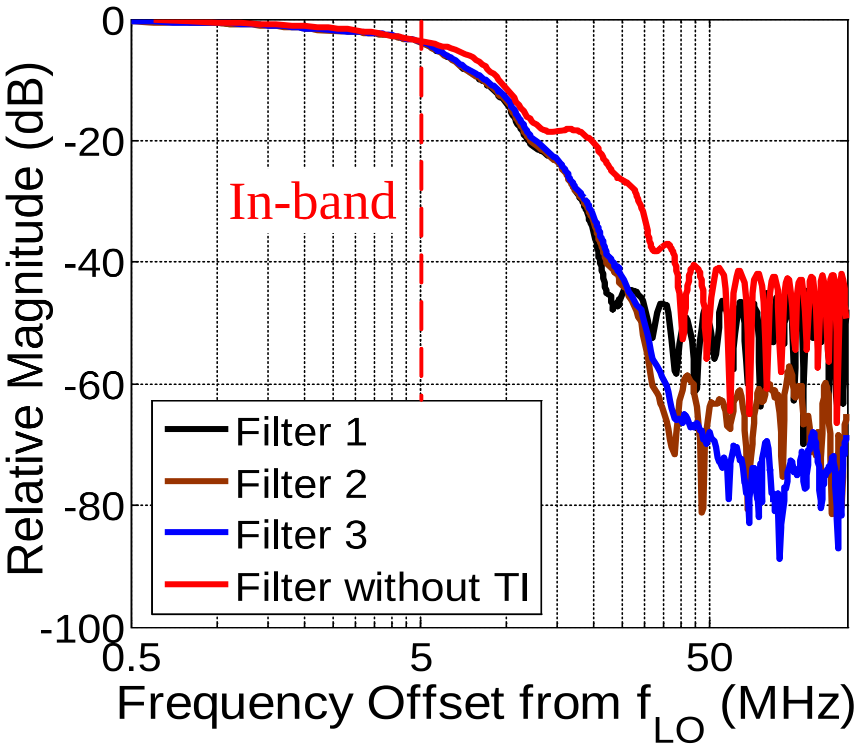


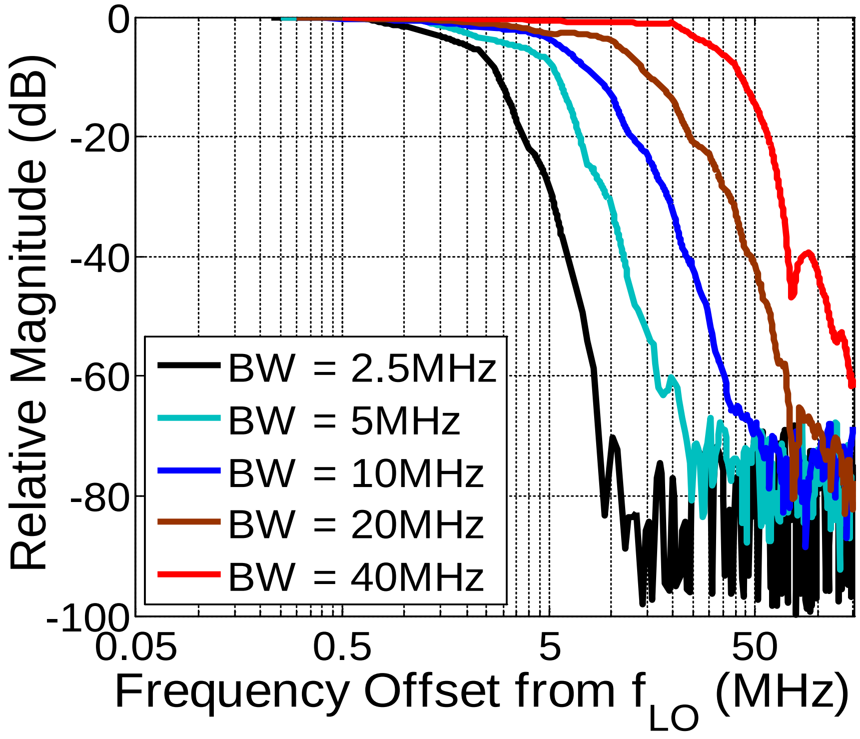
Implemented IC



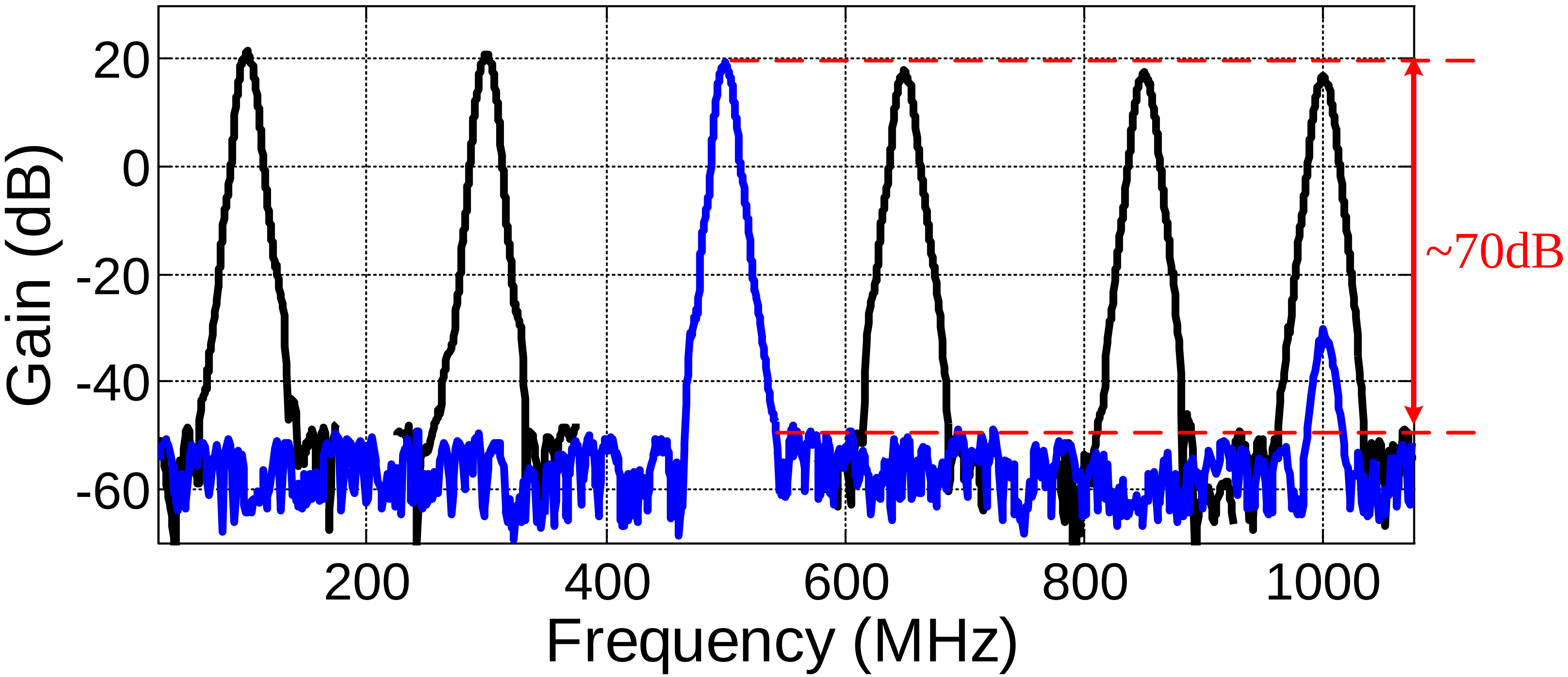
- 65nm CMOS
- $2.3mm^2$ active area

Filter Programmability

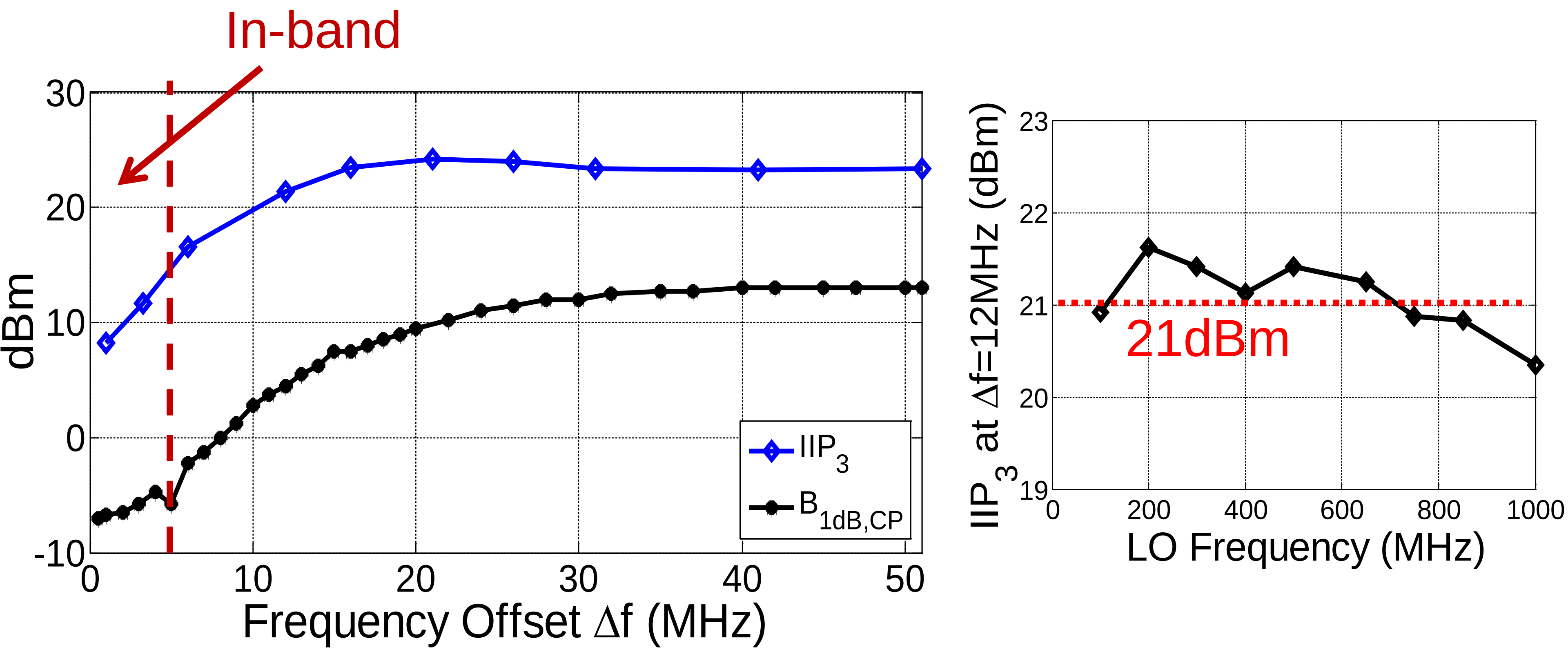




LO Programmability

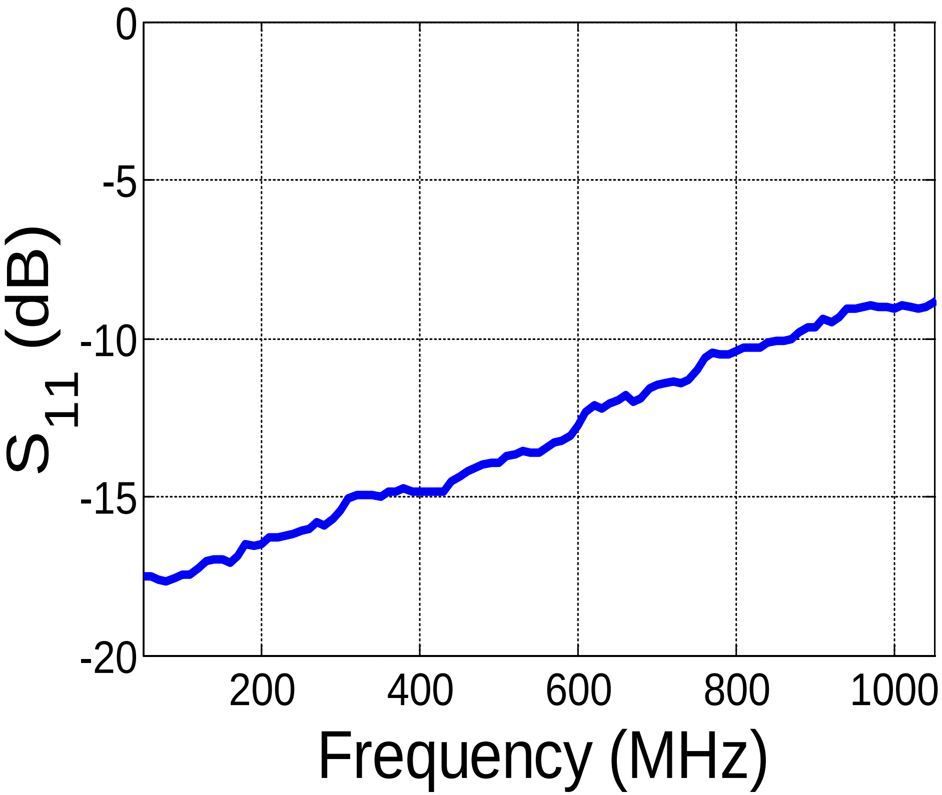


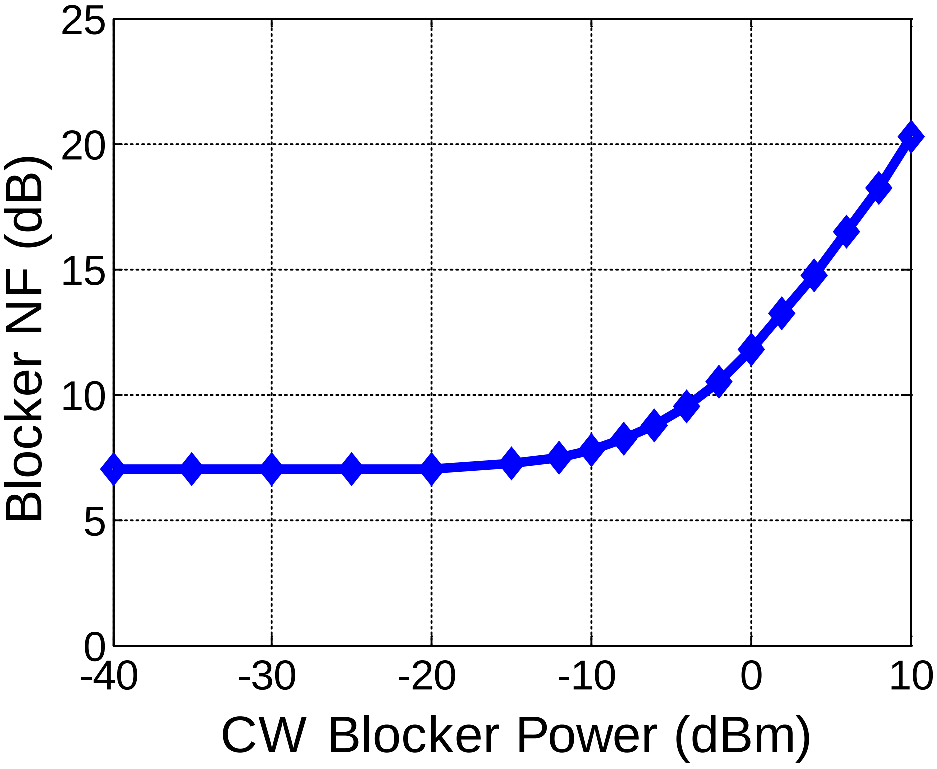
Receiver Linearity



Linearity vs. Offset from LO, IIP_3 (Δf=12MHz) vs. LO for 10MHz BW Filters

Wideband S_{11} and Blocker NF



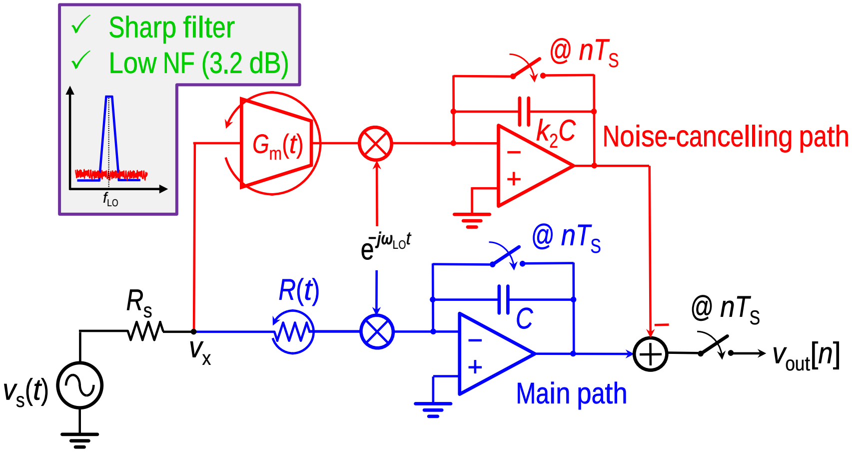


Comparison with Prior Art

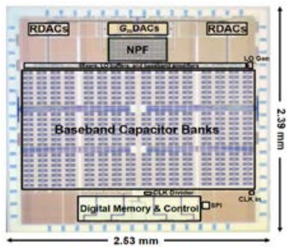
Metric	[1]	[2]	[3]	[4]	This Work
Architecture	N-path	N-path + DT filtering	Mixer-first with Noise Cancelling	FA	FA with Time Interleaving
Technology	65nm	40nm	40nm	65nm	65nm
RF Frequency (GHz)	0.1-1.2	0.1-0.7	0.08-2.7	0.1-1	0.1-1
RF Input	Differential	Differential	Single-ended	Single-ended	Differential
BW (MHz)	8	6.4-9.6	4	2.5-40	2.5-40
Stop-band Rejection (Transition BW)	59dB (12×BW)	>70dB (~8.5×BW)	NA	>35dB (2.5×BW) >50dB (6.5×BW)	>45dB (1.7×BW) >70dB (4×BW)
In-band IIP_3 (dBm)	-12	NA	-20	+1	+8
Out-of-band IIP_3 (dBm)	+26 (Δf=6.25×BW)	+24 (Δf=4.7×BW)	+13.5 (Δf=20×BW)	+17 (Δf=1.2×BW)	+21 (Δf=1.2×BW)
Out-of-band IIP_2 (dBm)	NA	NA	+55	+60	+64
$B_{1dB,CP}$ (dBm)	+7 (Δf=6.25×BW)	+14.7 (Δf=4.7×BW)	-2 (Δf=20×BW)	+0.7 (Δf=2×BW) +8 (Δf=4×BW)	+9.5 (Δf=2×BW) +13 (Δf=4×BW)
S_{11} (dB)	-5 to -8	<-10	<-8.8	<-10	<-9
Gain (dB)	25	40	72	18.9	23
NF (dB)	2.8	6.8-9.7	1.9	6.5	7
Supply Voltage (V)	1.2	1.2/1.6	1.2/2.5	1.2/1	1.2/1
Power Consumption	15-48mA	59-105mW	27-60mA	56-62mA	64-84mA
Active Area (mm^2)	0.27	2.03	1.2	2	2.3

Further Evolution

- ❑ Noise cancellation in time-varying receivers



- Time-varying noise cancellation path
- 3.2dB NF demonstrated
- JSSC'20

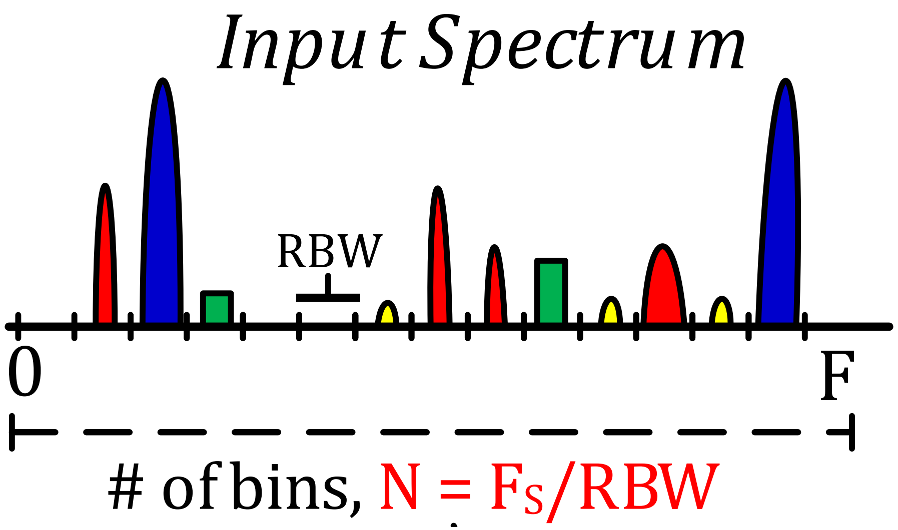


- ❑ Channel aggregation
  - ➢ Modifications to make input impedance time-invariant
  - ➢ Allow multiple channels to operate in parallel
  - ➢ More details in ISSCC'21

Outline

- Problem and prior art
- Filtering-by-Aliasing
  - Concept of using sampling aliases for sharp filtering
  - Designing FA filter: some examples
- Example applications
  - Agile RF front ends
  - Spectrum scanners

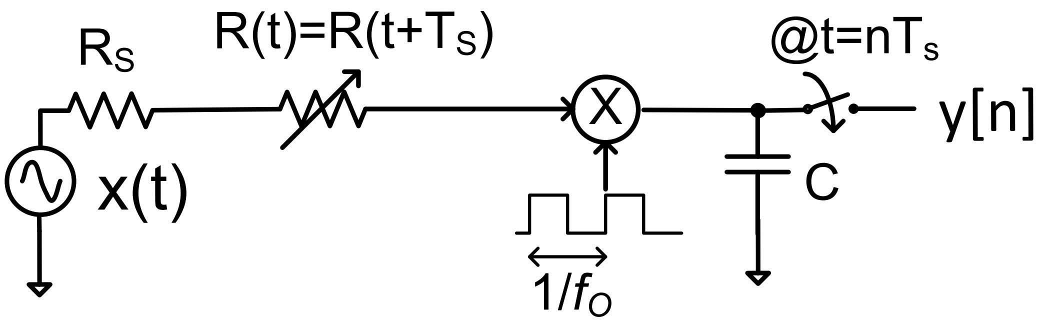
Spectrum Scanner: Requirements



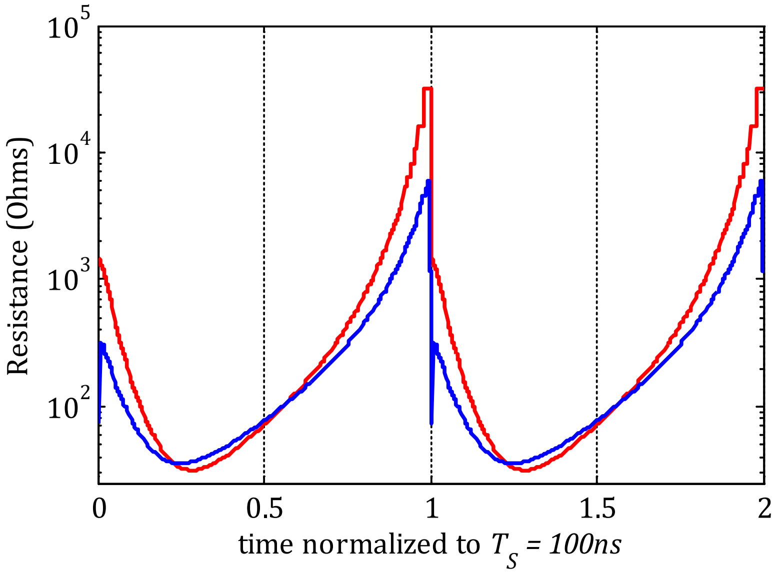
- BPFs with programmable center frequency, RBW
- Excellent linearity needed
- <u>Excellent harmonic rejection needed</u>
- Low power consumption

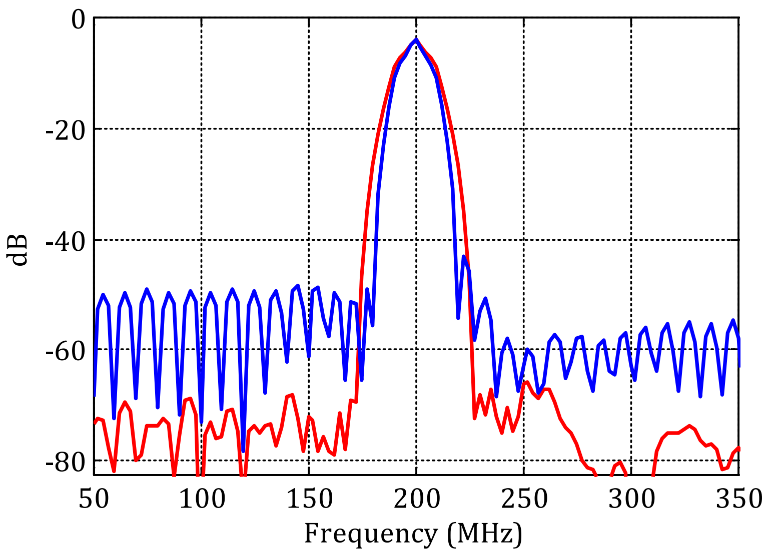
FA-Based Spectrum Scanner

- <u>Amplifier-less, passive implementation</u> ➔ linear, low power



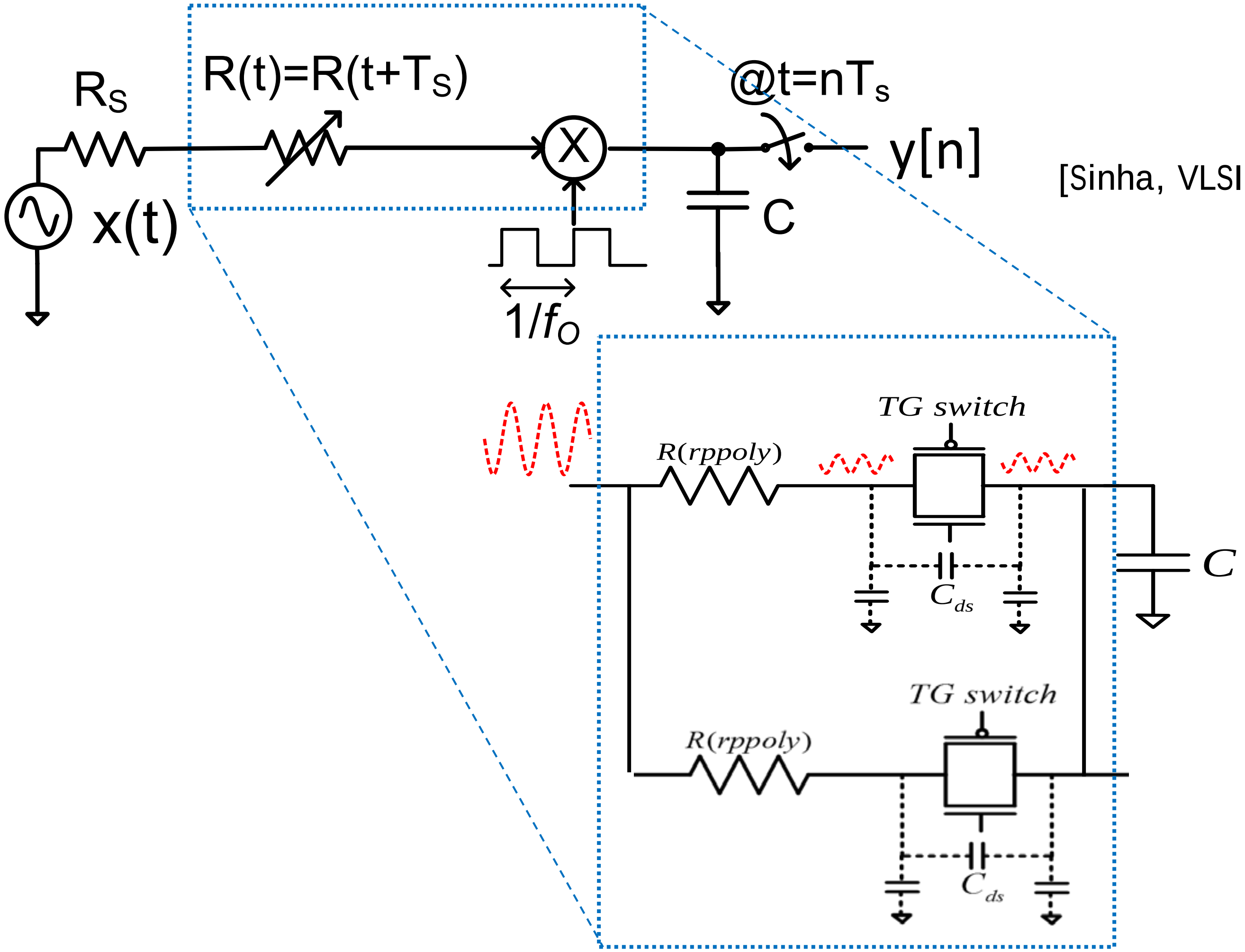
[Sinha, VLSI 2015, RFIC 2016]





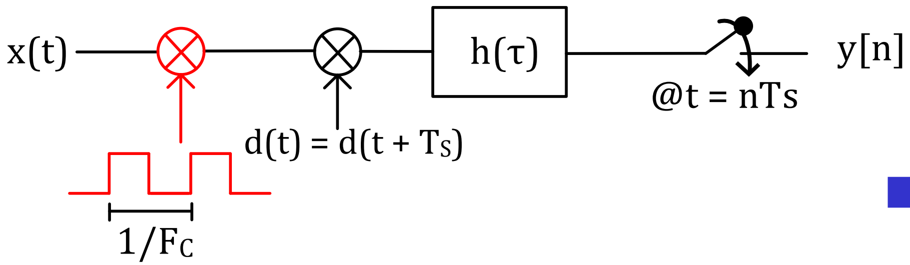
Linearity & Low Power

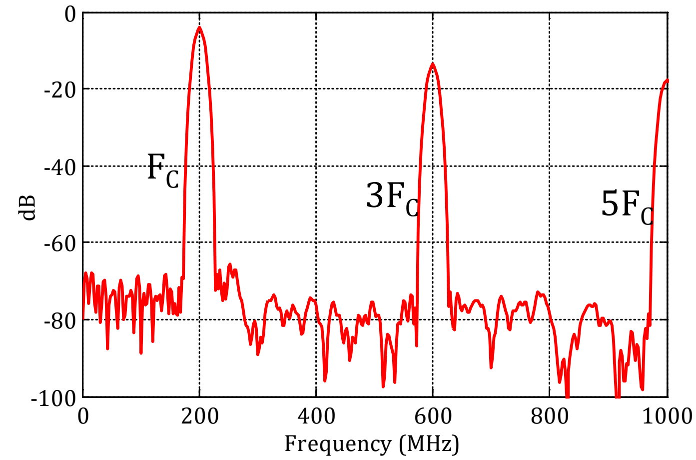
- Low power, excellent linearity



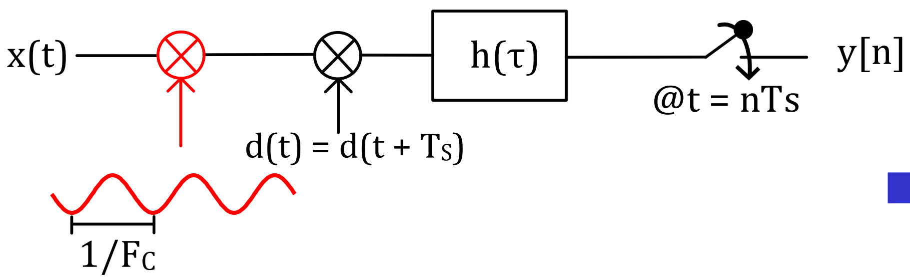
[Sinha, VLSI 2015, RFIC 2016]

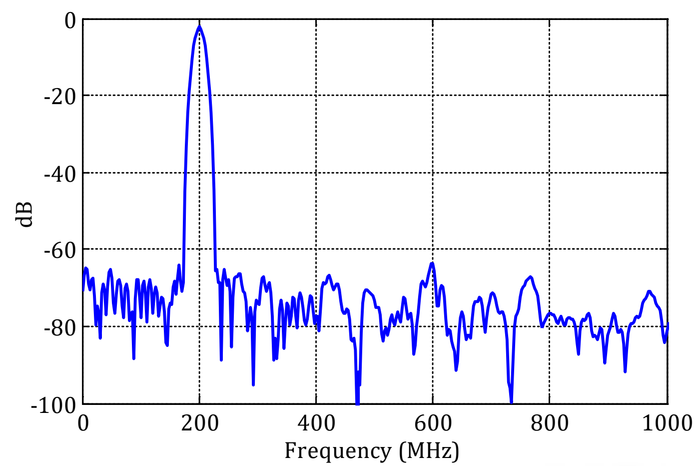
Harmonic Rejection



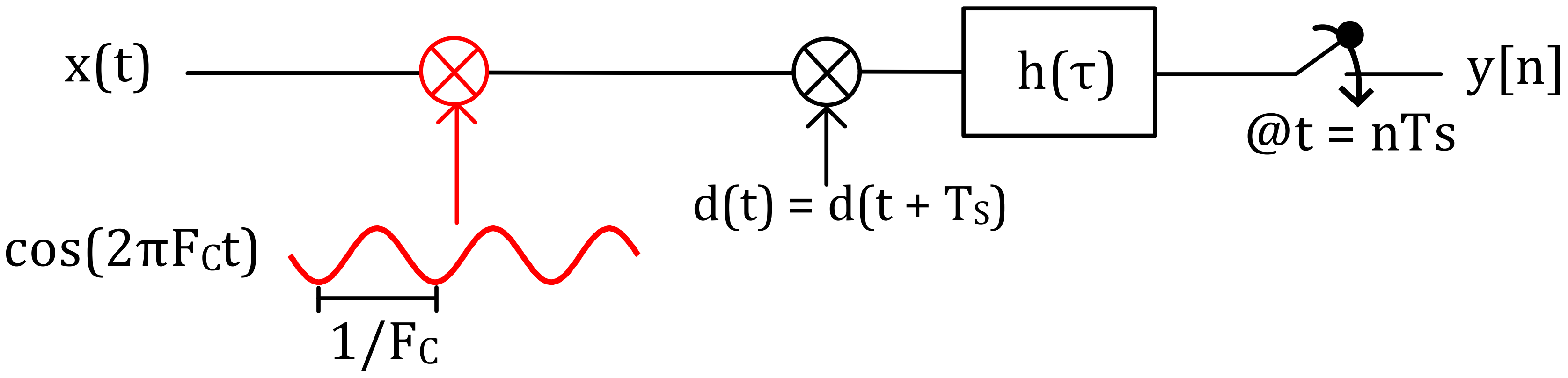


Sinusoidal mixing desired!

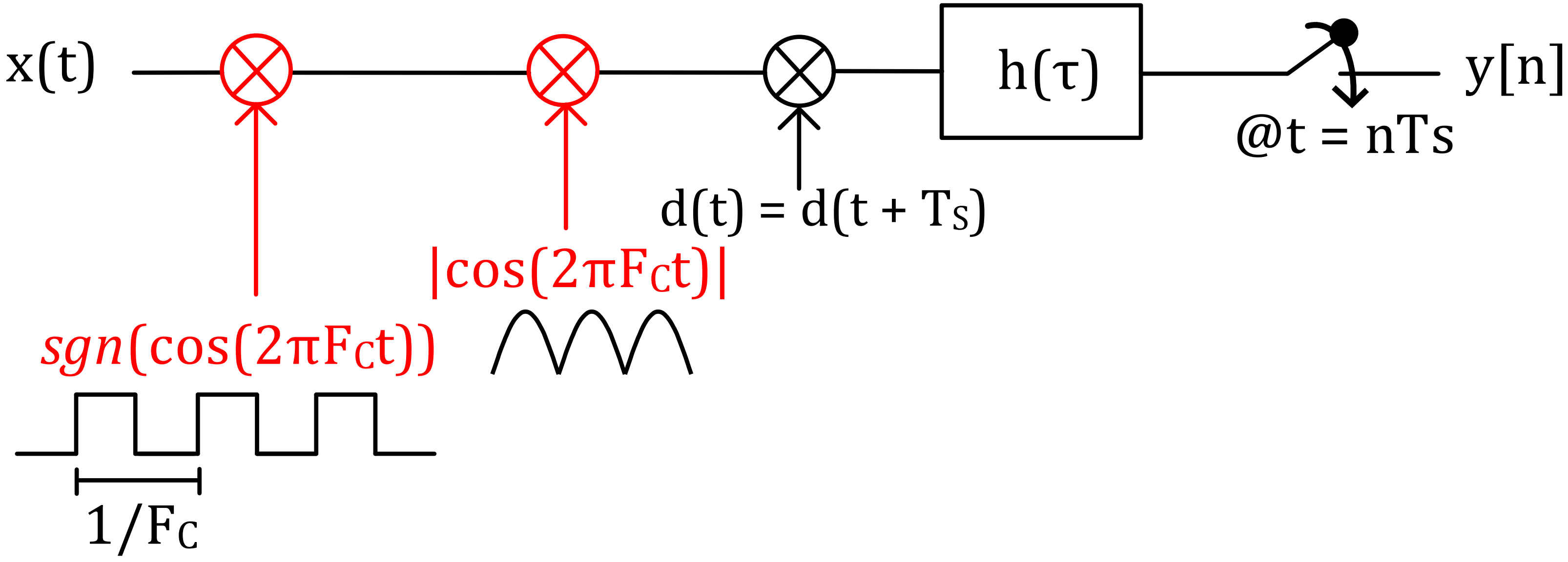




Harmonic Rejection

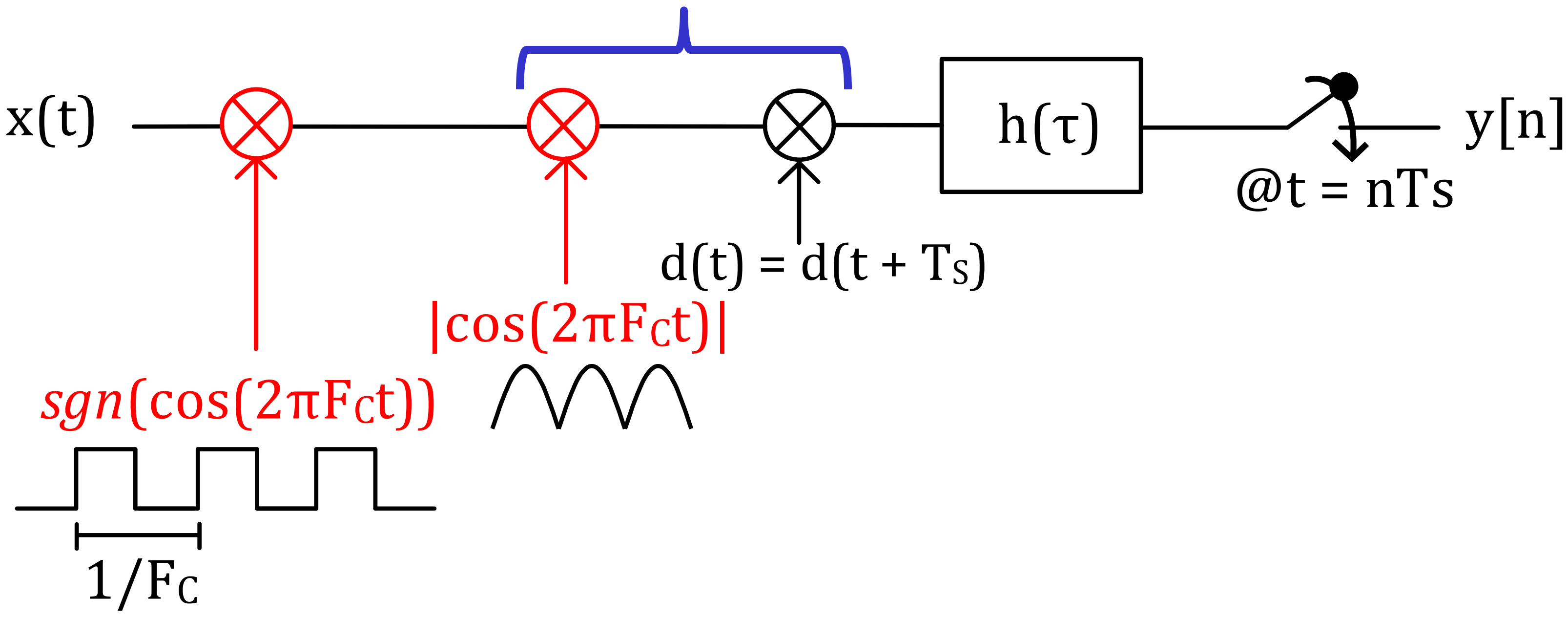


Harmonic Rejection



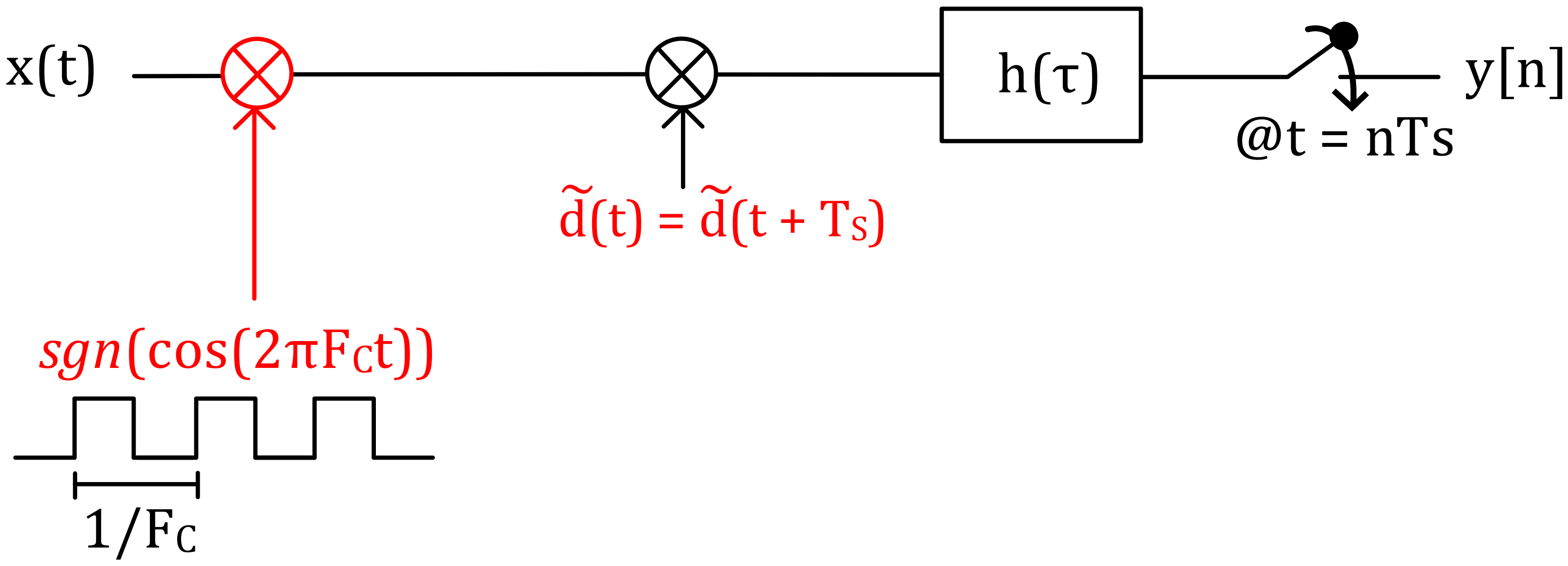
Sinusoid = square-wave x envelope

Harmonic Rejection



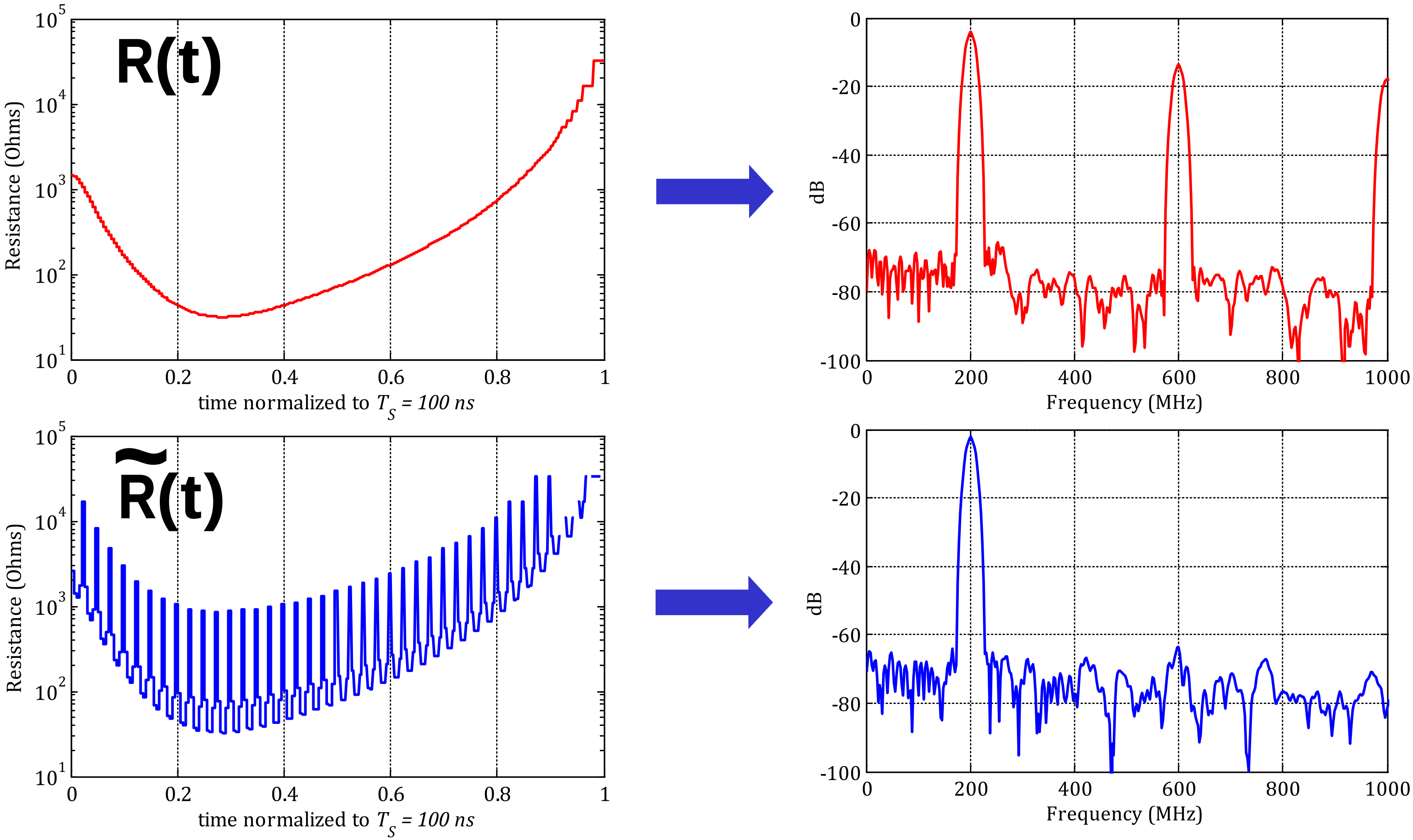
Include envelope in the design of d(t)

Harmonic Rejection

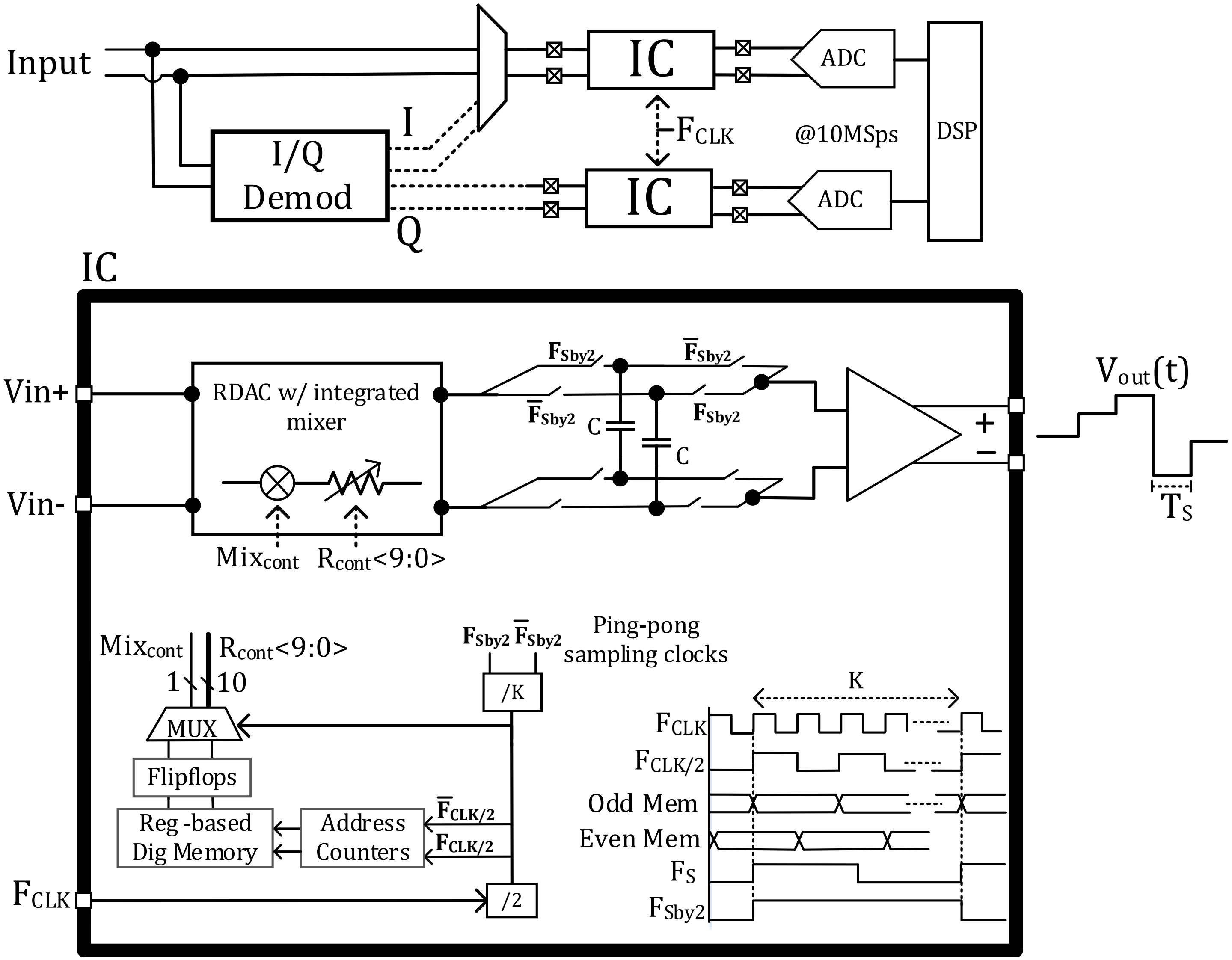


Change R(t) to $\tilde{R}$(t) to realize $\tilde{d}$(t)

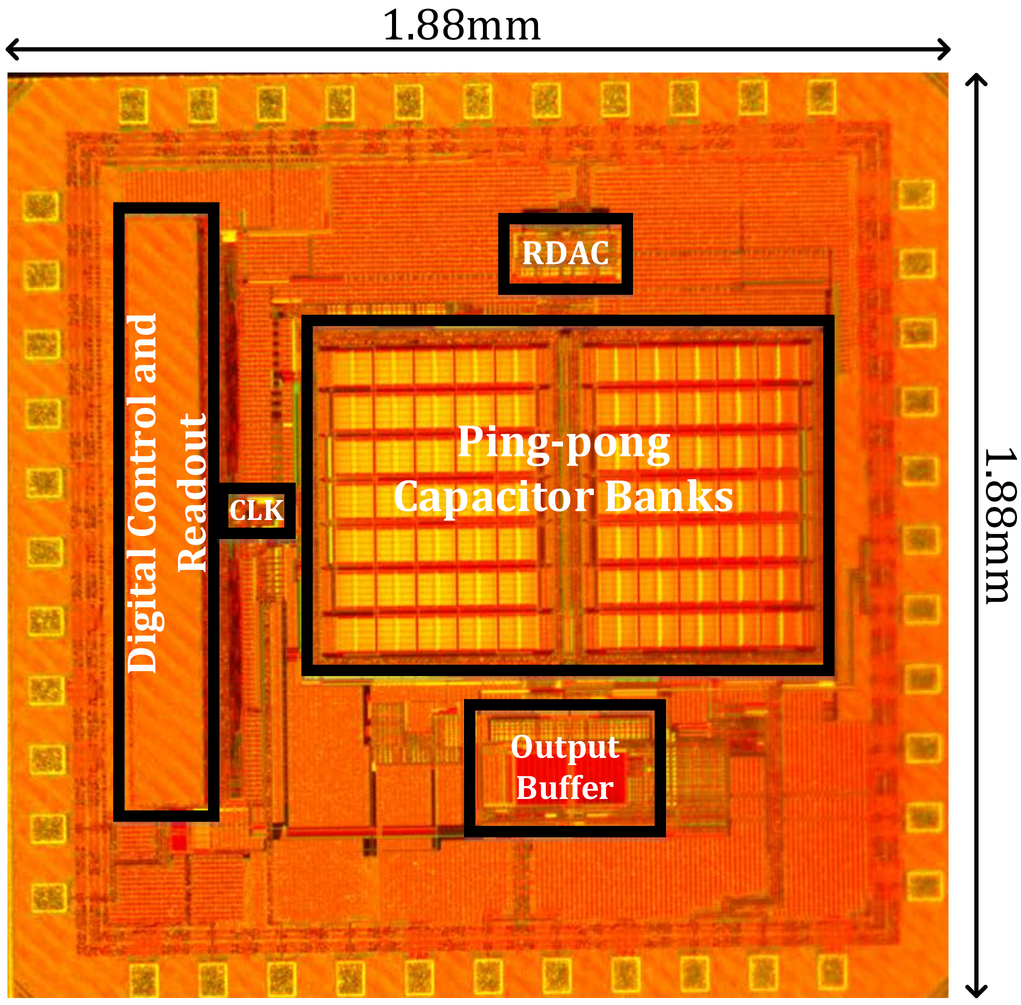
Harmonic Rejection



System Block Diagram

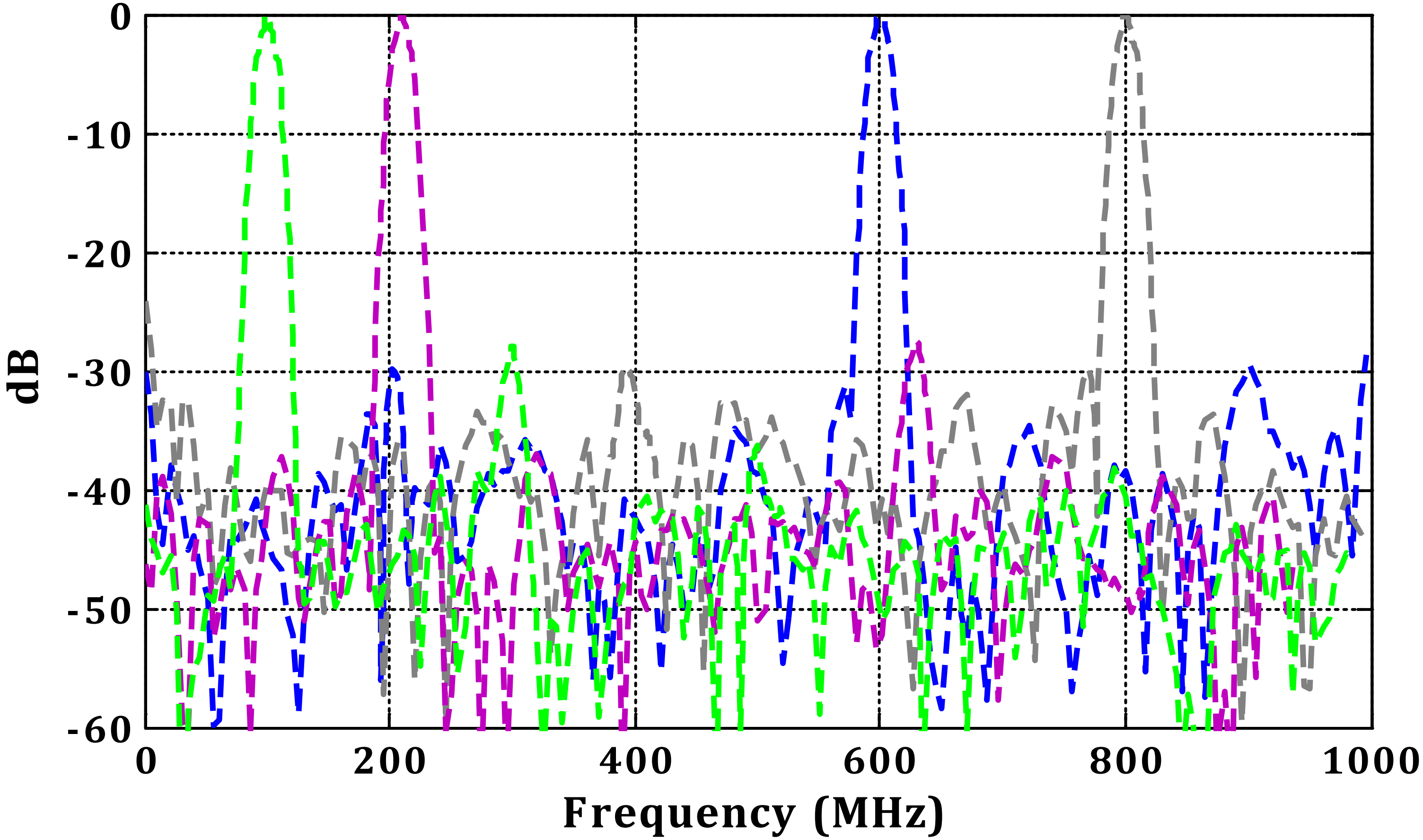


Chip Micrograph



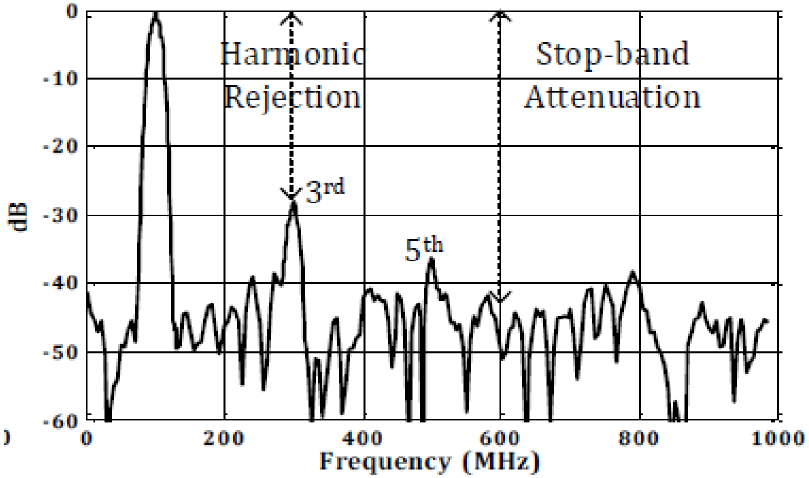
- TSMC 65nm CMOS
- 1.68mm^2 active area

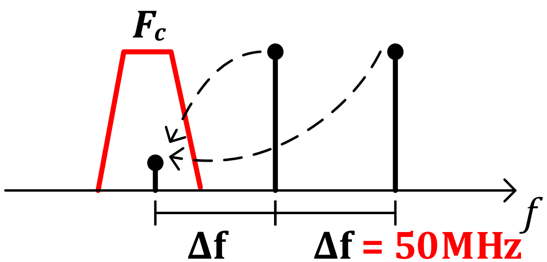
Frequency Bin Tunability

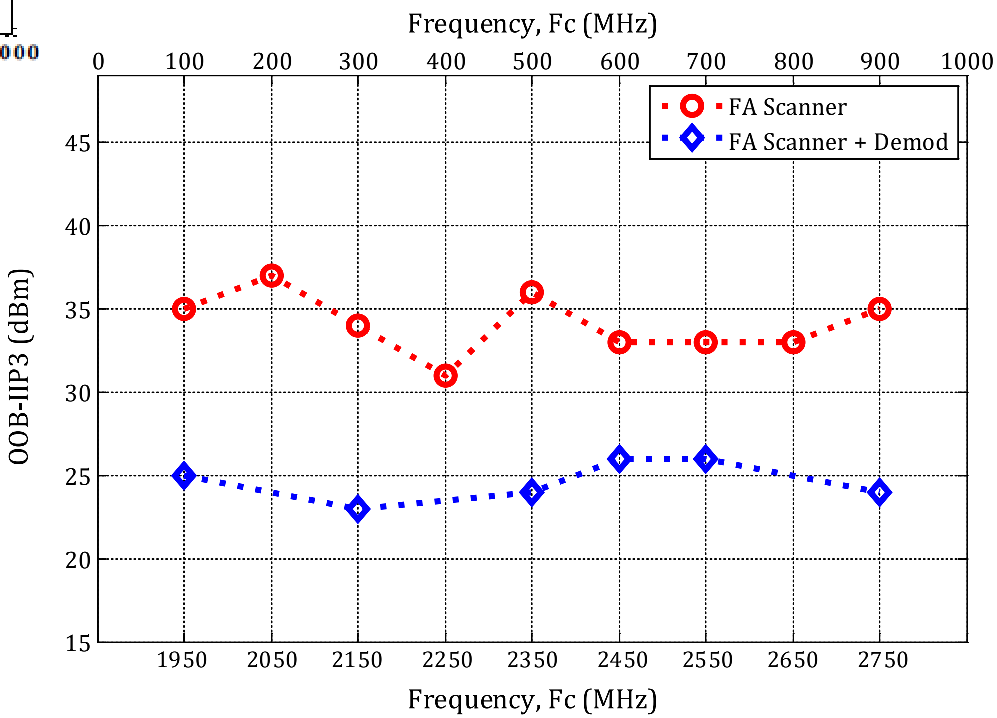


10MHz RBW, 1GHz span

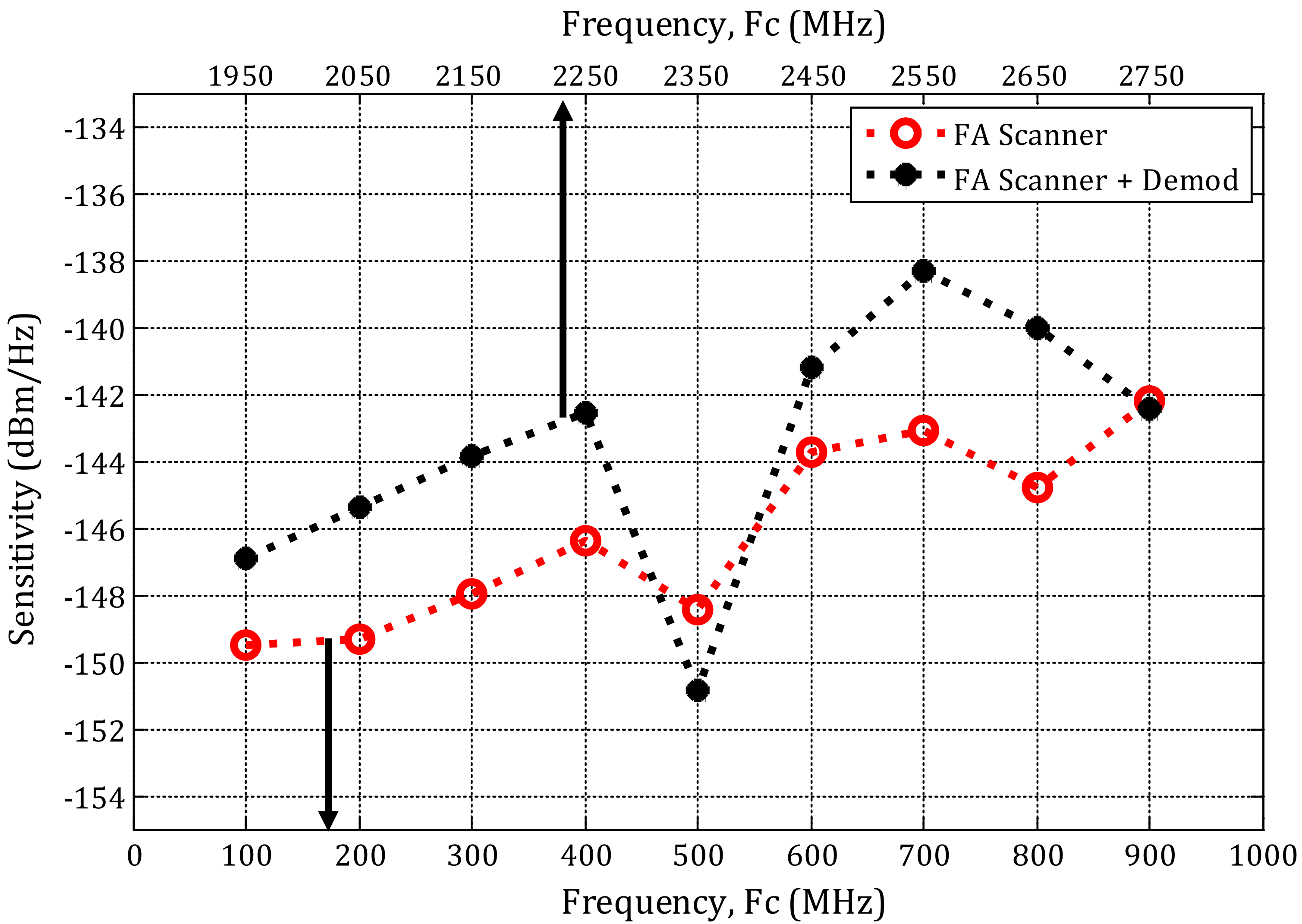
Sample Filter & Linearity







Measured Sensitivity



Comparison with Prior Art

	This work	Goel [1]	Alink [2]	Ingels [3]-[4]	Yazicigil [5]
Technology	**65nm**	130nm	65nm	40nm	65nm
Architecture	**Filtering by Aliasing**	Dual Up/Down Conversion	Cross-Correlation	Digital and Analog Multi-band Sensing	Compressive Sensing
Frequency Span (GHz)	**0 - 1**	0.1 - 6	0.3 - 1	0.5 – 2.5	2.7 - 3.7
Power (mW)	**< 8**	227 (697[a])	36-61	33-99 (66-143[a])	81
OOB IIP3 (dBm)	**> +31**	+10	+5	-16	N/R
OOB IIP2 (dBm)	**+70**	+40	N/R	+53	N/R
Sensitivity (dBm/Hz)	**< -142**	-145	-158 (-172[b])	-167	-142
SFDR in 1MHz RBW (dB)	**75**	63	69 (78)	61	N/R
Analog RBW (MHz)	**10,20[c]**	0.4-11	20	0.2-20	10,20
Scan Time for 20MHz Analog RBW & 1GHz Span (us)[d]	**50**	50	50	50	4.4

Summary

- Can use sampling aliases to our benefit
  - Sharp, integrated, programmable filtering
  - Excellent linearity and low power consumption

- Demonstrated agile RF front ends & spectrum scanners
  - Best in class in filter sharpness, linearity, and power

- Lot of potential
  - Can be extended to other circuit topologies and applications
  - Need good analysis techniques

Selected FA Related Publications

1. M. Rachid, S. Pamarti, B. Daneshrad, "Filtering by Aliasing", *IEEE Transactions on Signal Processing*, vol. 61, no. 9, May 2013, pp. 2319 – 2327.

2. N. Sinha, M. Rachid, S. Pamarti, “An 8mW, 1GHz Span, Passive Spectrum Scanner with +31dBm Out-of-Band IIP3,” *IEEE 2016 RFIC Symposium*, May 2016, pp. 1286-1289.

3. H. Sameed, N. Sinha, M. Rachid, S. Pamarti, “A Programmable Receiver Front-End Achieving >17dBm IIP3 at <1.25xBW Frequency Offset,” *IEEE 2016 ISSCC*, pp. 446-447, February 2016.

4. S. Hameed, S. Pamarti, “A Time-Interleaved Filtering-By-Aliasing Receiver Front-End with >70dB Suppression at <4xBandwidth Frequency Offset,” *IEEE 2017 ISSCC*, pp.418-419, February 2017.

5. N. Sinha, M. Rachid, S. Pavan, and S. Pamarti, “Design and Analysis of an 8 mW, 1 GHz Span, Passive Spectrum Scanner with >+31dBm Out-of-Band IIP3 Using Periodically Time-Varying Circuit Components, *IEEE JSSC*, pp. 2009-2025, August 2017.

6. S. Hameed, S. Pamarti, “Design and Analysis of a Programmable Receiver Front End Based on Baseband Analog-FIR Filtering Using an LPTV Resistor,” *IEEE JSSC*, 2018, IEEE Explore Early Access.

7. S. Hameed, S. Pamarti, “Impedance Matching and Re-radiation in LPTV Receiver Front-Ends: An Analysis Using Conversion Matrices,” *IEEE TCAS-I*, 2018, IEEE Explore Early Access.