Multi-band RF Time Delay Element based on Frequency Translation

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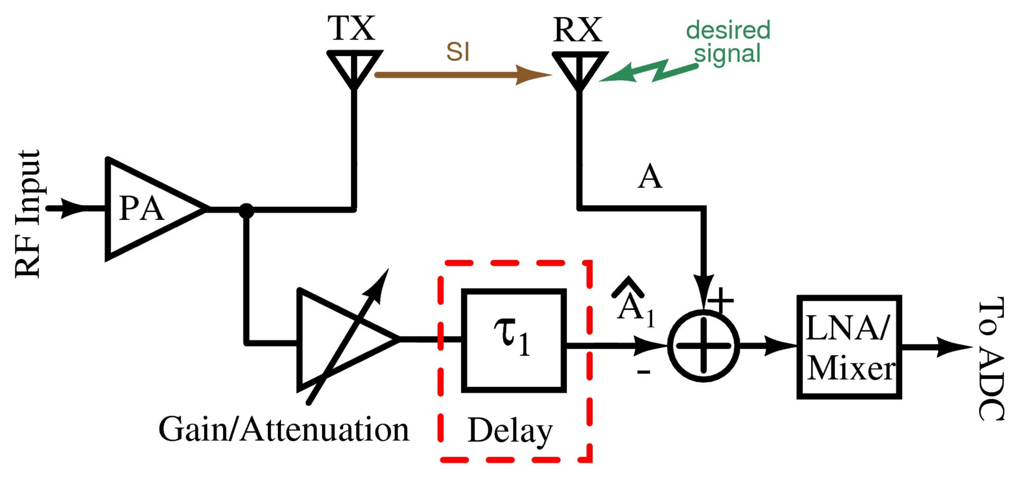
Motivation

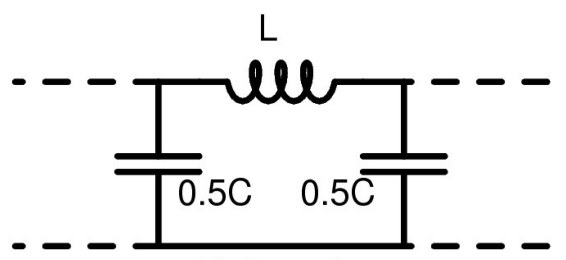
- Single-channel full-duplex wireless :
  - Adaptive cancellation of strong TX leakage at the RX
  - Time delay requirements of the order of several RF carrier cycles
  - Cancellation highly sensitive to amplitude and delay mismatch



Two antenna self- interference cancellation system

Prior approach 1: True Time Delay Cells

- Based on LC implementation of transmission line [1]
  - ✓ Excellent Linear phase characteristics for $f << f_c$
  - X On-chip Inductors are ***bulky*** and ***lossy***



Unit section

$$f_c = \frac{1}{\pi\sqrt{LC}}$$

$$T_D = n\sqrt{LC}$$

Narrowband Approximation to time delay

- For a narrowband signal, the delay can be approximated by phase shift of the carrier only

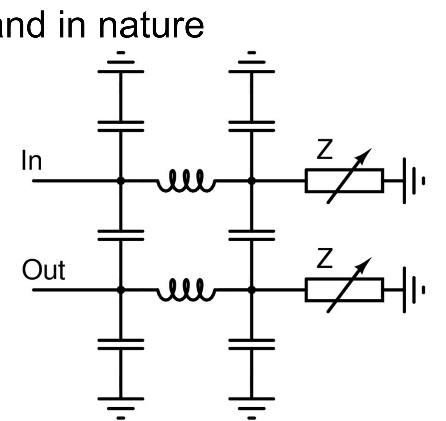
$$x(t-\tau) \approx a(t)\cos[\omega_c(t-\tau) - \varphi(t)]$$
$$= a(t)\cos[\omega_c t - \theta - \varphi(t)]$$

Where $\theta = \omega_c\tau$

- Good approximation only when the 'signal envelope' does not change significantly during delay time

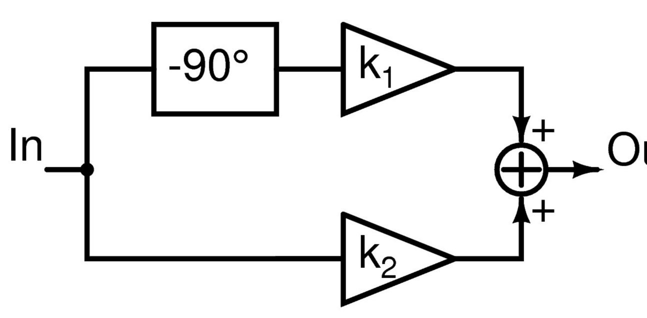
Prior approach 2: Reflection Type Phase Shifters

- By changing the complex termination of a circulator/ coupler, the phase of signal can be changed [2]
  - X Implementation uses Inductors → Bulky and lossy
  - X Not multi-band in nature



Prior approach 3: Vector Modulator based PS

- Add suitably weighted quadrature components [3]
  - X Quadrature splitters are narrow-band
  - X Active circuits produce noise, distortion and are power hungry at RF



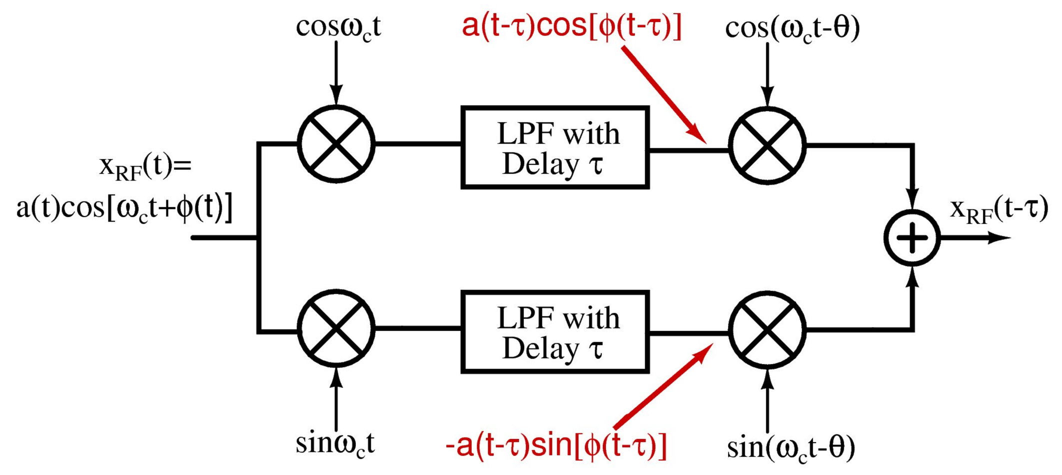
$$\theta = \tan^{-1}\frac{k_1}{k_2}$$

Proposed Technique: Better time delay approximation

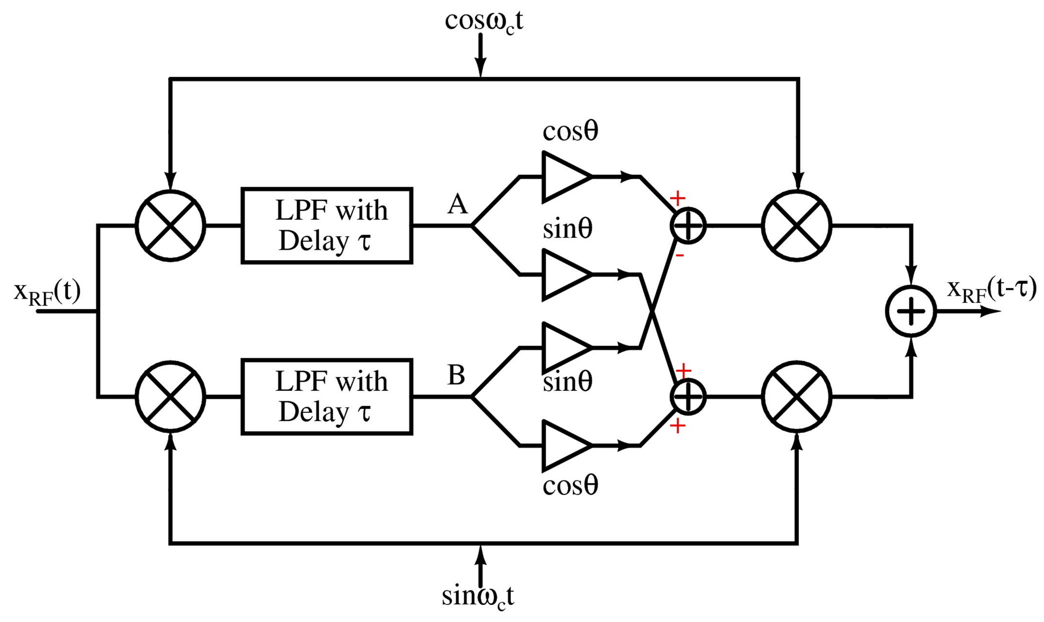
- For narrowband signal, time delay can be seen as **Envelope delay + carrier phase shift** $(0 - 2\pi)$
- Mathematical representation:

$$x(t-\tau) = a(t-\tau)\cos[\omega_c(t-\tau) - \varphi(t-\tau)]$$
$$= a(t-\tau)\cos[\omega_c t - \theta - \varphi(t-\tau)]$$

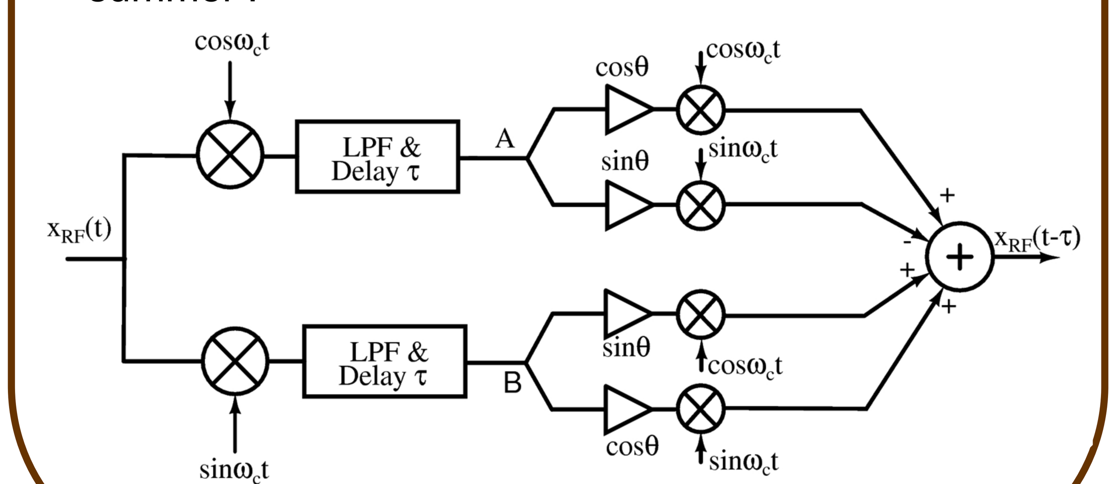
Where $\theta = \omega_c\tau$ (mod) 2π



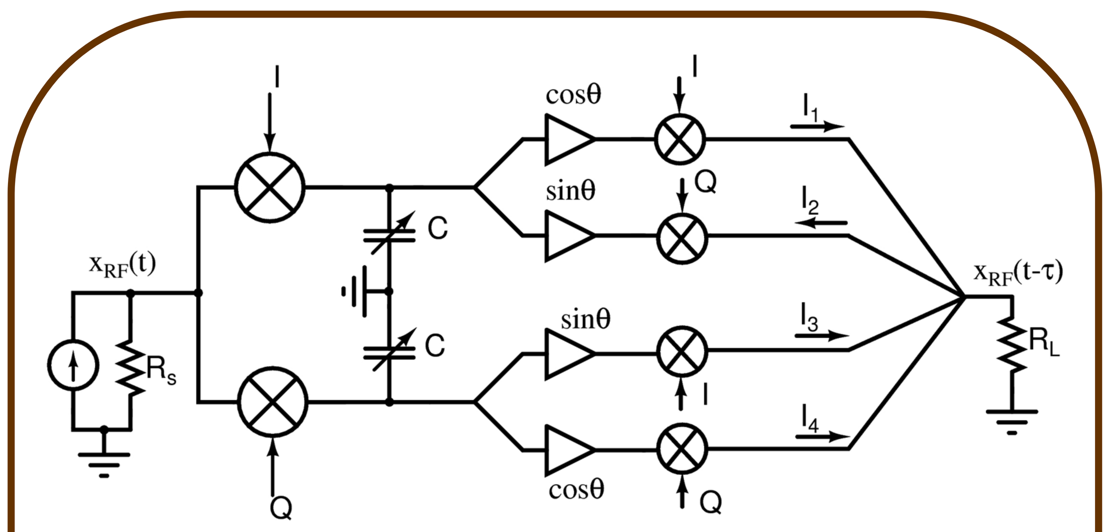
- LPF with $f_c \gg BW$ acts as a Linear phase filter → Use LPF as a time delay
- Most modern modulation schemes have asymmetric baseband spectra → Quadrature down-conversion
- Another implementation of the same topology is obtained by expanding the shifted carrier term :



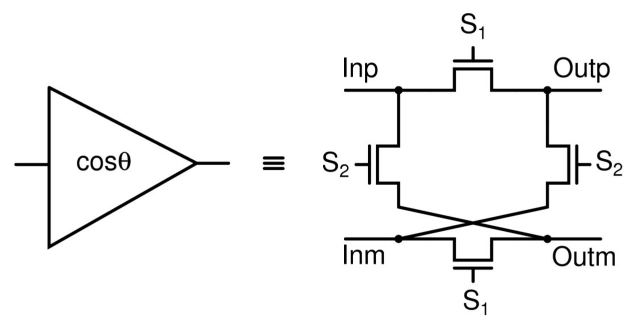
- Desired LO phase shift obtained by applying suitable weights to baseband quadrature signals
  - ✓ Phase shift of high frequency LO not required
- An alternate architecture eliminating baseband summer :



CMOS Implementation

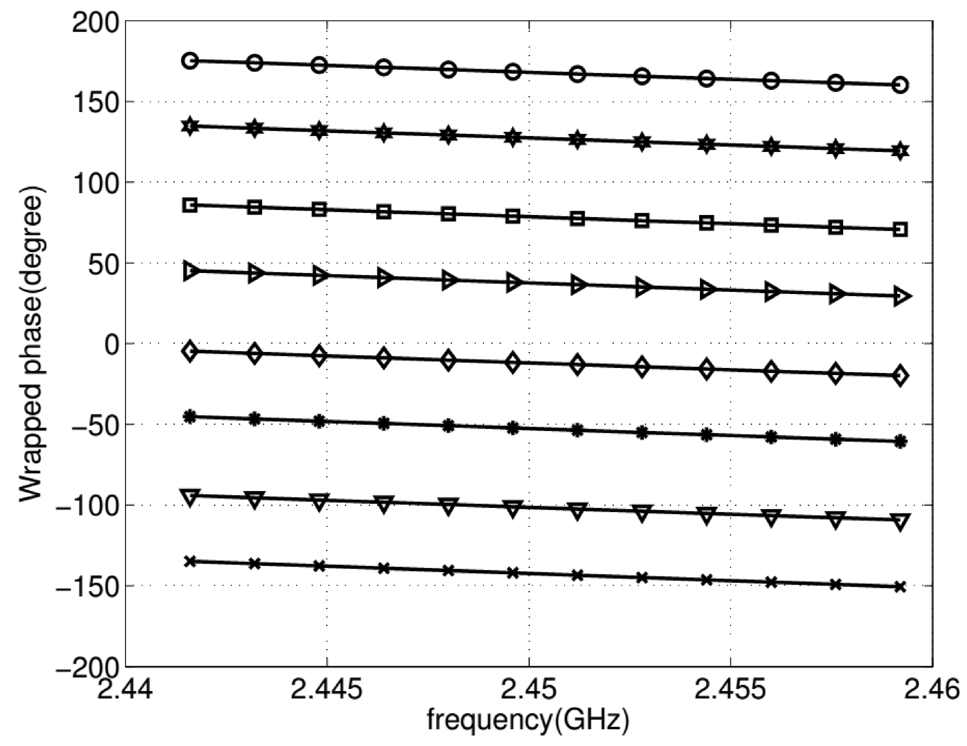


- Fully differential current mode implementation with 25% duty-cycle LO driven passive mixer
  - Direct summation of output RF current
  - Excellent Linearity, negligible flicker noise
- R_s and R_L depend on circuit impedance levels
- LPF configured to provide envelope delay of 2.5 ns (≈ 6 LO cycles at 2.5 GHz)
  - Can be tuned using capacitor C.
- Carrier phase tuned by changing $\cos\theta$ and $\sin\theta$
  - Always between -1 and +1, irrespective of carrier→ Multi-band operation possible



- Gain of +1, -1 and 0 implemented by MOS switches.
  - 45° phase step
- Due to mixer switching, output also contains signal around odd LO harmonics.
  - Can be suppressed by filtering

Phase Range



Phase shift vs frequency for different phase settings.

Performance Comparison

Parameters	This Work	[2]	[3]	[4]
Topology	Frequency Translation	Active RTPS	Vector Modulator	Switched TLPS
Frequency (GHz)	Multi-band	2.4-2.5	1-2.1	2.5-3.2
Phase tuning range (°)	360	120	90	360
Gain (dB)	-3.4/-13	-5 to 0	4.8	-2.5
Input noise current (pA/√Hz)	28	280	101	37
Power (mW)	9.84	111	4.2	60
Area (mm²)	0.10	0.36	0.06	4.16
Technology	130 nm CMOS	180 nm CMOS	180 nm CMOS	180 nm CMOS

Conclusion

- A better approximation to true time delay is demonstrated based on frequency translation.
- The proposed architecture is capable of operating across multiple frequency bands.
- Implementation with passive mixers is likely to benefit immensely with downscaling of CMOS technology in terms of area and power consumption.

References

[1] H. Zarei *et al.*, "A low-loss phase shifter in 180 nm CMOS for multiple-antenna receivers," *Proc. IEEE Int. Solid State Circuits Conf.*, 2004, pp.392-534.

[2] Y. Zheng *et al.*, "An ultra-compact CMOS variable phase shifter for 2.4 GHz ISM applications", *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 6, pp. 1349-1354, 2008.

[3] Y. Huang *et al.*, " An Ultra-Compact, Linearly-Controlled Variable Phase Shifter Designed With a Novel RC Poly-Phase Filter," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 2, pp. 301-310, 2012.

[4] M. Meghdadi *et al.*, " A 6-bit CMOS phase shifter for S-band," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 12, pp. 3519-3526, 2010.