A 67-μW Ultra-Low Power PVT-Robust MedRadio Transmitter

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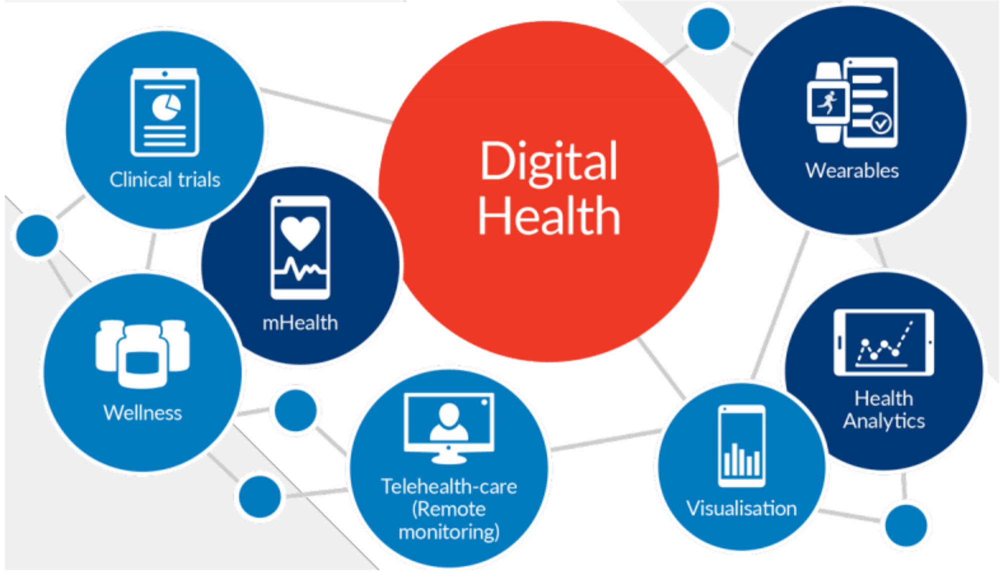
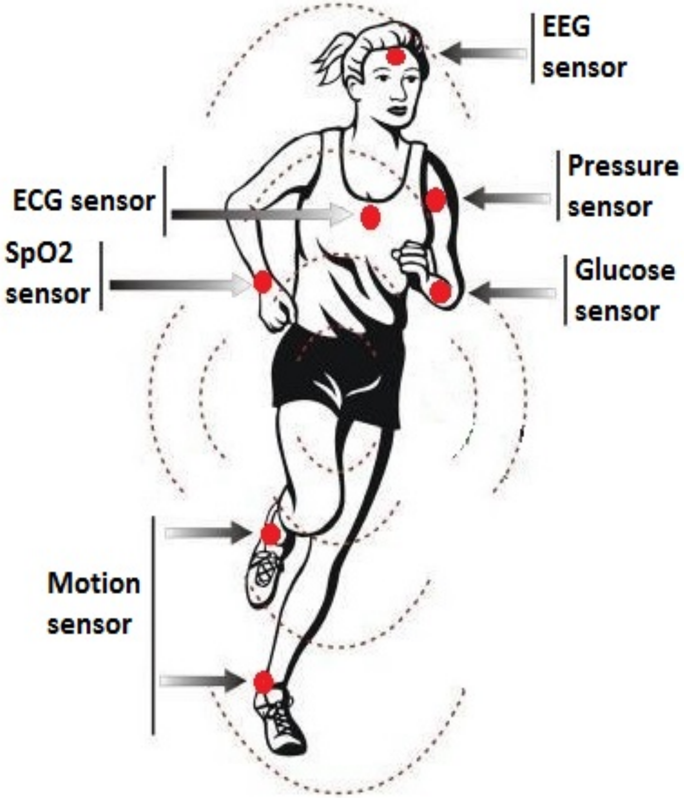
The Internet of *Medical* Things – Io(M)T

Miniaturized Wearable & Implantable Devices:

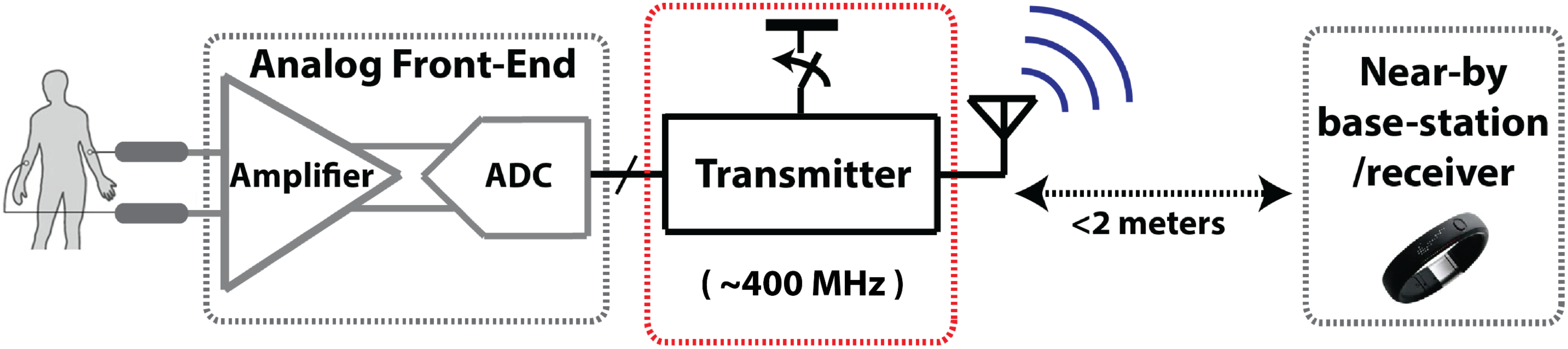
- ✓ Automated, remote monitoring
- ✓ Early detection/diagnosis





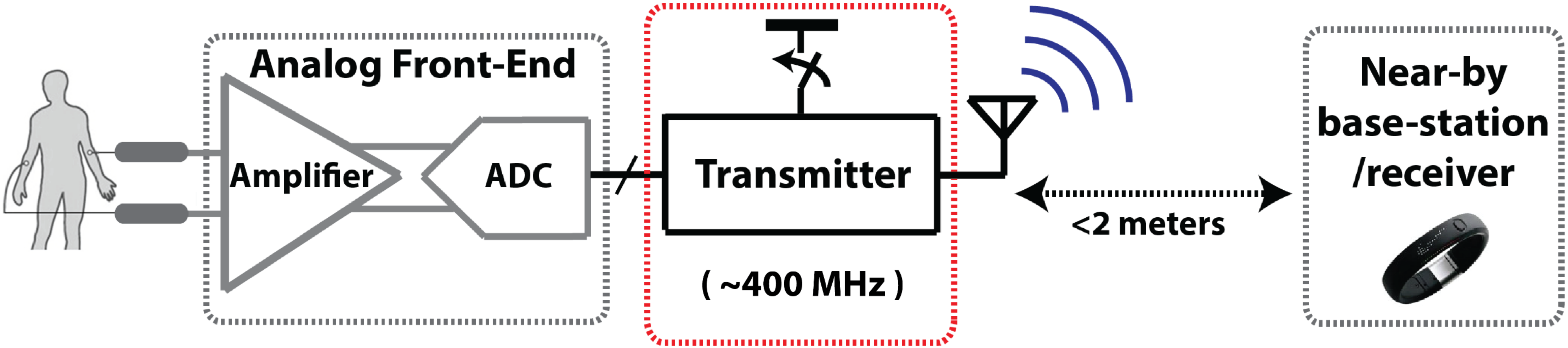
Enabling connected health applications

A Wireless Io*MT* BioSensor



- Medical Device Radiocommunications Service (MedRadio): ~400 MHz
- Short-range transmitter (<2 meters TX distance)
- Ultra low power → Duty-cycled operation

A Wireless Io*MT* BioSensor Node

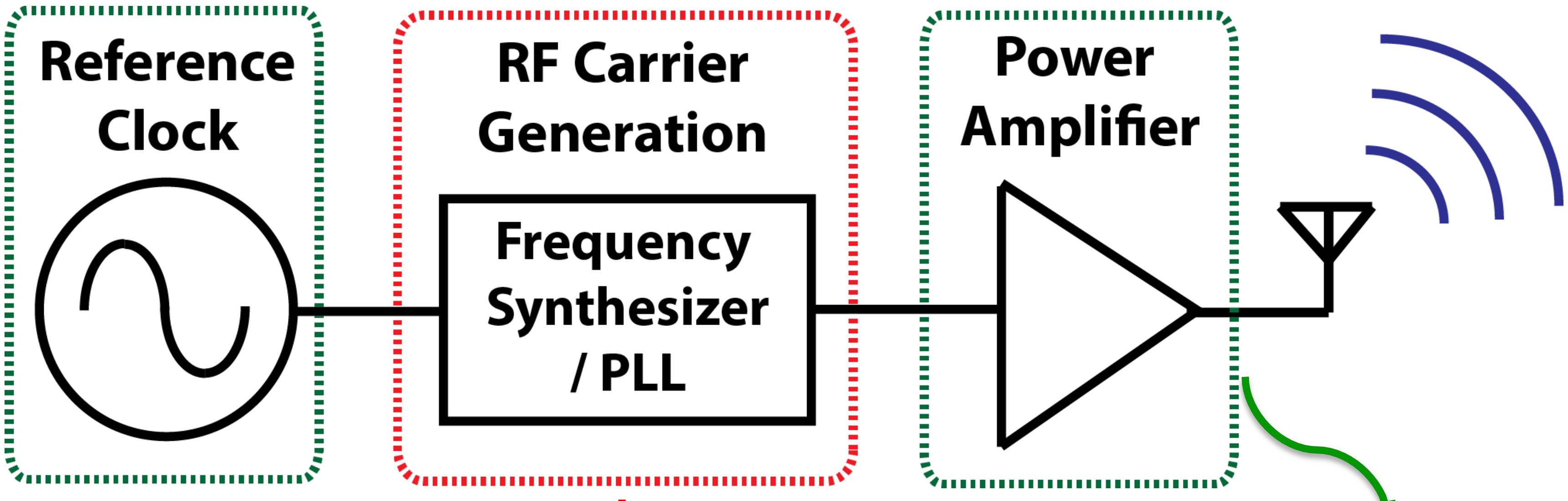


- Medical Device Radiocommunications Service (MedRadio): ~400 MHz

- **Frequency stability ±100 ppm/°C over 0 to 55 °C**
- **Attenuate out-of-band/spurious emissions by 20 dBc**

"Medical Device Radio Communications Service," in *Electronic Code of Federal Regulations (e-CFR)*, vol. Title 47,Chapter I, Subchapter D, Part 95, Oct. 2018.

Conventional Short-Range Transmitter



Power-hungry block
(400 MHz RF carrier)

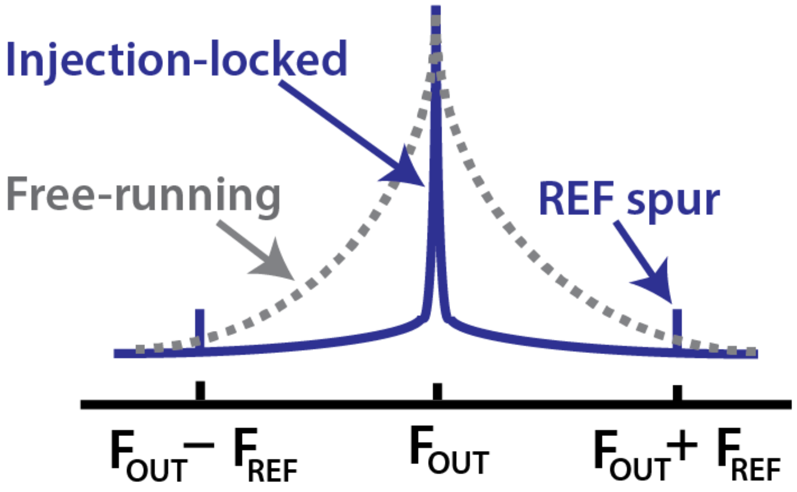
Short-range PA
(< -17 dBm or 20 μW output power)

Key challenge for an Io*MT* transmitter:
Low power RF frequency synthesis

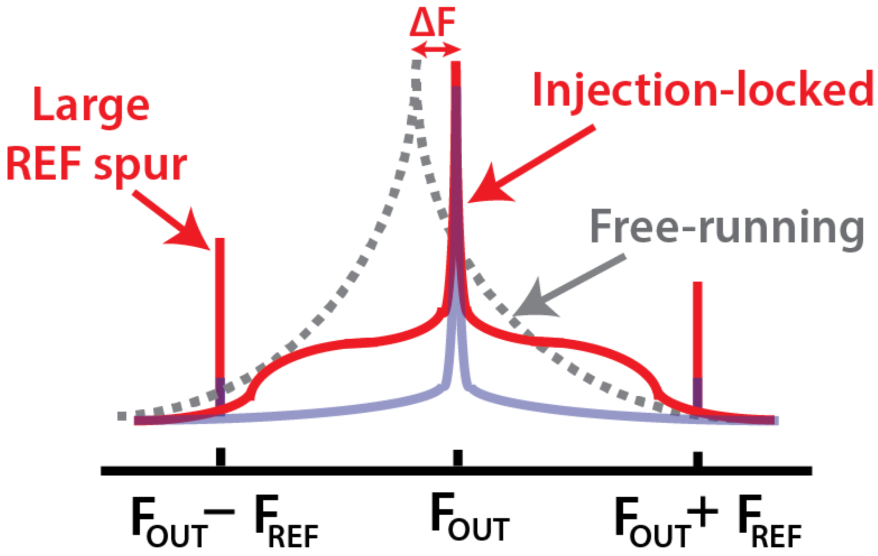
Low Power Frequency Synthesizers

Injection-locked clock multiplier (ILCM):

$$F_{OSC} = N.F_{REF}$$

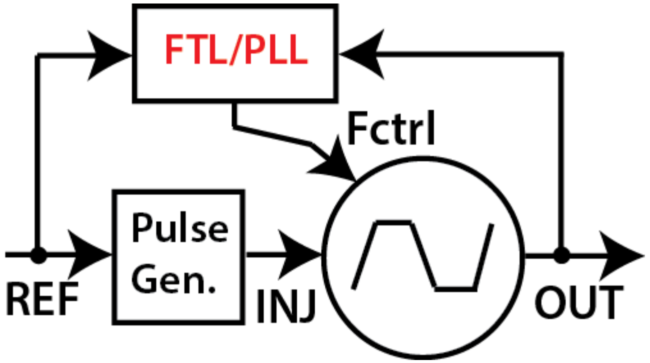


$$F_{OSC} < N.F_{REF}$$



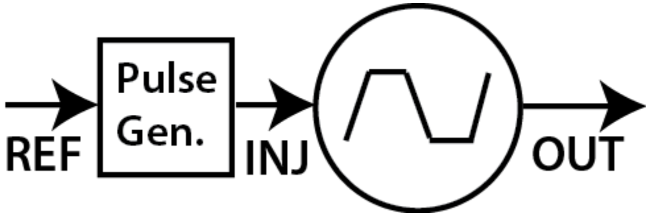
Low Power Frequency Synthesizers

Conventional ring oscillator based ILCM: [JSSC '02]



- ✓ Robust
- ✗ Power hungry
- ✗ Slow start-up

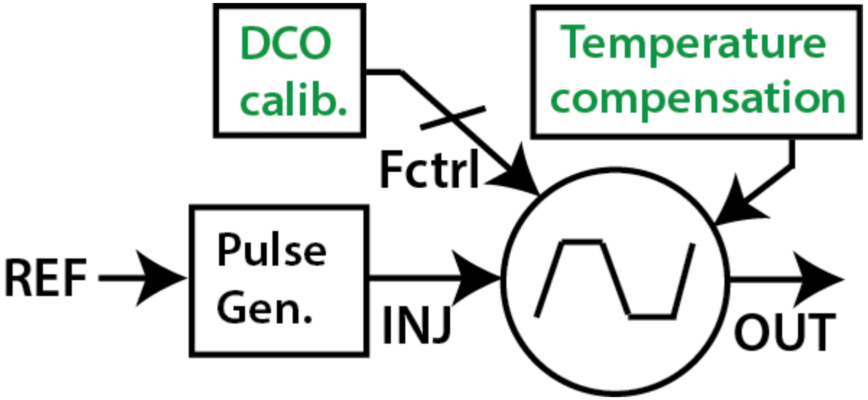
Open-loop ILCM: [JSSC '11]



- ✓ PLL-free ultra-low power
- ✗ Very sensitive to PVT
- ✗ Constant temperature assumed (human body)

☹ **Loss of lock** ☹ **Large REF spur**

Open-loop ILCM with Initial calibration [JSSC '14] [JSSC '17]; Temperature compensation [CICC'19]



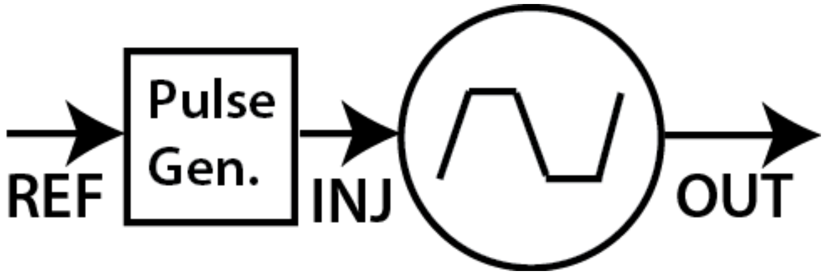
- ✓ PLL-free, fast start-up
- ✓ Robust to static PV, dynamic T
- ✗ Slow start-up (if calibrated each time)
- ✗ Dynamic V not addressed
- ✗ Low/moderate power

PVT robustness is a major issue

Motivation and Proposed Work

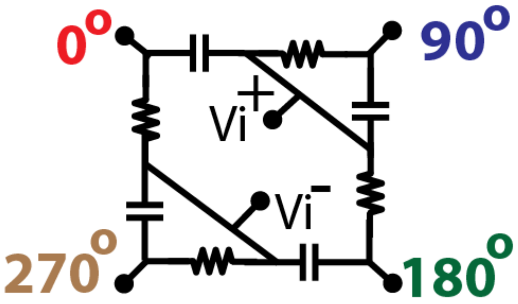
Open-loop ILCM:

- ✓ Low Power
- × PVT sensitive

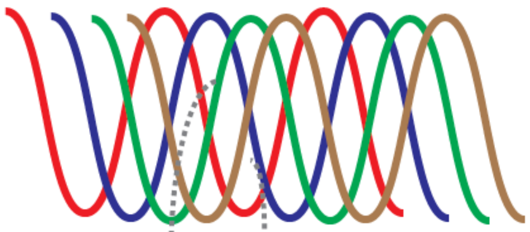


Proposed RF frequency synthesis:

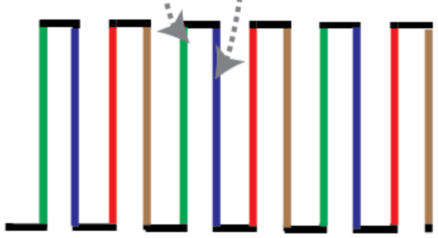
- ✓ Low power
- ✓ PVT robust



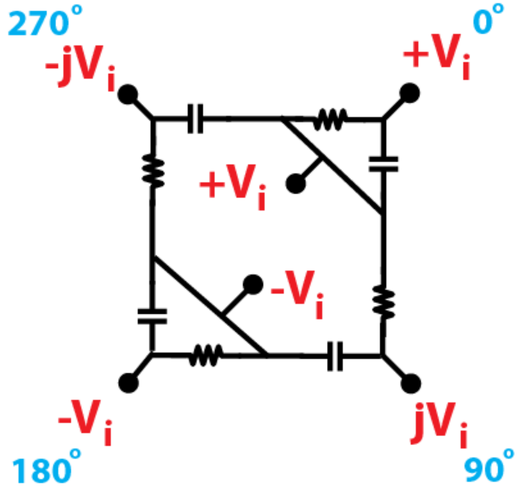
PVT-robust 4-phase sinusoids:



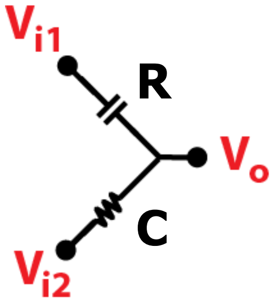
2× frequency multiplication by edge combining:



PVT Robust Polyphase Generation



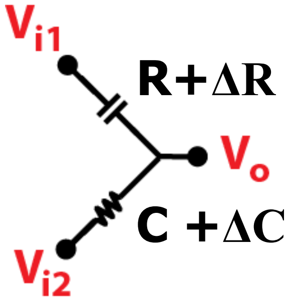
Ideal case:



$$V_{o,ideal} = \frac{V_{i1}j + V_{i2}}{1+j}$$

($@\omega CR = 1$)

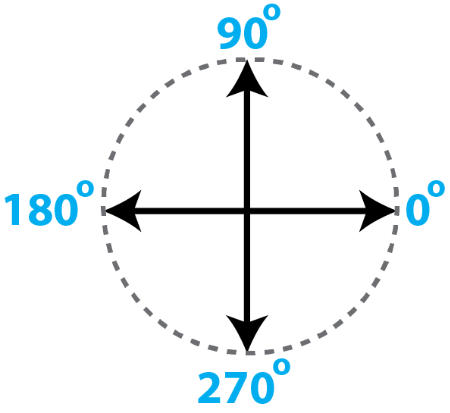
With P,T variations:

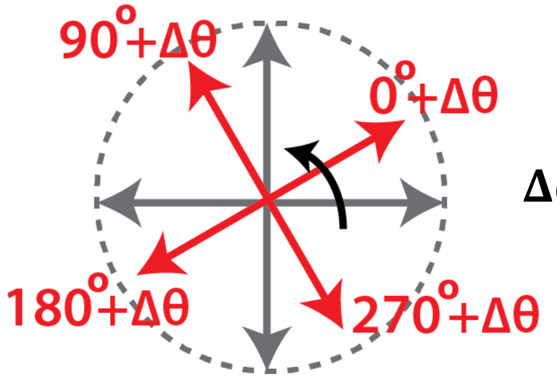


$$V_{o,\Delta RC} \cong V_{o,ideal}\ \frac{\Delta RC.\omega+2}{j.(\Delta RC.\omega+1)+1}$$

(assuming small ΔR, ΔC)

Phasors:

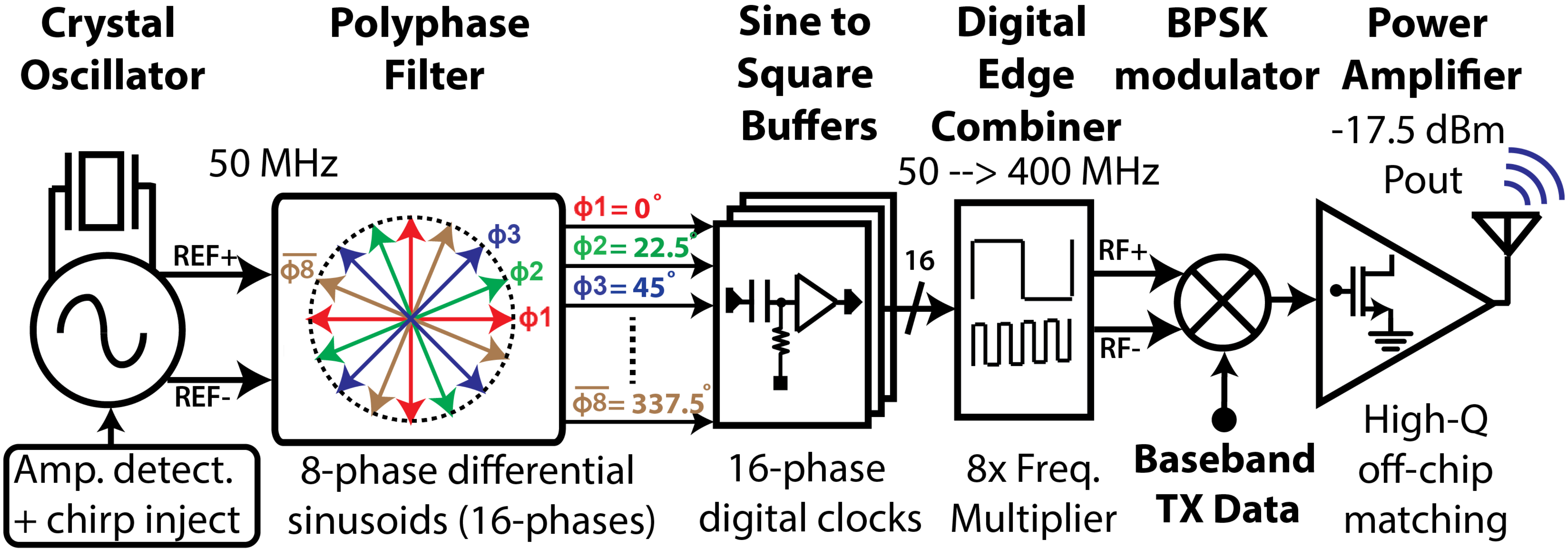




$$\Delta\theta = \frac{\Delta RC}{2RC}$$

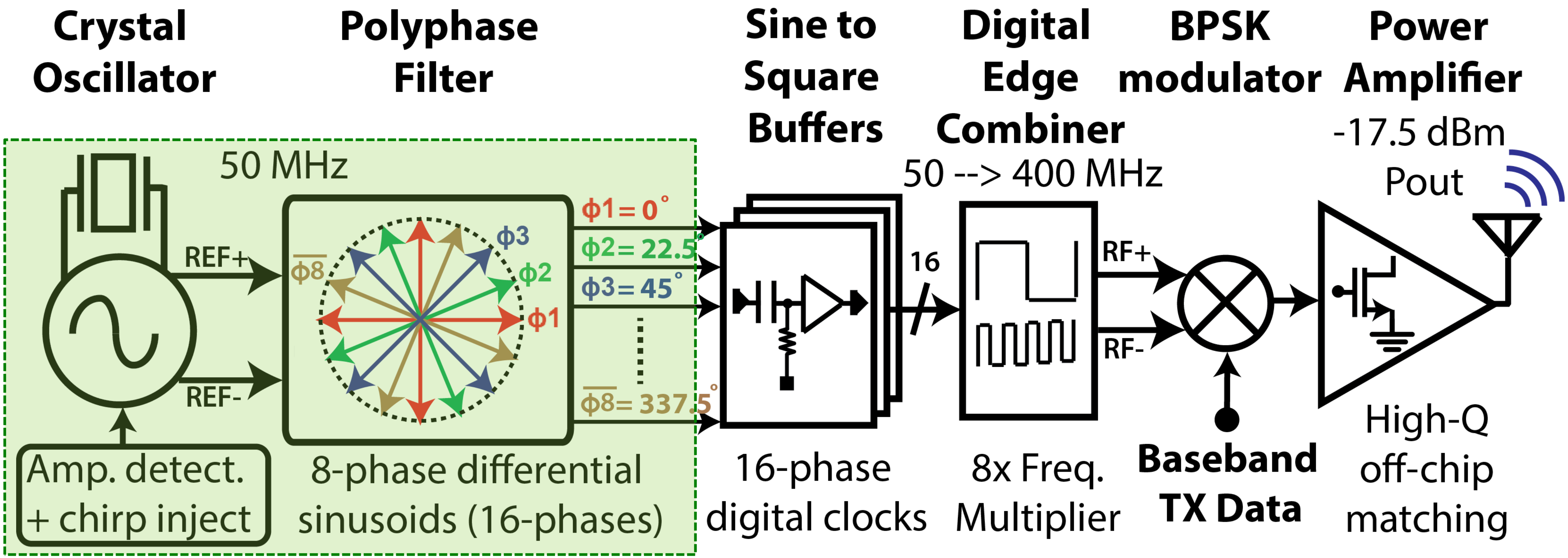
Each phasor shifted equally by $\Delta RC/2RC$ and attenuated

Proposed Short-Range Transmitter Overview



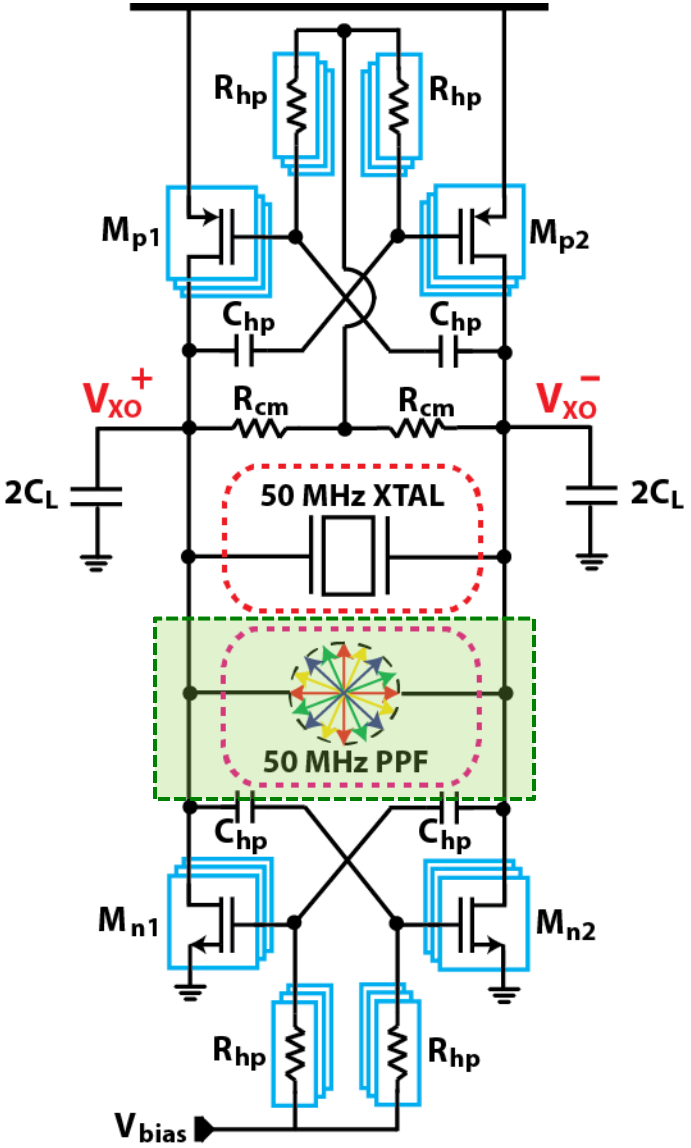
Ultra low-power, PLL-free, PVT-robust MedRadio Tx

Proposed Short-Range Transmitter Overview



Polyphase filter (PPF) integrated with crystal oscillator

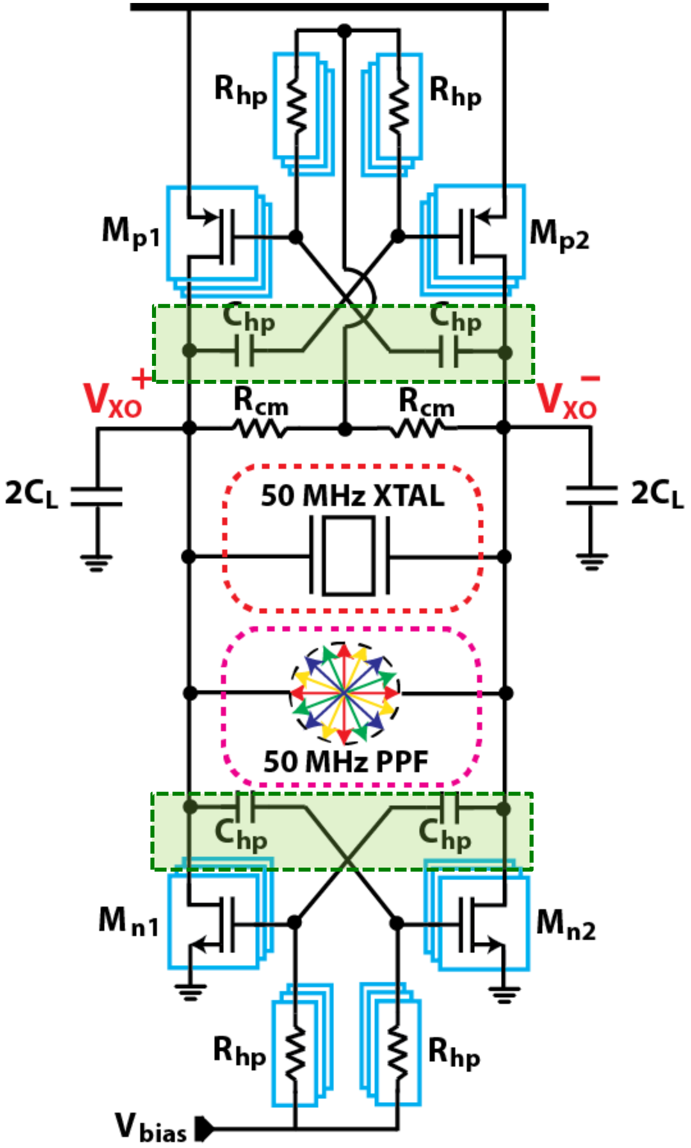
Circuit Implementation: Crystal Oscillator



- PPF **integrated within** crystal oscillator
- [Nadeau ESSCIRC'17] reported PPF integrated with FBAR resonator for QPSK

No power overhead to drive the PPF!

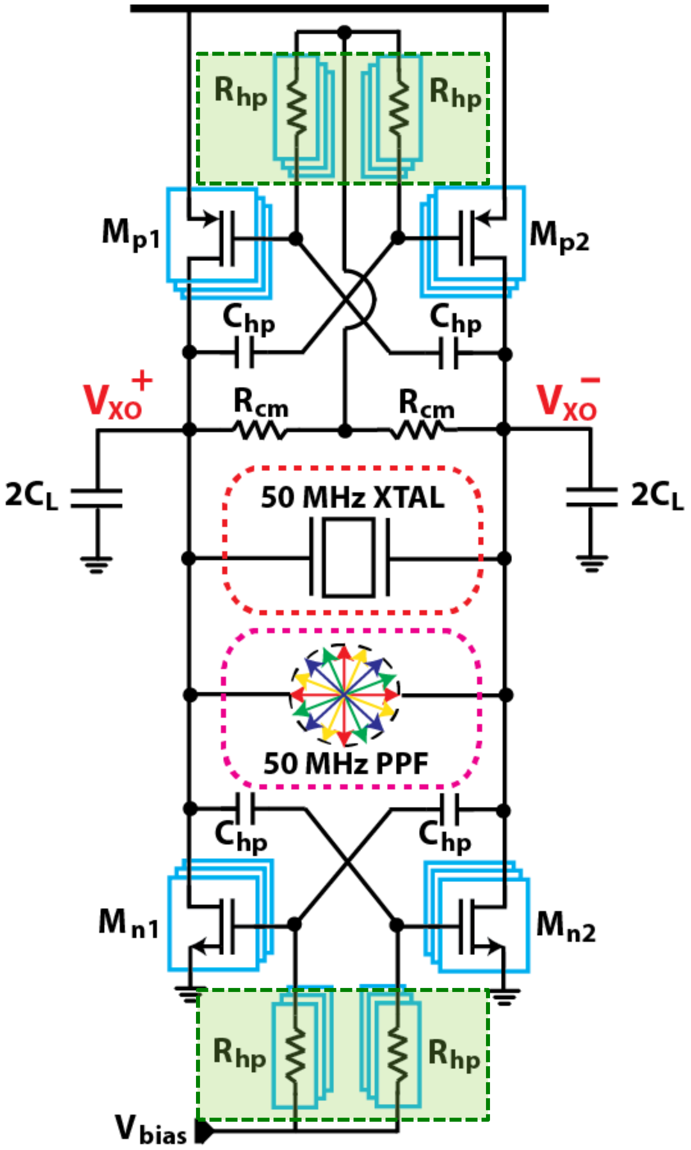
Circuit Implementation: Crystal Oscillator



- **ac-coupled cross-coupled g_m**

→ Avoid latch-up due to high-dc gain

Circuit Implementation: Crystal Oscillator



- **ac-coupled cross-coupled *g*$_m$**

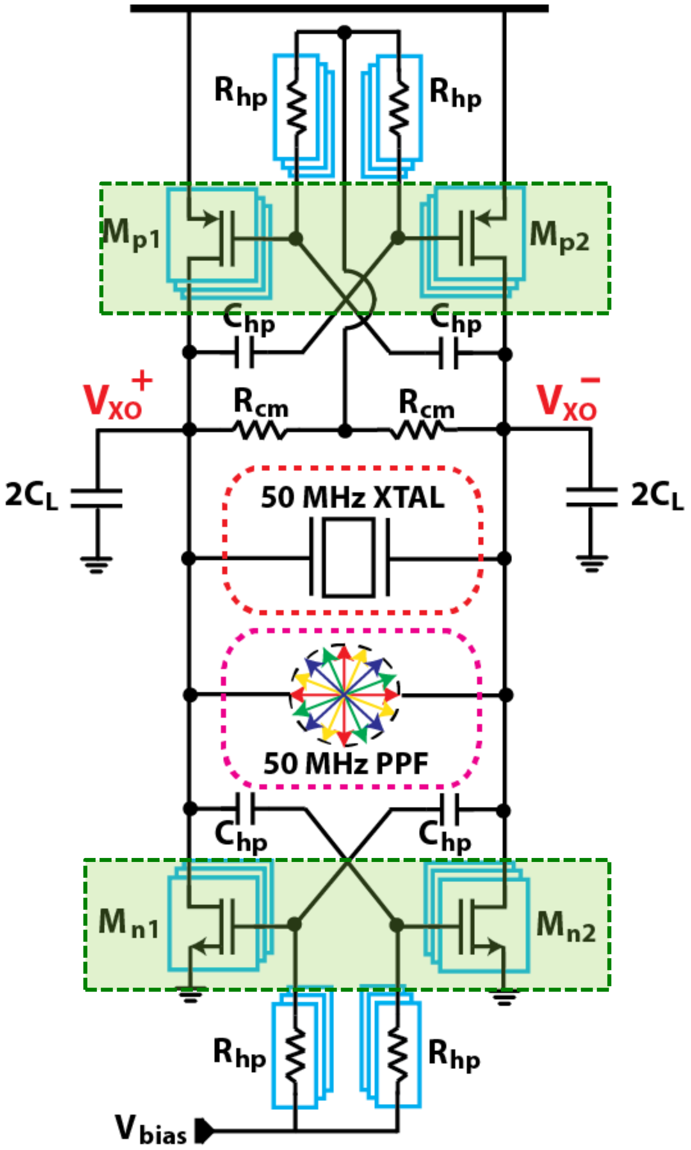
→ Avoid latch-up due to high-dc gain

- **Parasitic oscillation mode**

→ Due to negative capacitor

→ Resistive bias to damp these oscillations

Circuit Implementation: Crystal Oscillator



- **ac-coupled cross-coupled g_m**

→ Avoid latch-up due to high-dc gain

- **Parasitic oscillation mode**

→ Due to negative capacitor

→ Resistive bias to damp these oscillations

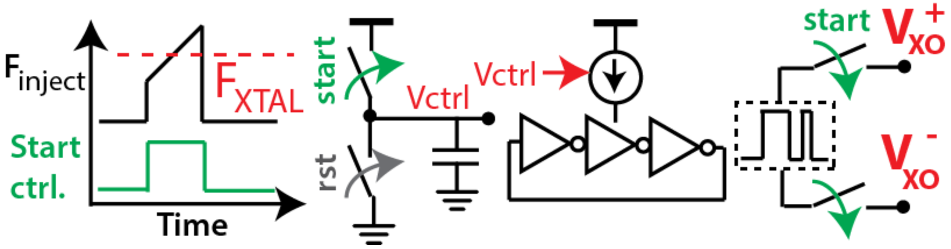
- **ac-coupled**

→ Allows complementary topology

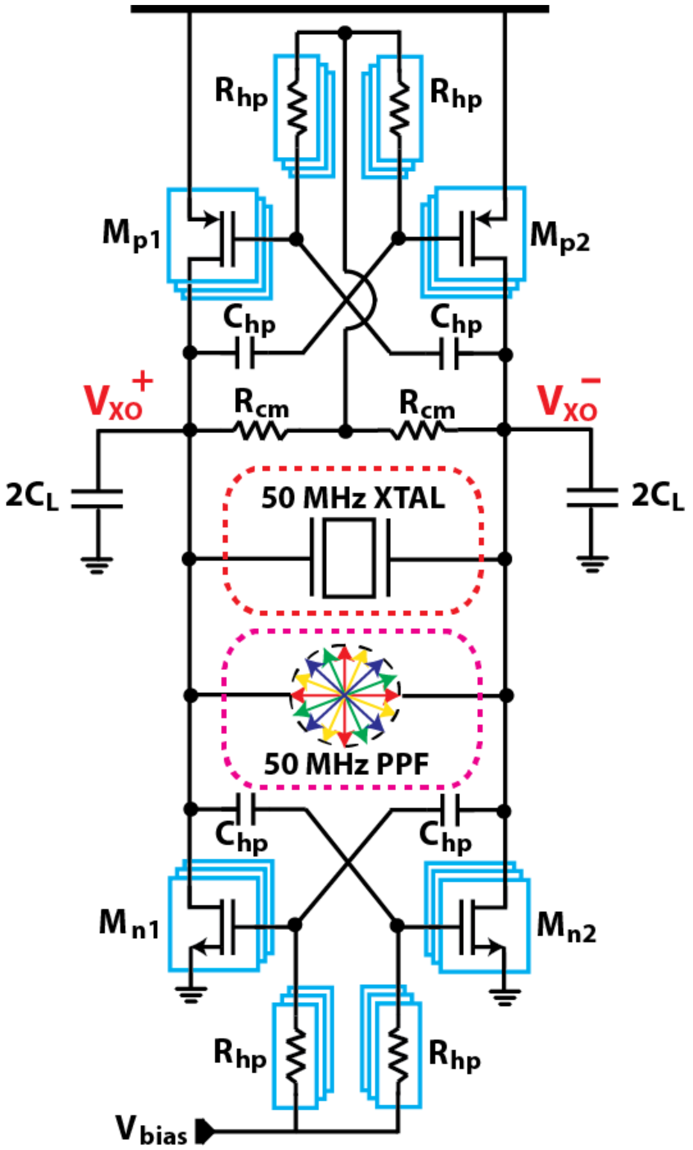
→ 2× g_m

Circuit Implementation: Crystal Oscillator

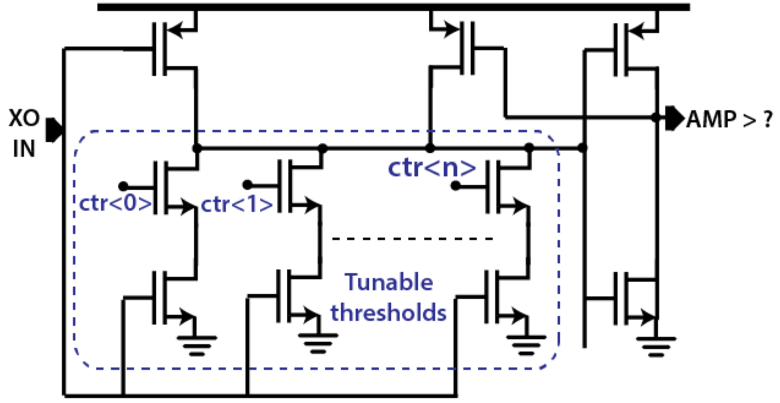
Chirp injector
→ fast start-up



- Frequencies around 50 MHz
- Swept using a ring voltage-controlled oscillator (VCO)



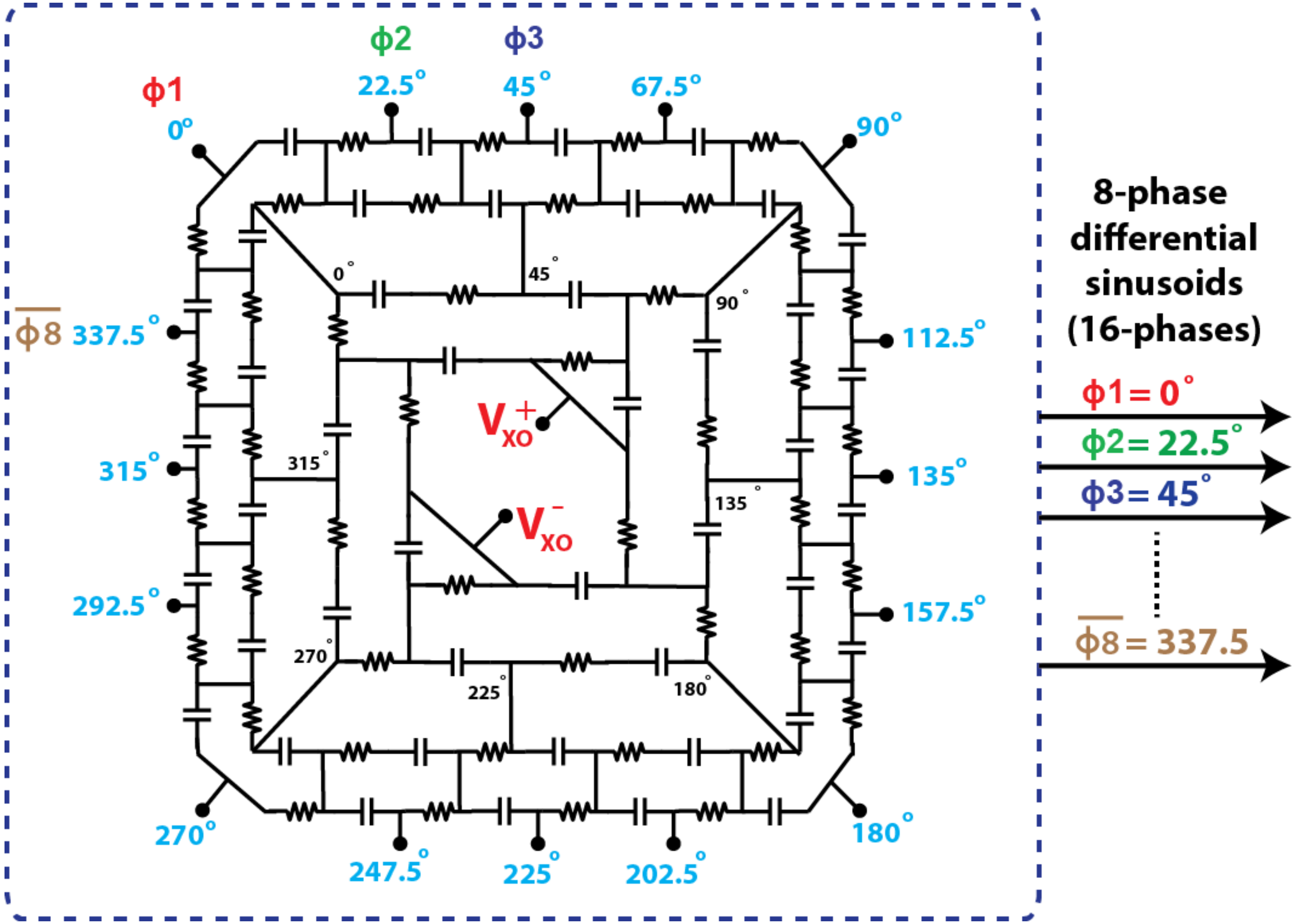
Amplitude control
→ lower power



- Schmitt-trigger based amplitude comparator
- Digitally programmable comparison thresholds

Circuit Implementation: Polyphase Filter

Passive RC Polyphase Filter (PPF):

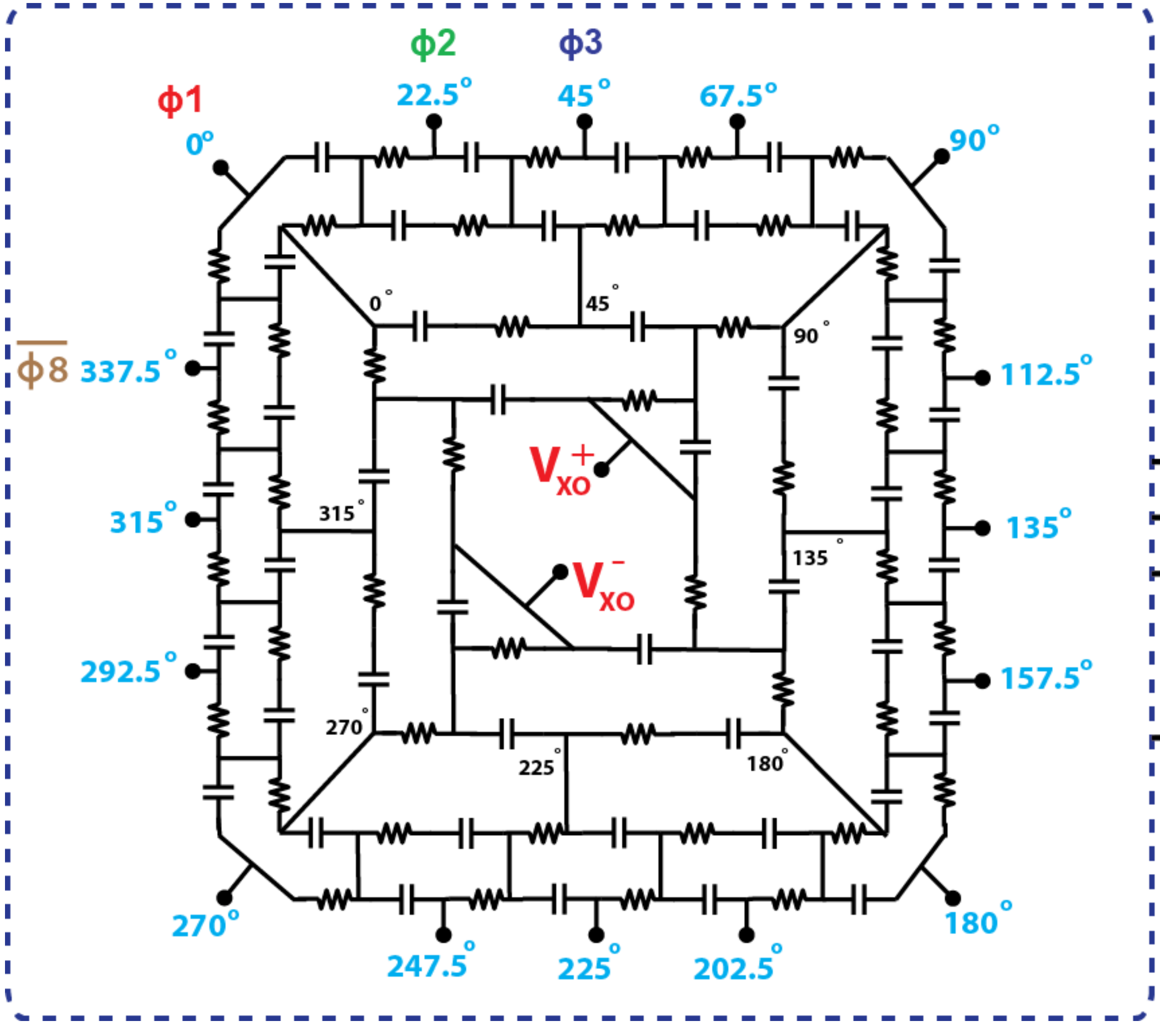


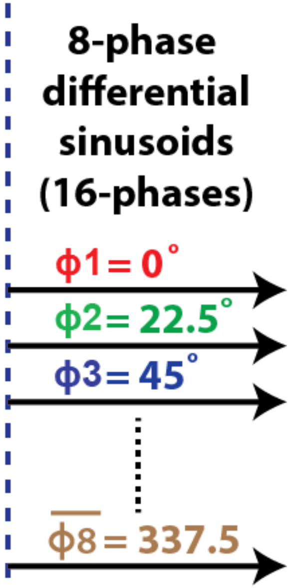
Polyphase sinusoids at 50 MHz:

- ✓ No frequency error
- ✓ No voltage dependence
- ✓ Robust to PT variations

Circuit Implementation: Polyphase Filter

Passive RC Polyphase Filter (PPF):





- **Three inner rings**

→ 16-phase generation

- **Fourth balanced ring**

→ phase averaging and maintaining symmetry with loaded outputs

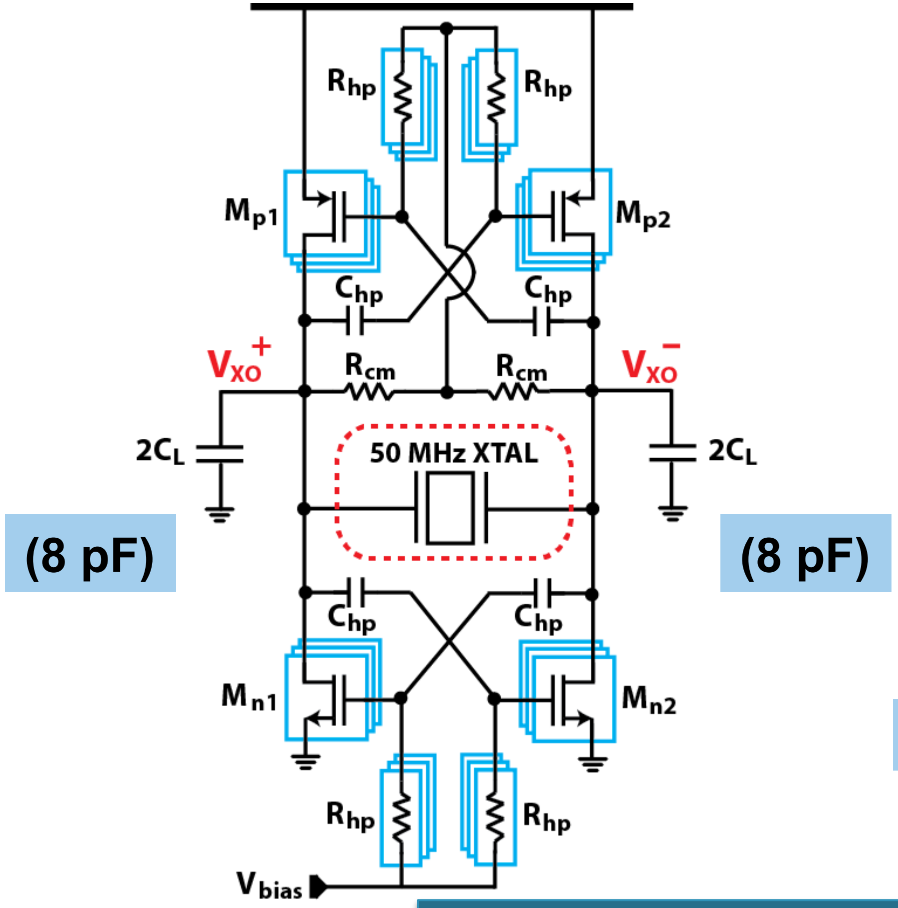
- **Mismatch, systematic imbalances**

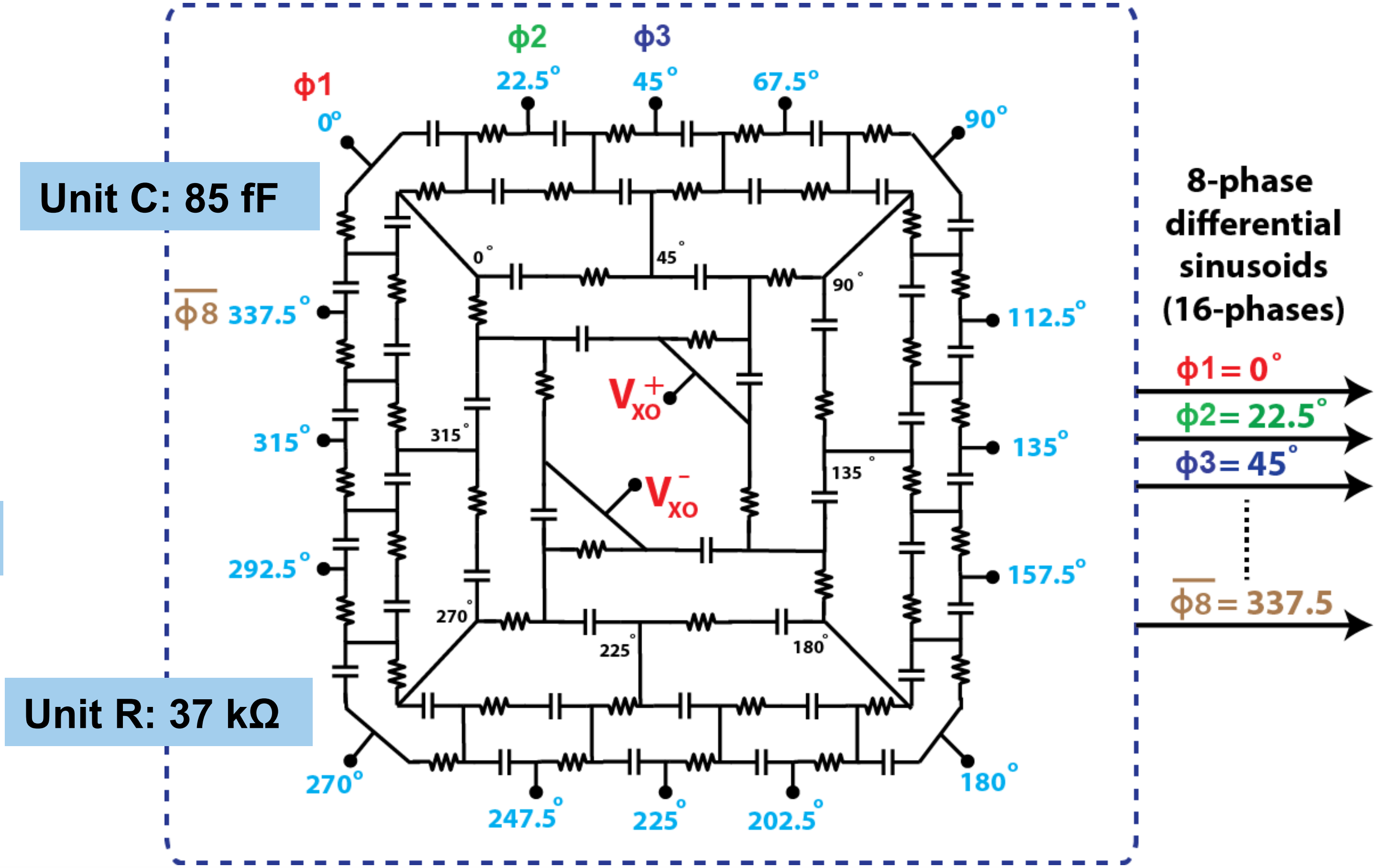
→ small spurs @ multiples of 50 MHz

→ good carrier to spur ratio (CSR) due to harmonic suppression by PA

Circuit Implementation: Polyphase Filter

Integrated PPF with Crystal Oscillator

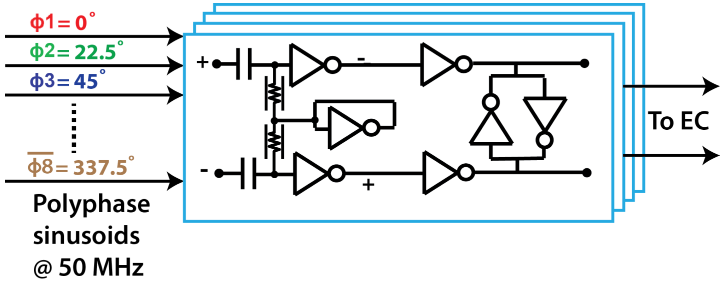




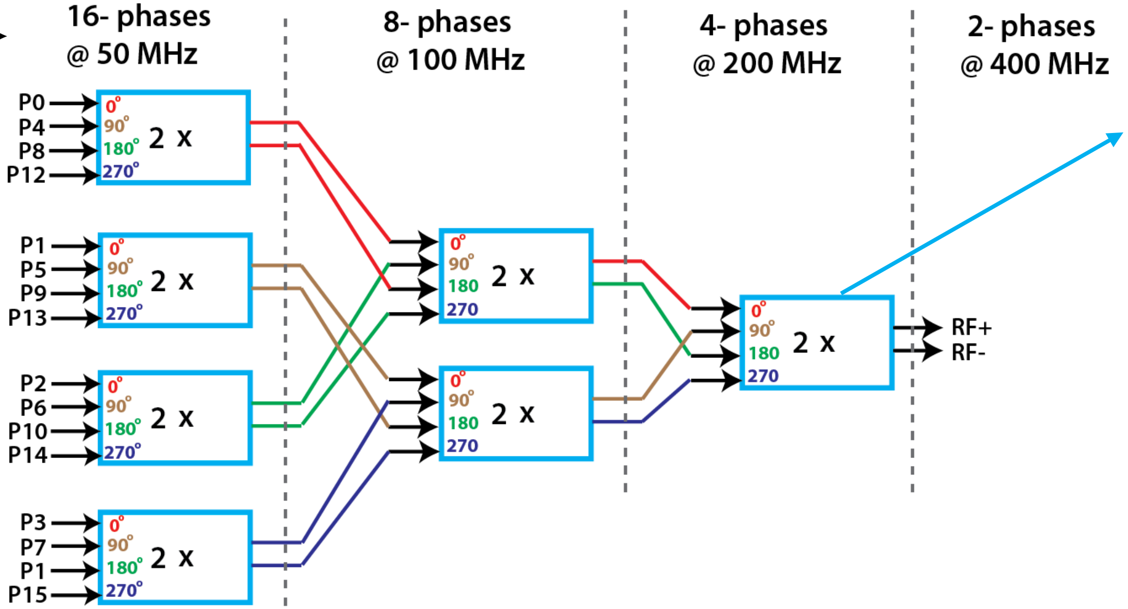
- PPF loads the crystal oscillator negligibly
- No power overhead for driving the PPF

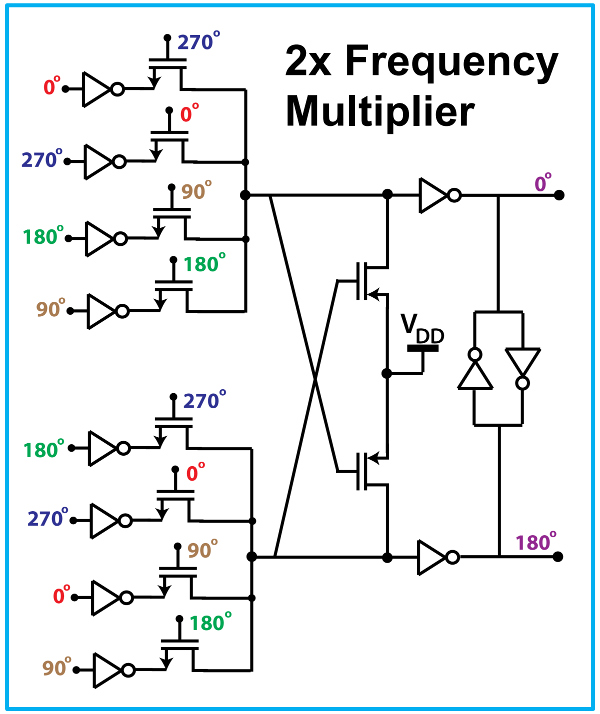
Circuit Implementation: Edge Combiner

PPF output buffer

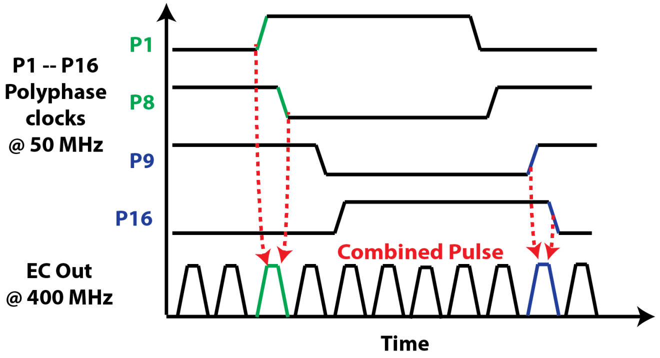


Digital Edge Combiner





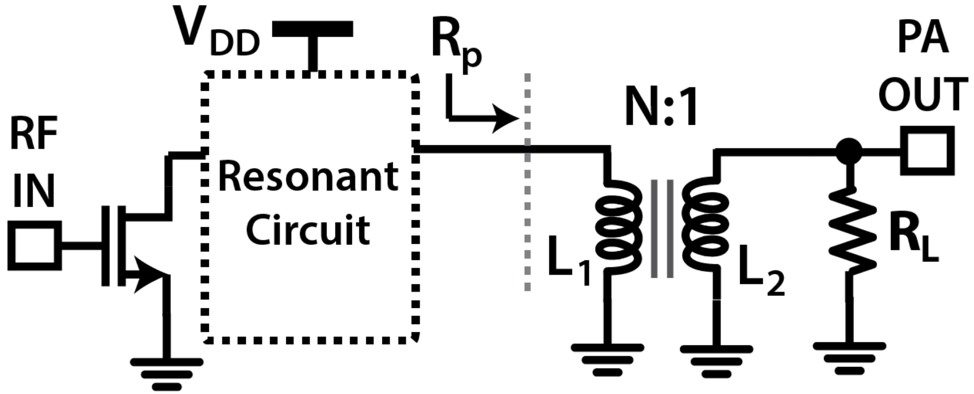
Edge Combining Transient:



Low power digital circuits for 8× frequency multiplication

Circuit Implementation: Power Amplifier

A Generic PA:



$P_{\mathrm{out}} \propto V_{\mathrm{DD}}^2 / R_{\mathrm{p}}$

- **Conventional long-range PAs**

→ Require down-transformation of the 50 Ohm antenna
→ R_{p} is typically a few Ωs

- **Short-range PAs**

→ Require up-transformation of the 50 Om antenna
→ R_{p} is typically a few kΩs

- $R_{\mathrm{p}} = N R_{\mathrm{L}}$
- $N > 1$ → losses in impedance transformation network
  (as R_{p} comparable to the equivalent parallel parasitic R_{par} of the impedance transformation)

Losses in impedance transformation network limits short-range PA efficiency

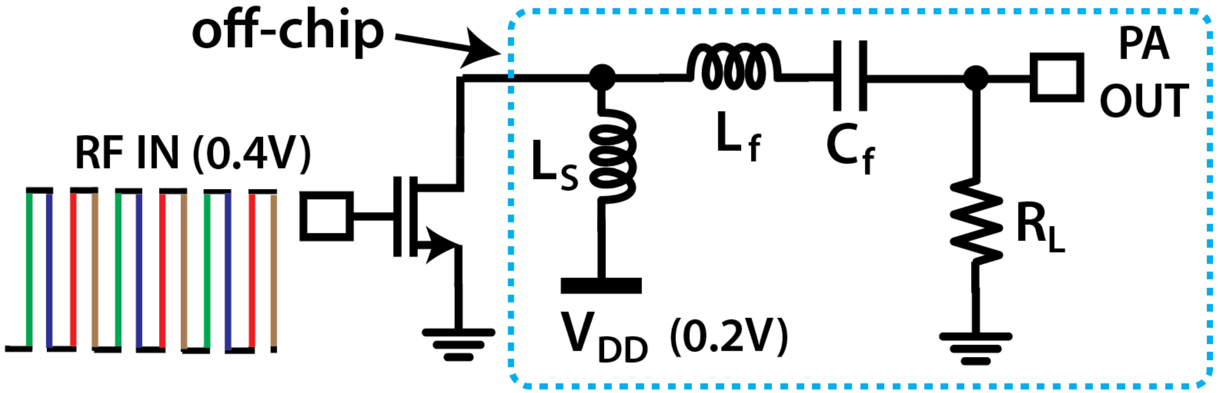
Circuit Implementation: Power Amplifier

Comparison of PA topologies

PA Type	Output power P_{out}	Theoretical Efficiency η_{max}
Digital PA [Pandey JSSC'11]	$0.5V_{DD}^2/R_p$	63%
Class-F	$0.63V_{DD}^2/R_p$	~100%
Class-E with shunt capacitor	$0.57V_{DD}^2/R_p$	~100%
Class-E with shunt inductor	$0.06V_{DD}^2/R_p$	~100%

- Conventional PAs intended to deliver high P_{out}
- **Low P_{out} readily delivered with class-E inverse** [Kazimierzuk JSSC'81]

Class-E inverse PA

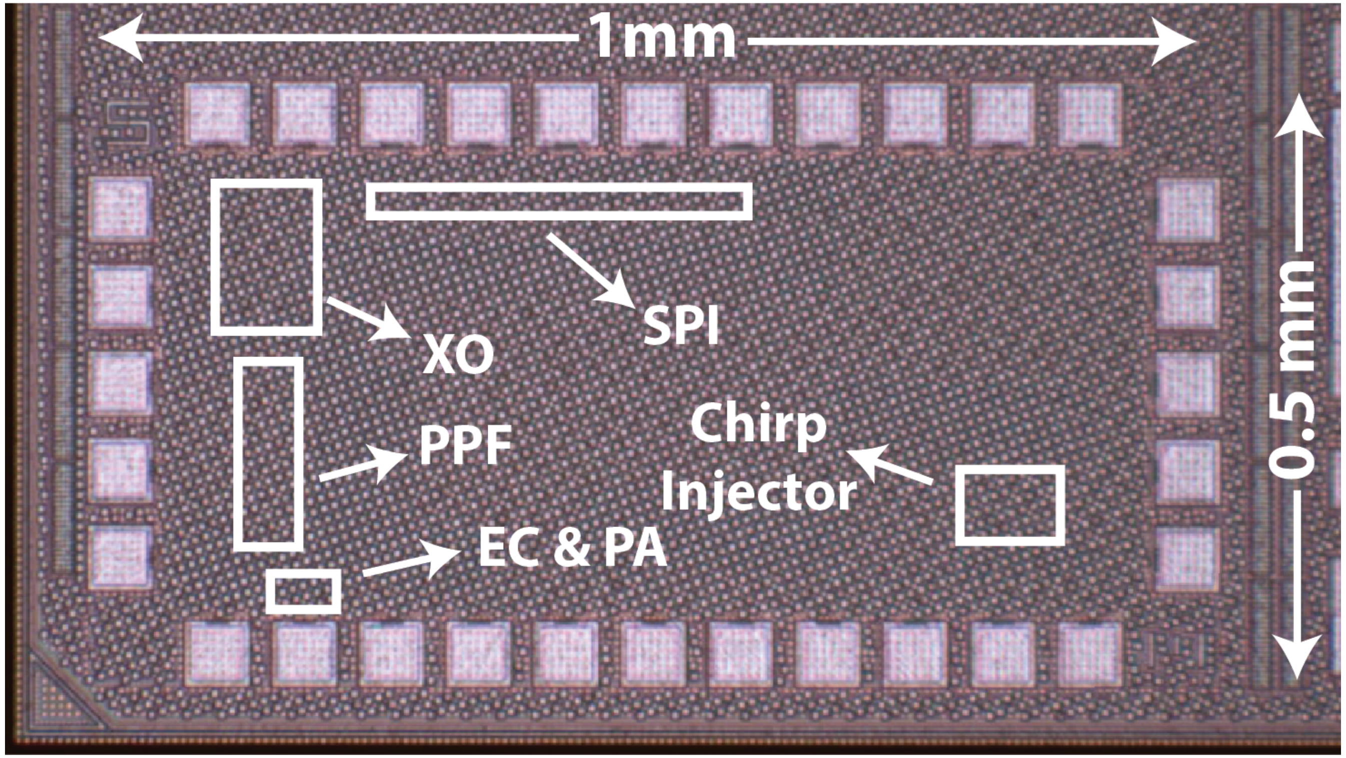


$$P_{out} = \frac{8}{\pi^2(\pi^2+4)} V_{DD}^2/R_p = 0.058\, V_{DD}^2/R_P$$

✓ Low 0.2V V_{DD}
✓ No impedance transformation network

Class-E with shunt inductor a good choice for short-range PAs

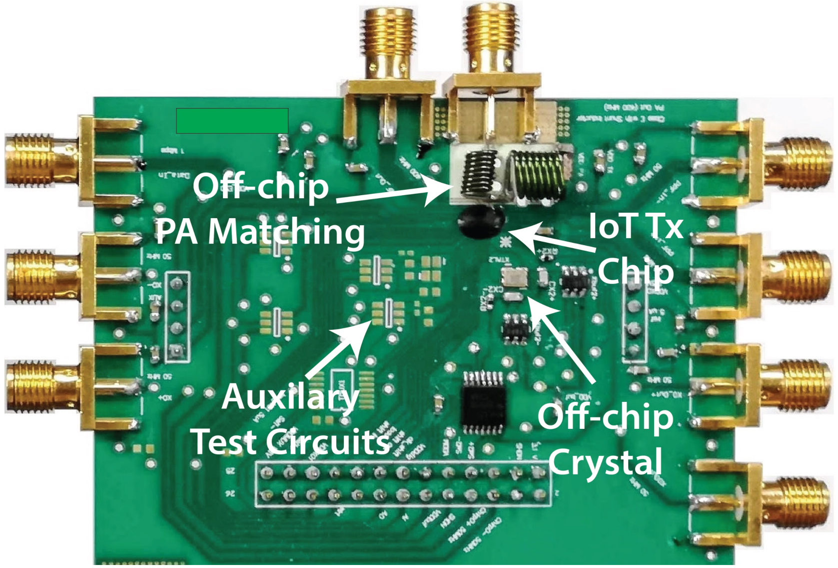
Chip Micrograph



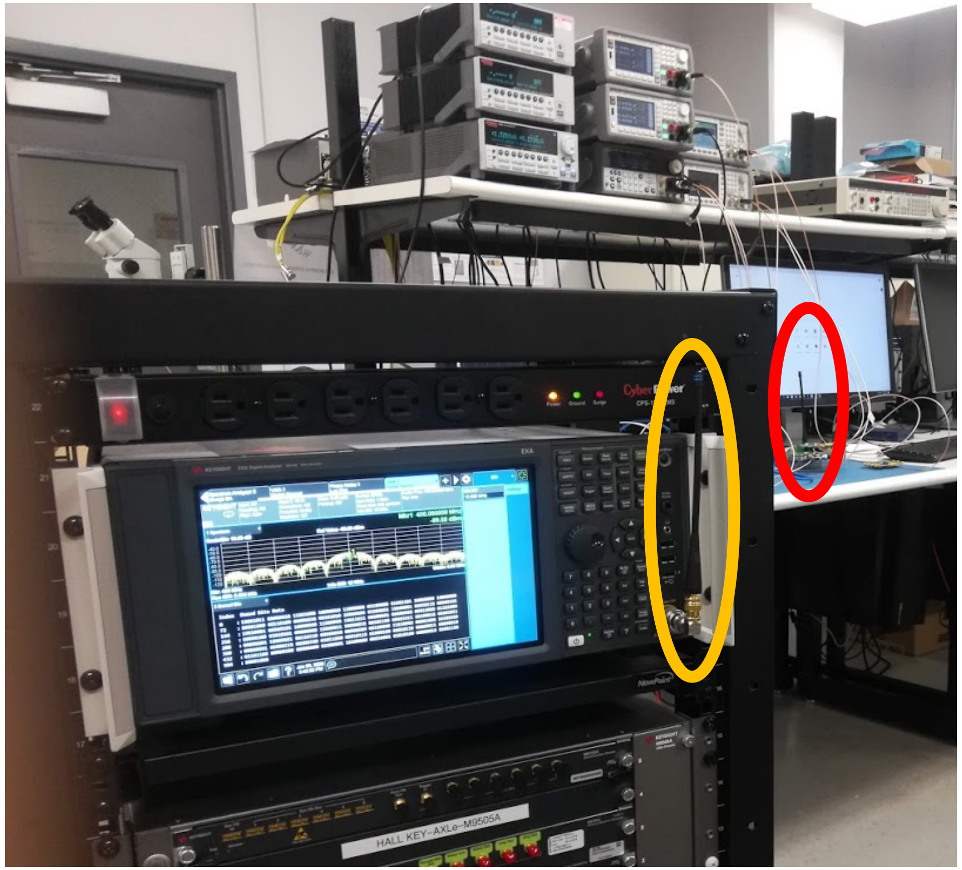
PPF occupies roughly same area as XO
→ 2× area overhead for PVT-robust operation

Ultra-low power transmitter in 22 nm CMOS FDX

PCB Photo and Measurement Setup

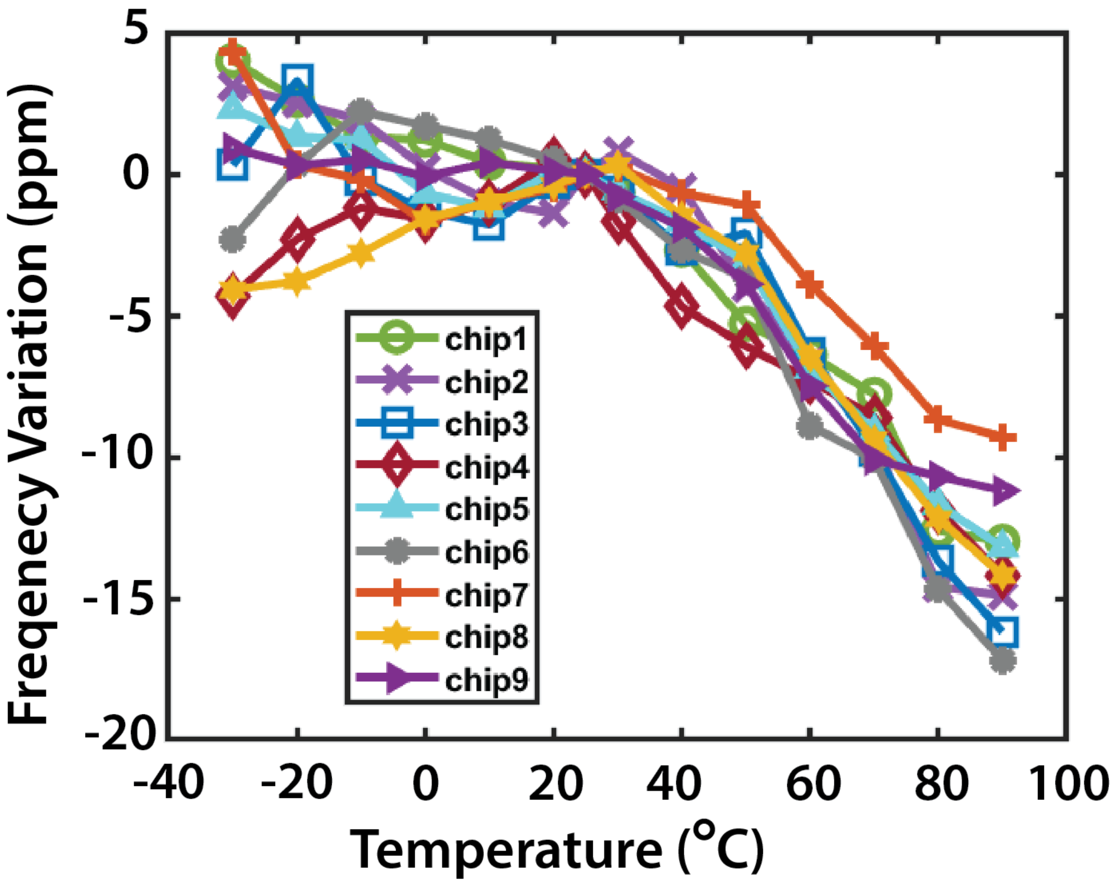


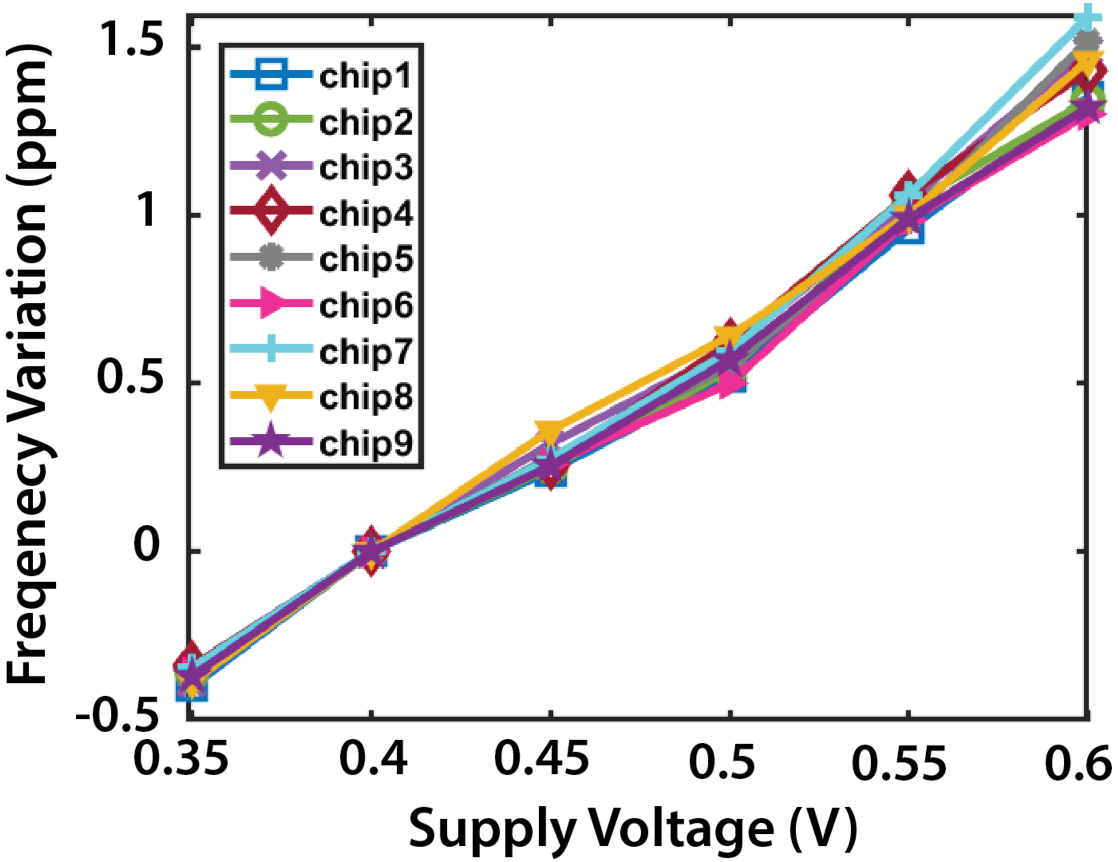
Off-chip crystal and inductors



Short-range communication ~ 1 meter

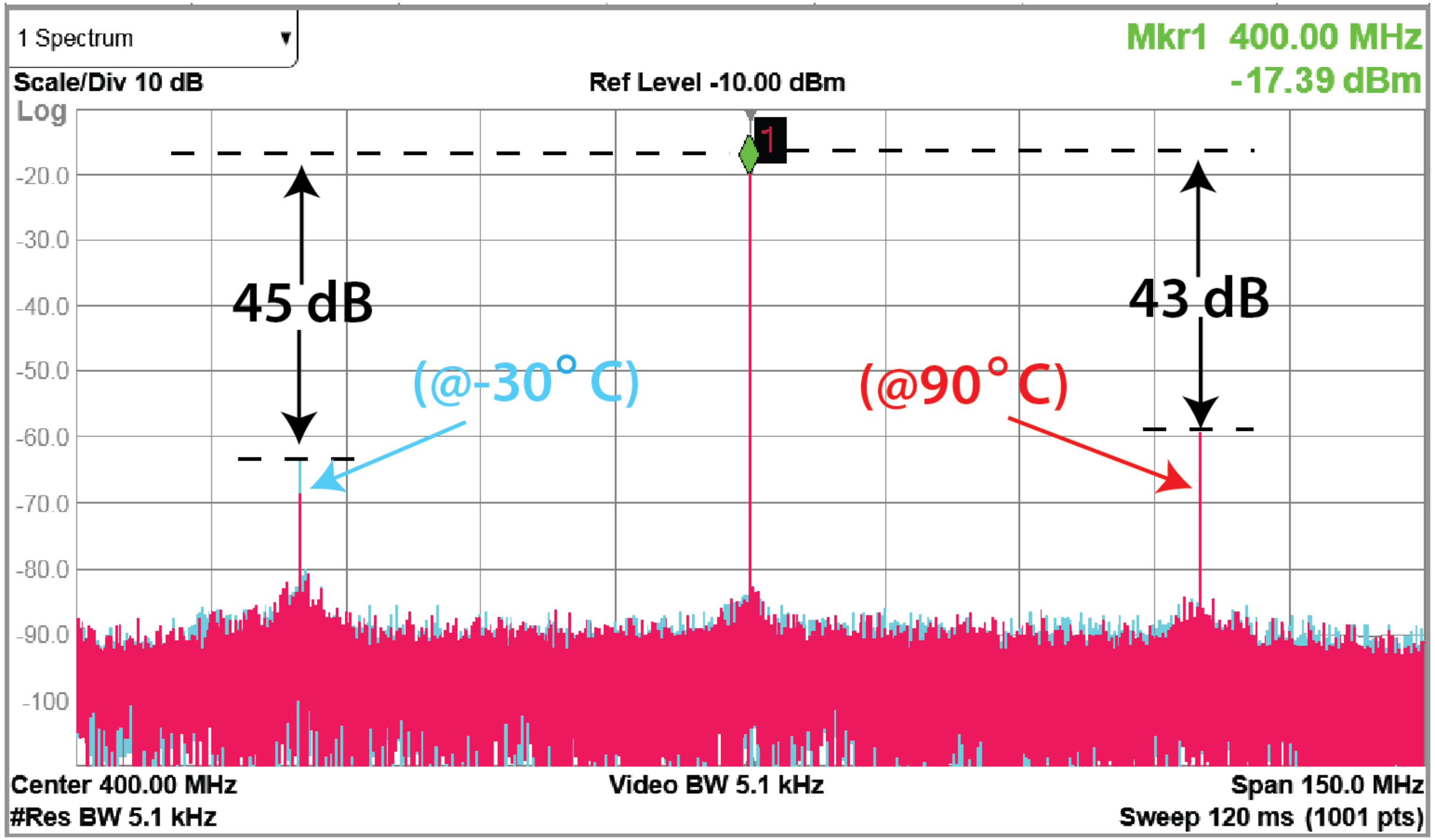
Measurement Results: Robustness to Temperature and Voltage Variations





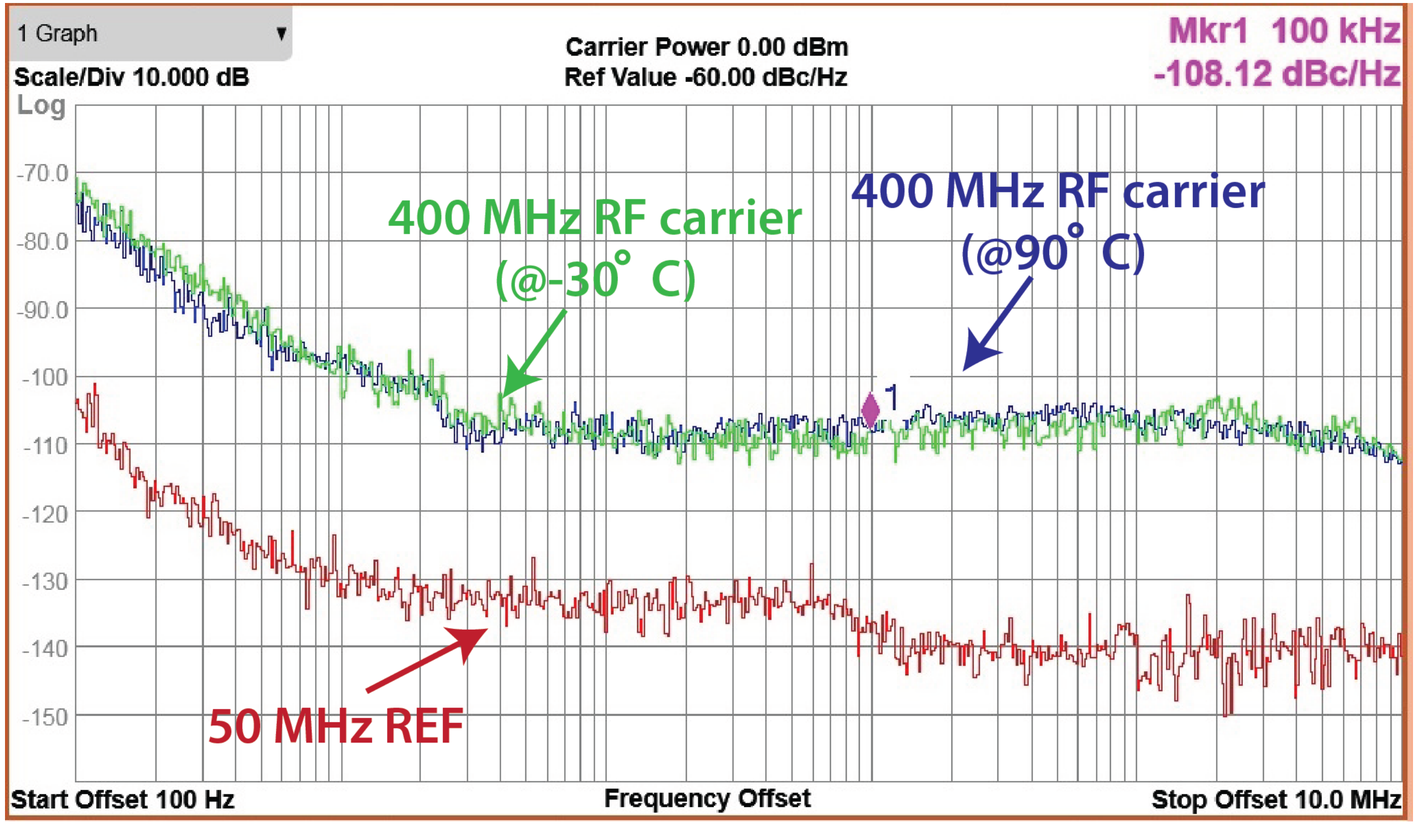
Temperature sensitivity < 25 ppm; Supply sensitivity < 2 ppm

Measurement Results: RF Carrier Spectra



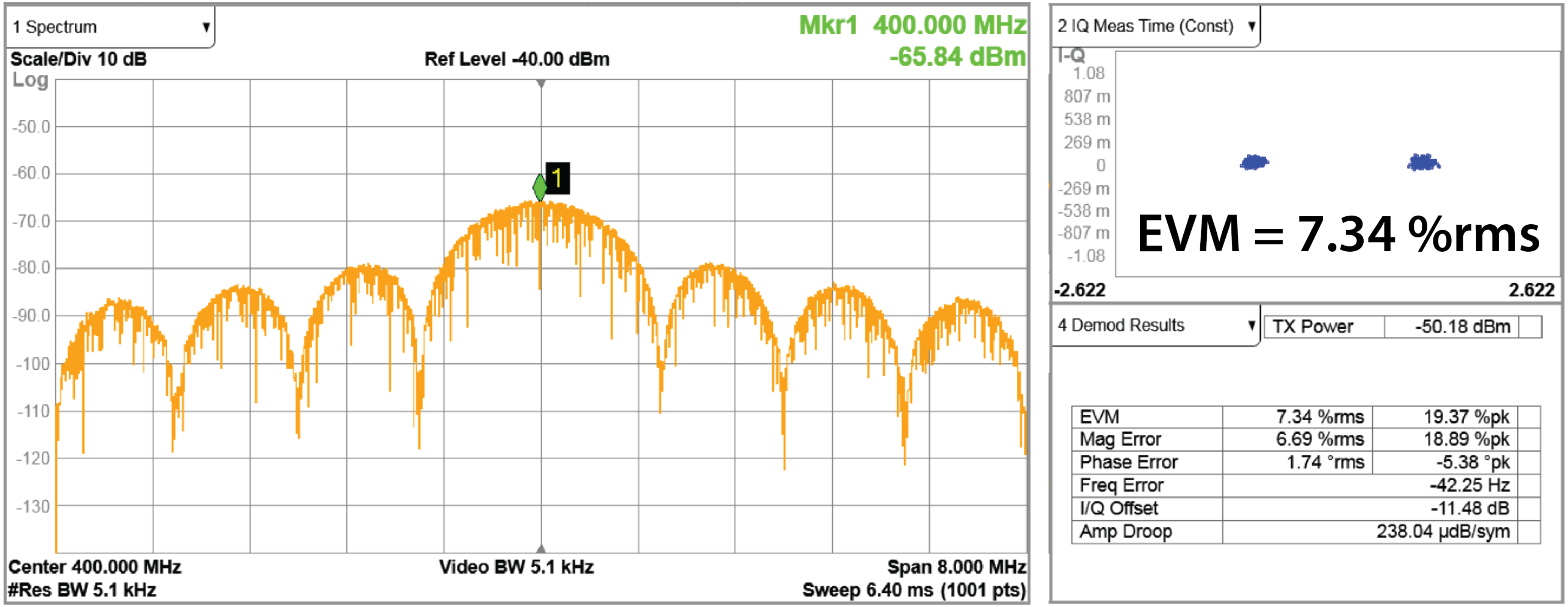
Carrier to spur ratio (CSR) > 40 dB across -30 to 90 °C

Measurement Results: Phase Noise



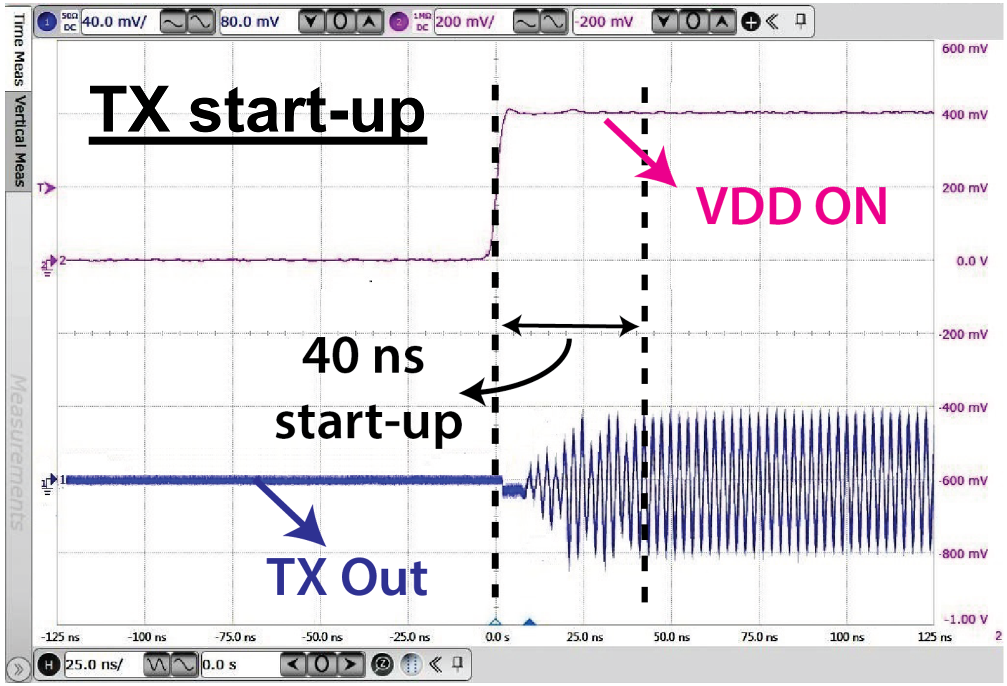
-110 dBc/Hz @ 300 kHz across temperature

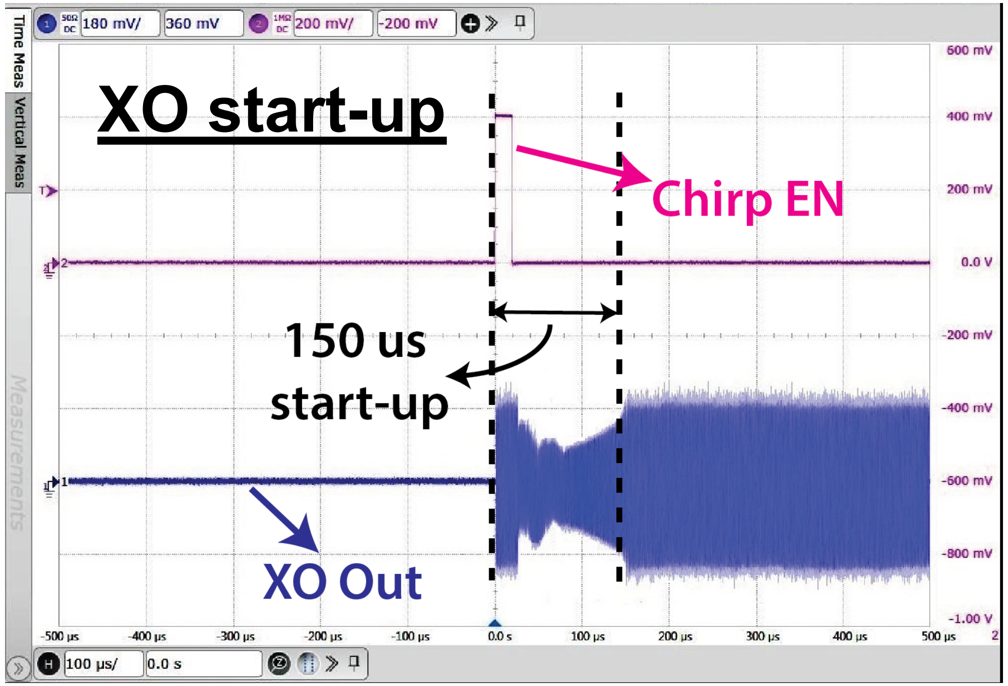
Measurement Results: Received Spectra



BPSK modulated spectra at 1 Mbps received at 1-meter distance from the transmitter

Measurement Results: Start-up Transients



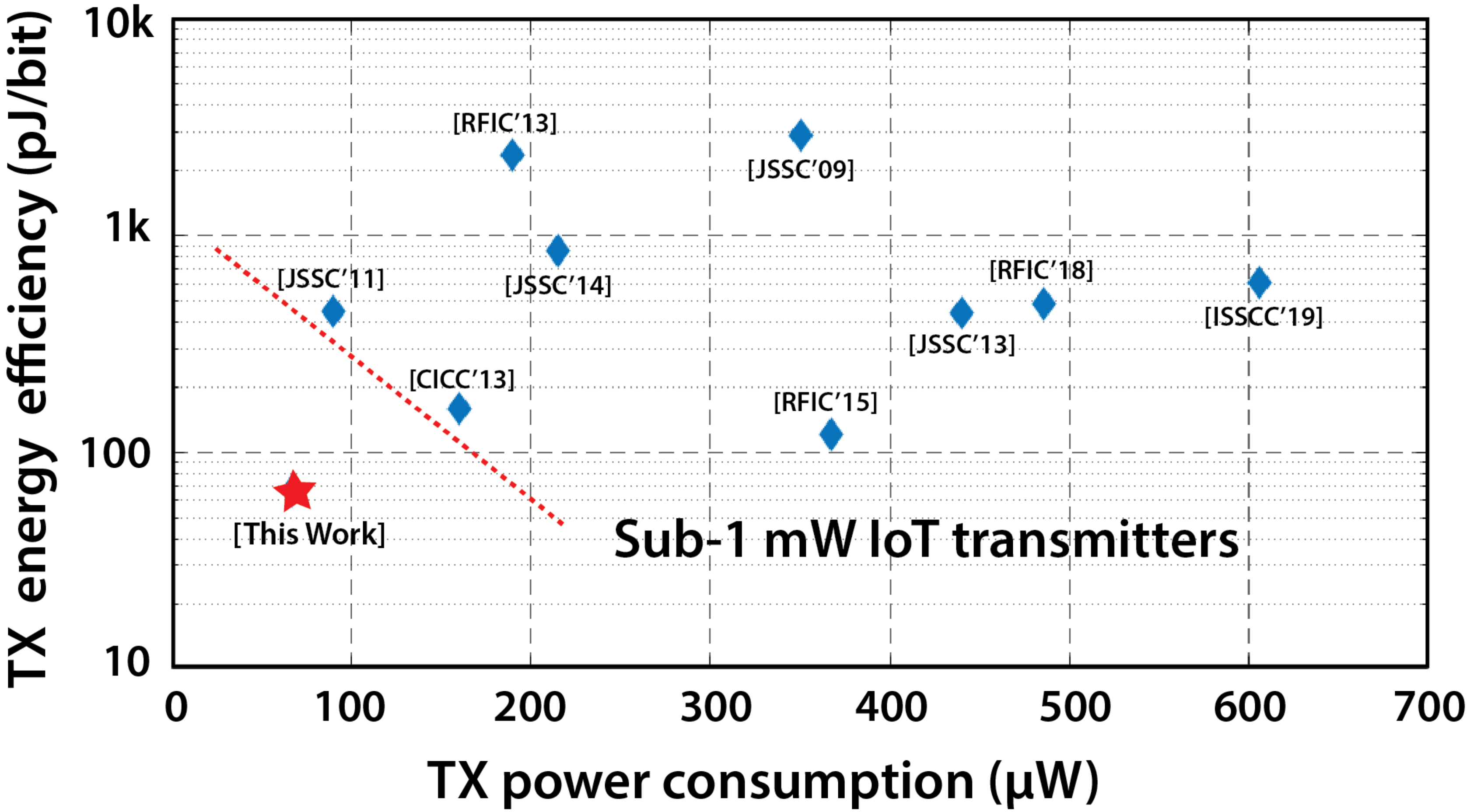


Fast Start-up ~ 40 ns; aggressive duty-cycling

Comparison to the State-of-the-Art

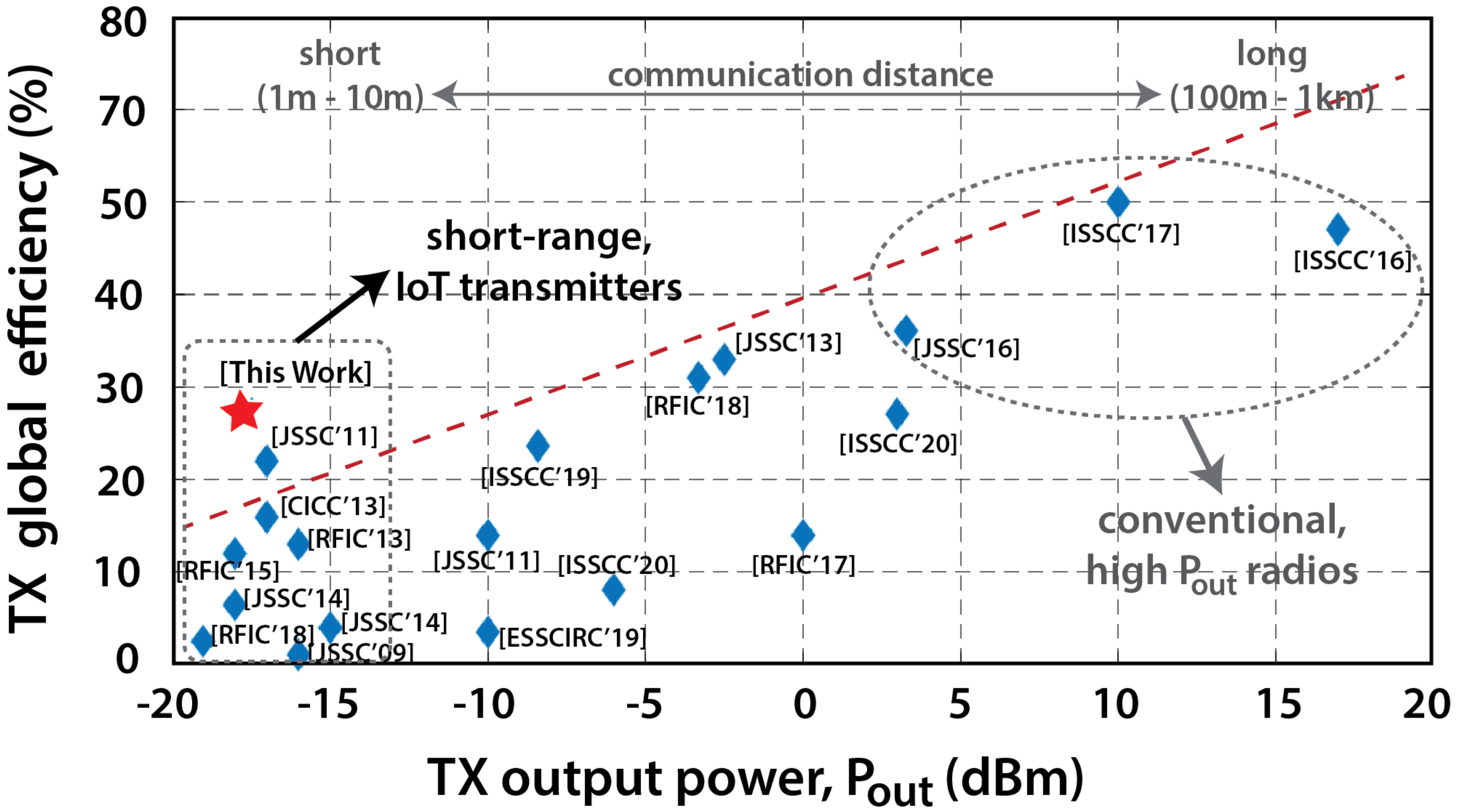
	JSSC'11	TBioCAS'13	RFIC'13	JSSC'14	RFIC'15	ISSCC'19	This work
Supply (V)	0.7	0.6	0.7/1.2	0.8	1.2	1.2	**0.4/0.2**
Technology (nm)	90	130	65	65	90	65	**22 FDX**
Active Area (mm^2)	0.04	0.06	0.41	0.08	0.29	0.49	**0.03**
Frequency (MHz)	400	400	400	900	915	2400	**400**
	Frequency Synthesizer						
Phase Noise (dBc/Hz)	-105.2 (@0.3 MHz)	-87.9 (@0.3 MHz)	-69 (@0.1 MHz)	-100 (@1 MHz)	-100.2 (@1 MHz)	-118 (@1 MHz)	**-109 (@0.1 MHz)**
Power (µW)	<78	-	72	538	224	-	**10**
Freq. Multiplier	9×	25×	25×	9×	60×	1×	**8×**
CSR (dB)	44	-	-	56	-	-	**45**
	Power Amplifier						
P_{out} (dBm)	-17	-17	-16	-15	-18	-8.4	**-17.5**
PA Efficiency (%)	30	-	33	9	12.5	-	**40**
Power (µW)	63	-	80	351	110	-	**44**
	Crystal Oscillator/Reference						
Frequency (MHz)	45	16	16	100	16	16	**50**
Power (µW)	<12	External	External	External	32	External	**13**
	Transmitter						
Topology	ILRO+EC-PA	2-step ILRO	PLL+PA	ILRO+PA	PLL+PA	PO.+PLL calib.	**XO-PPF+EC+PA**
Modulation	BFSK	OOK	BFSK	QPSK	OOK	GFSK	**BPSK**
Data-rate (kbps)	200	1000	80	100,000	3,000	1000	**1000**
Energy/bit (pJ/bit)	450	160	2375	13	124	606	**67**
Settling Time (ns)	250	250	-	88	-	-	**40 / 150 µs(w XO)**
PVT-robust?	P× V× T×	P✓ V× T×	P✓ V✓ T✓	P✓ V× T×	P✓ V✓ T✓	P✓ V✓ T✓	**P✓ V✓ T✓**
Calibration reqd.?	✓	✓	×	✓	×	×	×
Total Power (µW)	90	160	190	1300	374	606	**67**
Global Efficiency%	22	16	13	4	12	24	**27**

Comparison Landscape



Best energy-efficiency (67 pJ/bit) and lowest power among sub-1mW transmitters

Comparison Landscape



Highest TX global efficiency of 27 % among short-range radios in addition to PVT-robustness

Conclusions

PVT-robust Frequency Synthesis

A 67 μW, 27% GE MedRadio Transmitter

- ✓ Calibration-free
- ✓ Regulation-free
- ✓ Best-reported low power of 67 μW and global efficiency of 27% for short-range narrowband transmitters was achieved.

Future Work

- ✓ Integration with FBAR for higher frequencies *e.g.,* 2.4 GHz BLE
- ✓ Can, in theory, replace ILCMs with small frequency multiplication factor for several other applications *e.g.,* mm-wave frequency synthesis

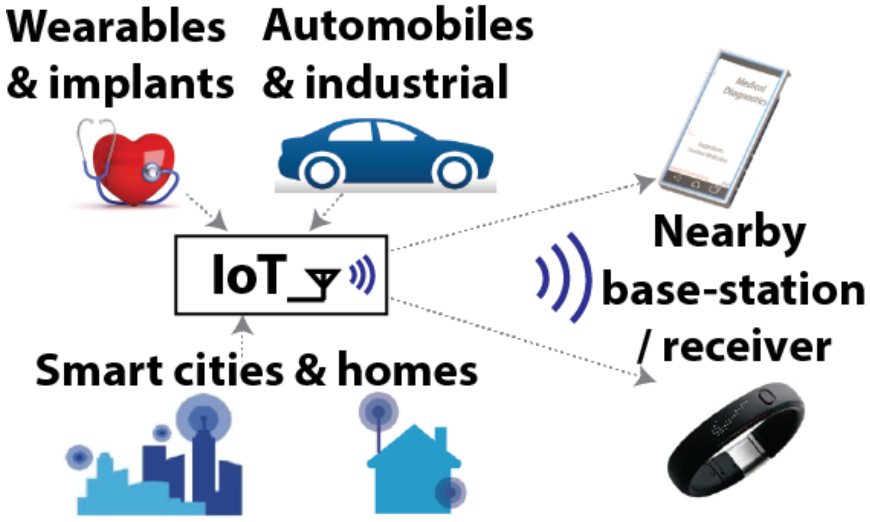
Acknowledgements

- Dr. Li Gao, Corentin Pochet and Prof. Peter Asbeck for technical help
- Global Foundries for chip fabrication

Backup Slides

The Internet of Things

- Miniaturized sensor nodes



- Communication to a nearby data-aggregator (e.g., smartphone, smartwatch, etc.)

Ultra-Low Power Operation