A WiFi and Bluetooth Backscattering Combo Chip Featuring Beam Steering via a Fully-Reflective Phased-Controlled Multi-Antenna Termination Technique Enabling Operation over 56 Meters

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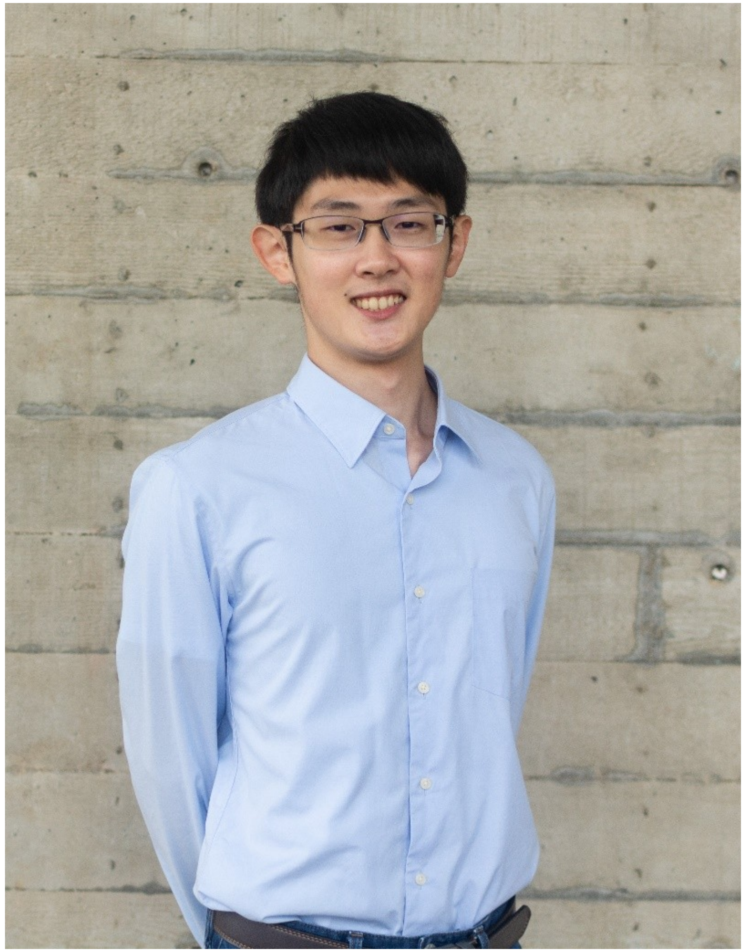
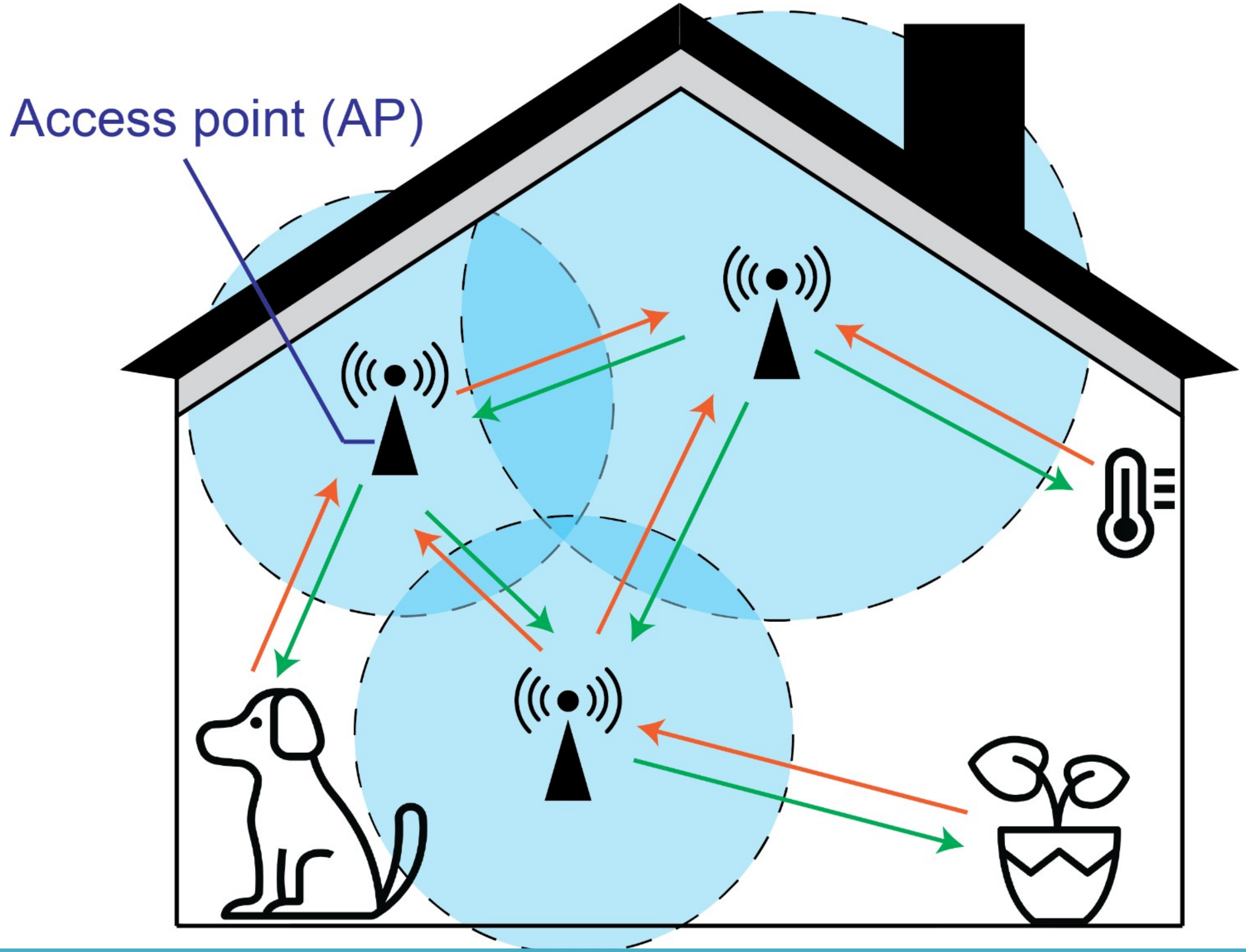
Self Introduction

- **B.S. degree in electrical engineering from National Taiwan University, Taipei, Taiwan, in 2019**
- **M.S. degree in electrical and computer engineering from the University of California at San Diego (UCSD), La Jolla, CA, USA, in 2021**
- **Currently Ph.D. student at UCSD**
- **Research interest: low power backscatter techniques, analog and RF IC design**



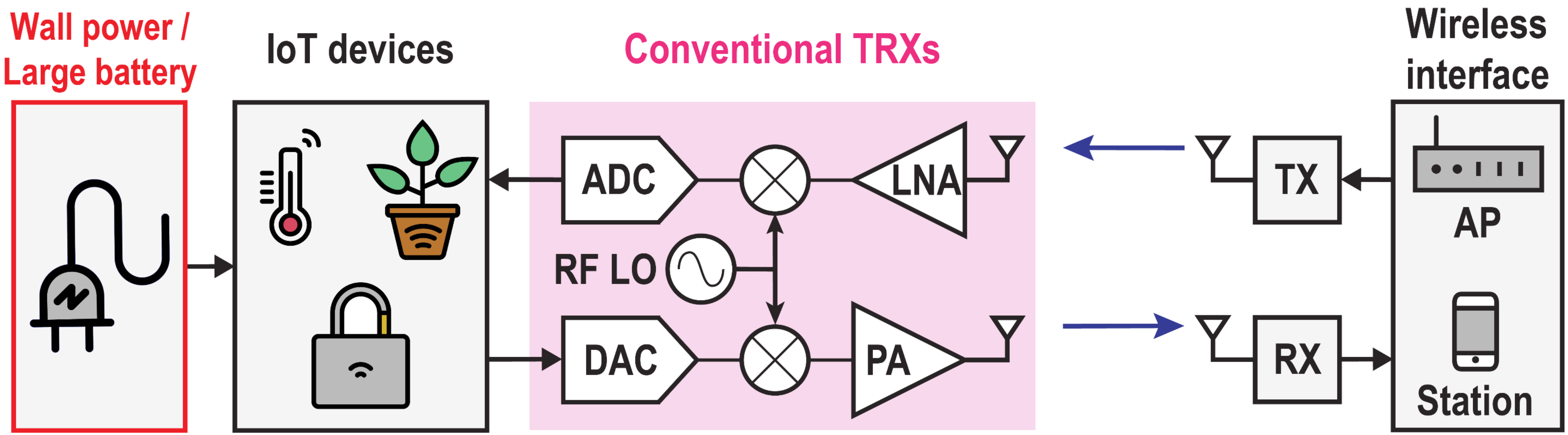
IoT devices in smart home/office



Existing commodity-compatible standard:
WiFi & BLE

How can small IoT devices leverage **existing WiFi/BLE mesh network** to communicate?

Method I: Conventional WiFi/BLE transceivers (TRXs)

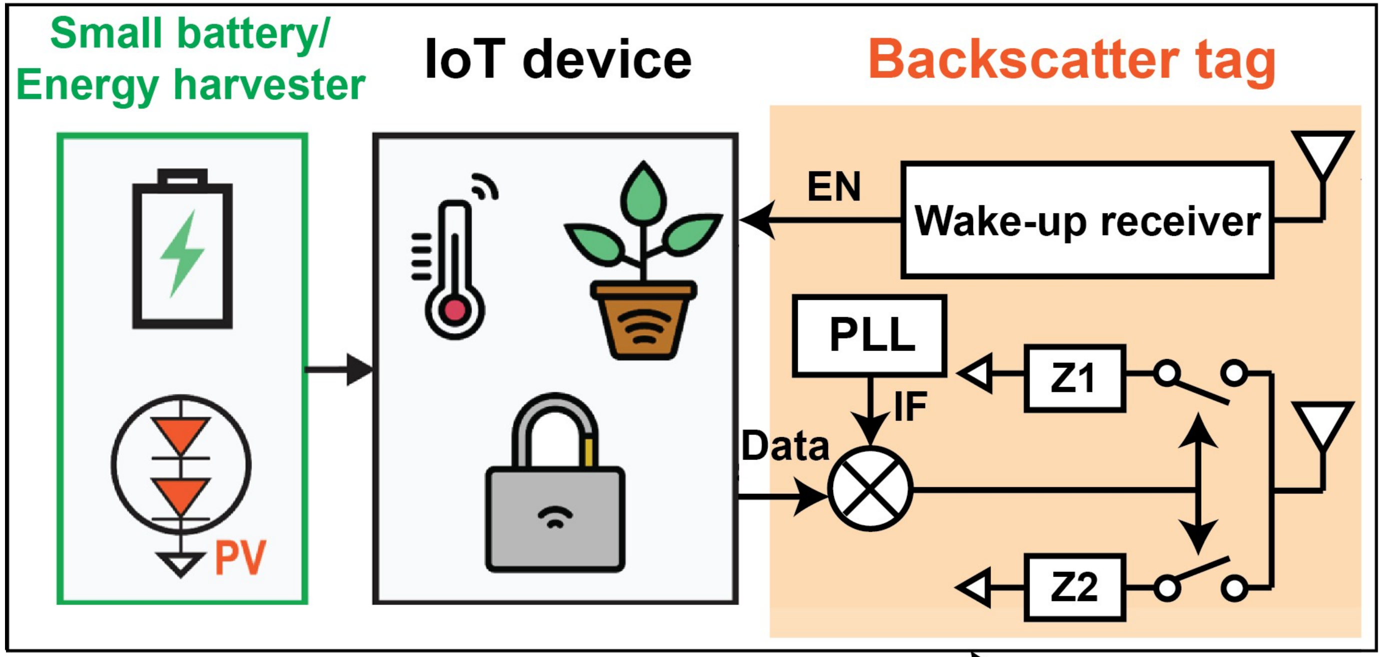


Robust communication with long range

But conventional TRXs require 10s~100s mW active power
⇒ Size and life of IoT devices are limited

Can we instead unlock a new way of ultra low power connection?

Method II: WiFi/BLE-compatible backscatter

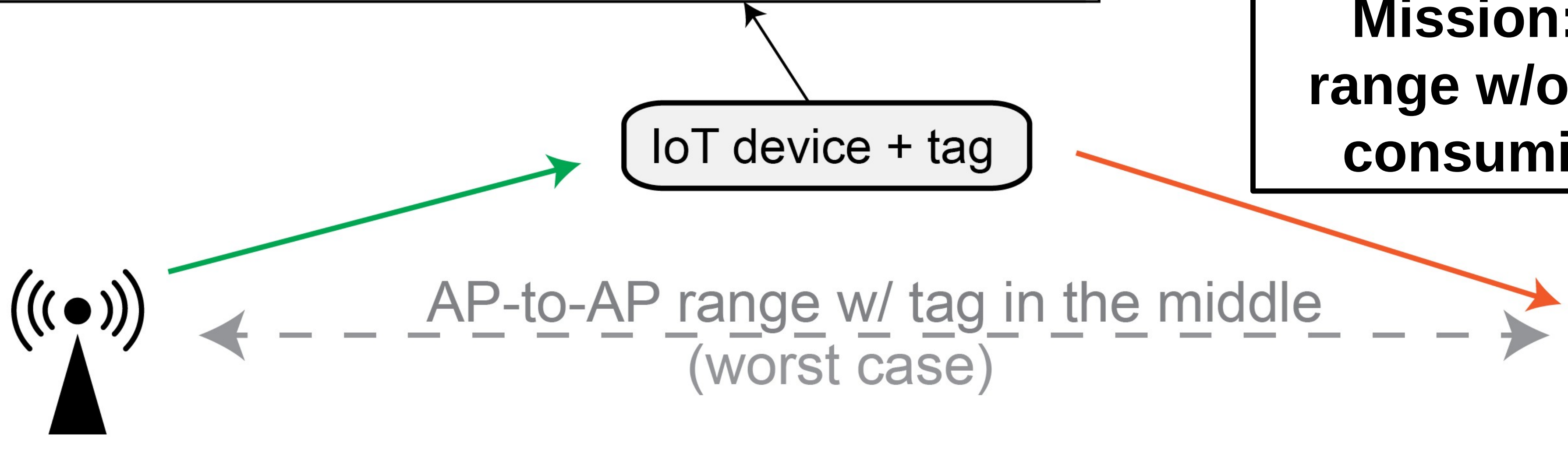


Elimination of active RF circuit enables low power consumption

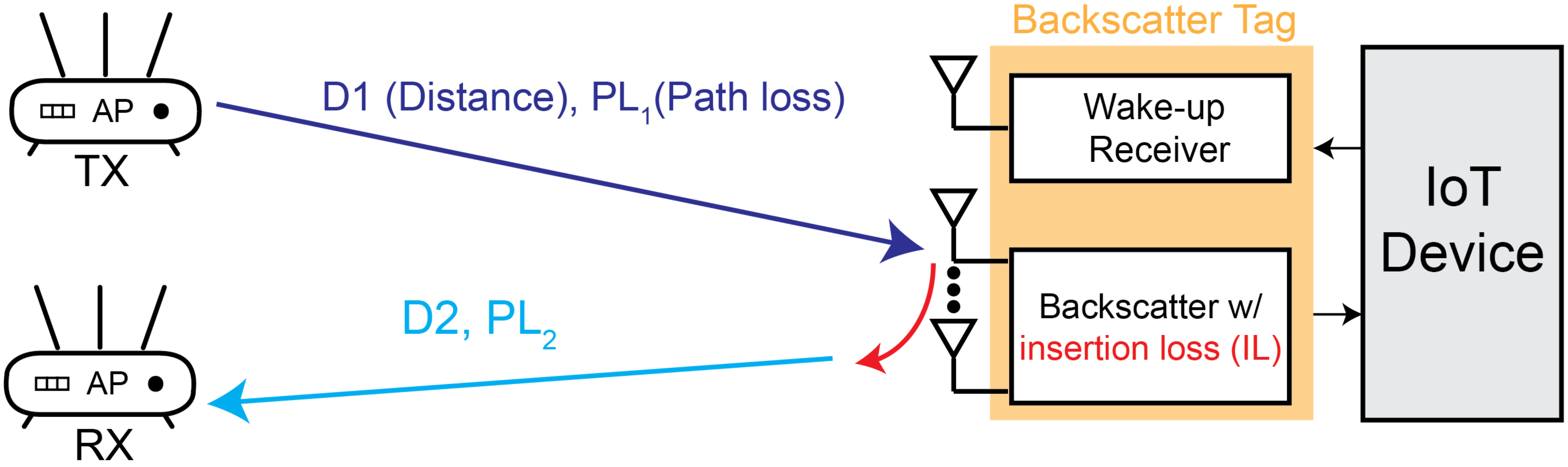
Range is limited due to passive nature

▭ More APs are required for robust communication

Mission: increase the range w/o extra AP while consuming low power



Backscatter link budget and range challenges



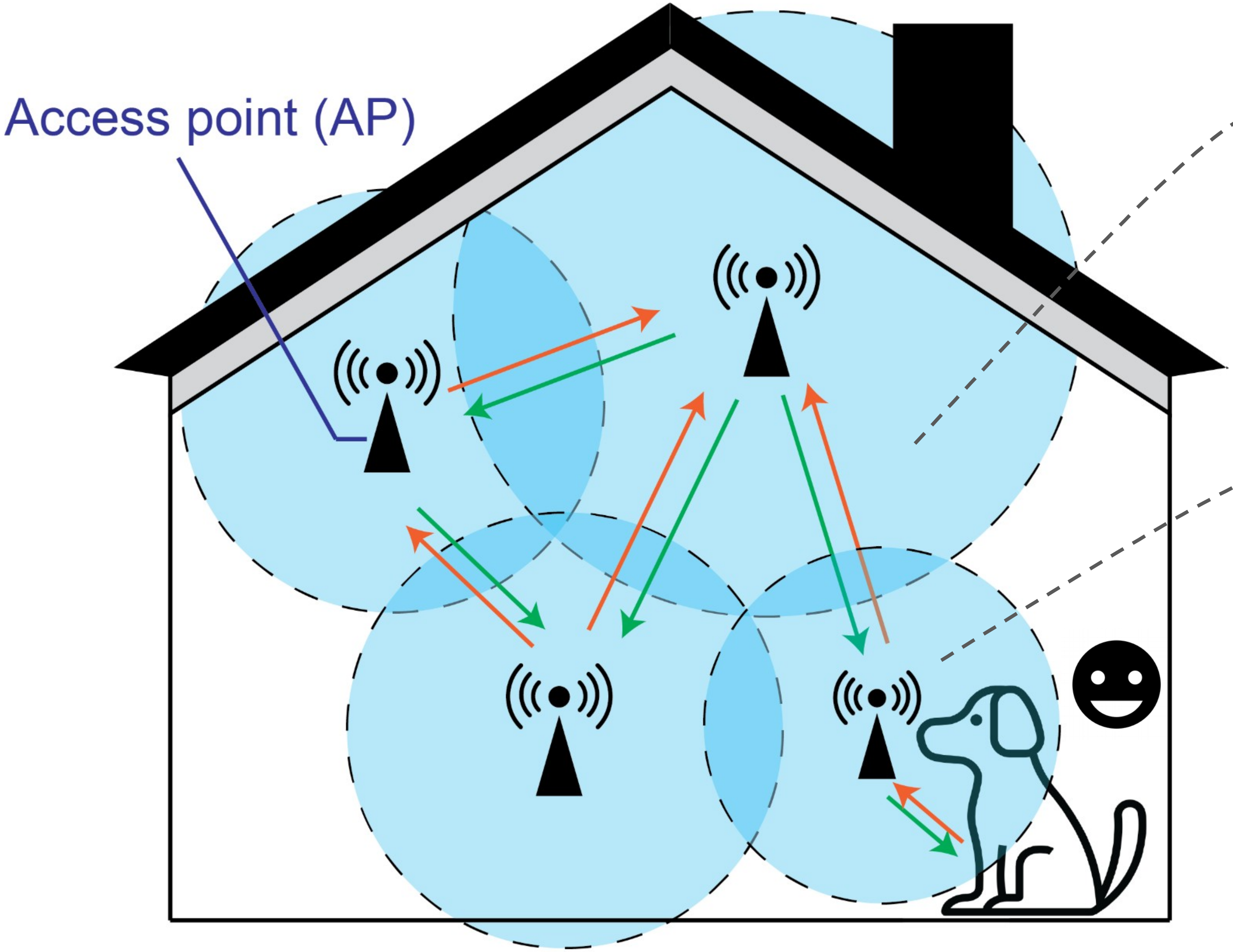
FCC limits to max. of 30dBm

Commodity AP sensitivity is -90 to -100dBm for 802.11b signal (BW=20MHz)

Link constraint: $P_{TX} - PL_1 - IL_{Tag} - PL_2 \geq P_{sens,RX}$

⇒ Limited range

Problems caused by limited backscatter range

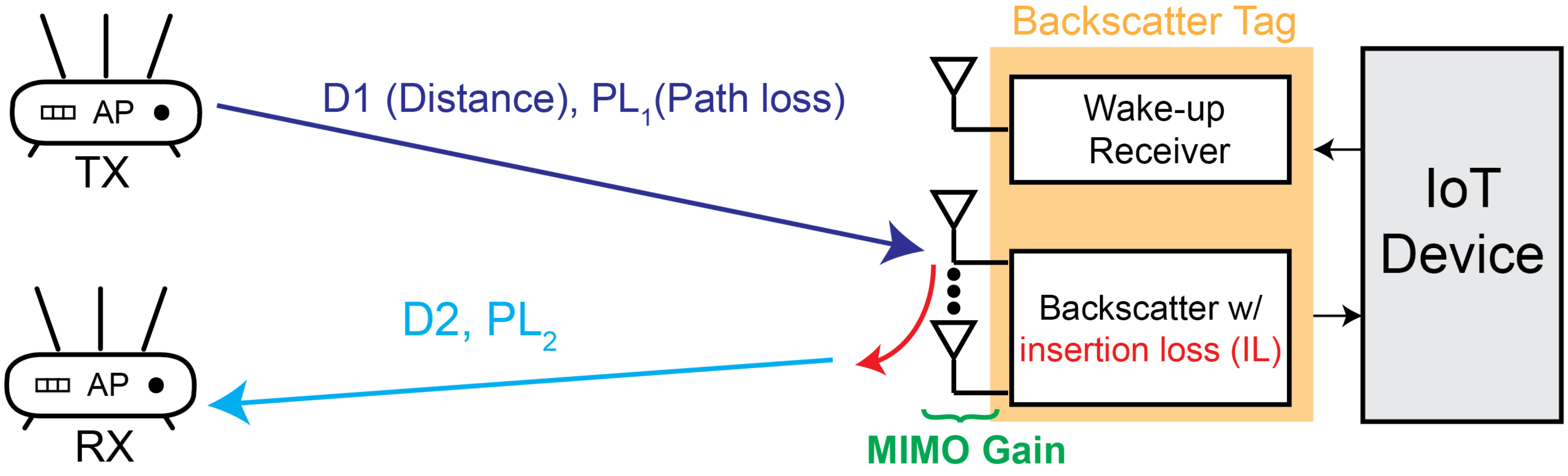


Cannot cover whole environment while adding devices

Only and simplest solution:
Add more APs

Expensive to deploy more APs just for adding new devices

How can we increase range for backscatter?



FCC limits to max. of 30dBm

Commodity AP sensitivity is -90 to -100dBm for 802.11b signal (BW = 20MHz)

$$\text{MIMO Gain} + P_{TX} - PL_1 - IL_{Tag} - PL_2 \geq P_{sens,RX}$$

Only possible approach to increase range:
Improve the insertion loss (IL) or apply MIMO gain

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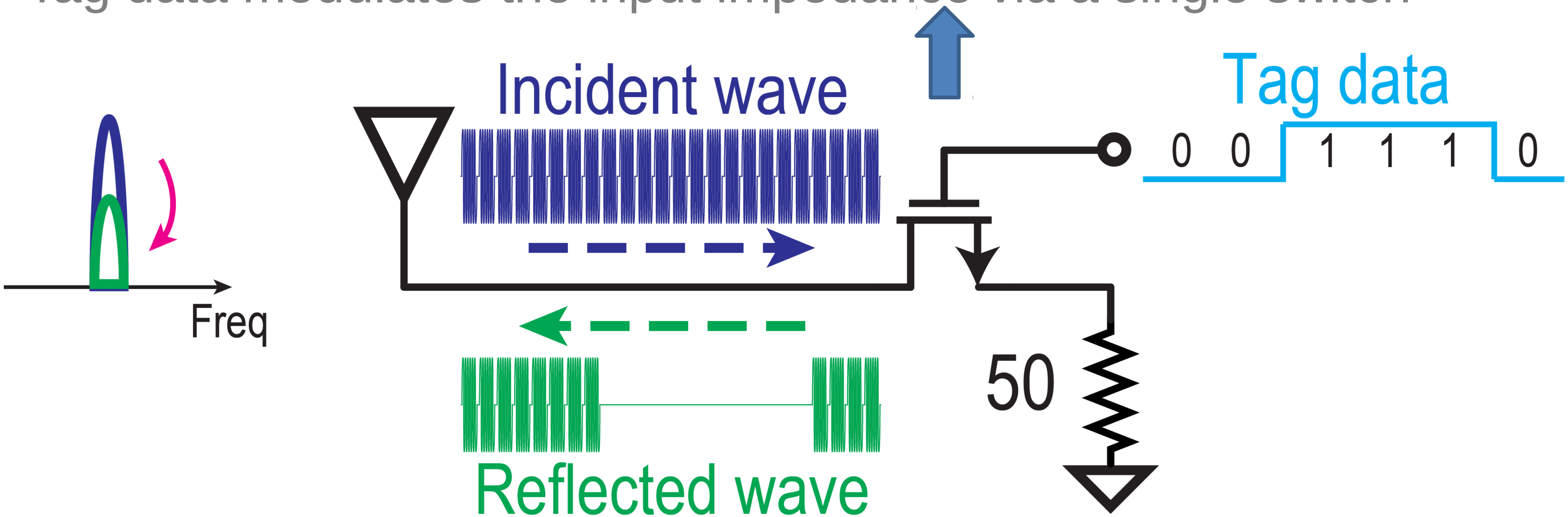
Conventional On-off Keying (OOK) backscatter

Tag data modulates the input impedance via a single switch

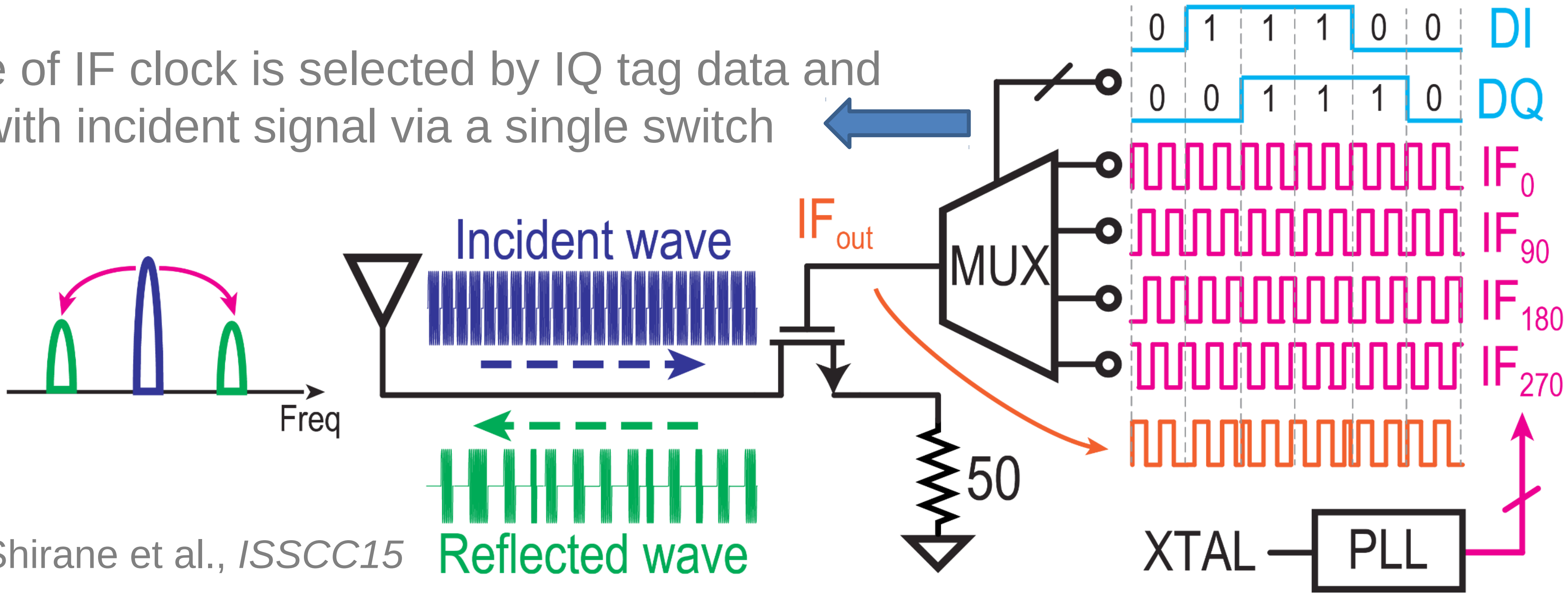


Udo Karthaus, Martin Fischer, *JSSC03*

OOK modulation only & reflected spectrum overlaps with incident one

Quadrature Phase Shift Keying (QPSK) frequency translation backscatter

4 phase of IF clock is selected by IQ tag data and mixed with incident signal via a single switch

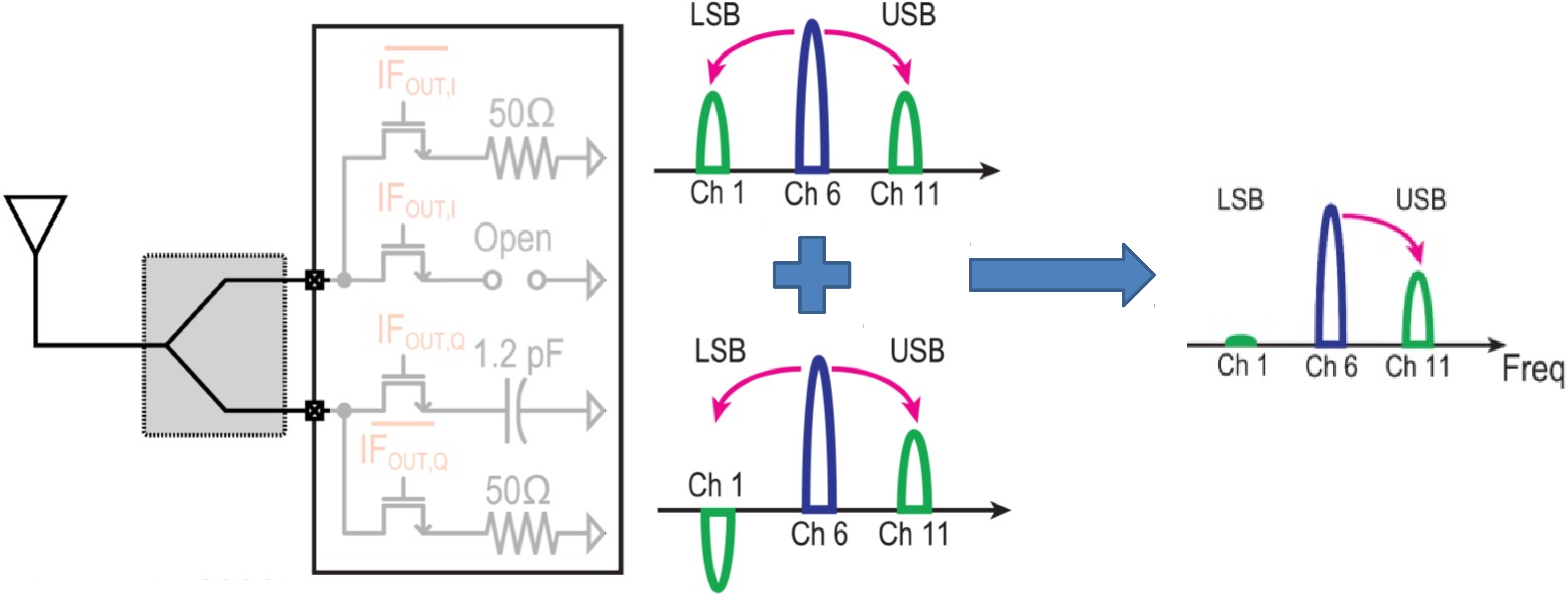


A. Shirane et al., *ISSCC15*

Double-side-band modulation occupies 2 adjacent channels

Single-side-band (SSB) modulation backscatter

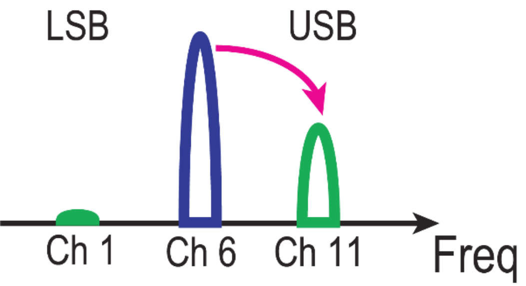
P.-H. P. Wang et al., *ISSCC20*

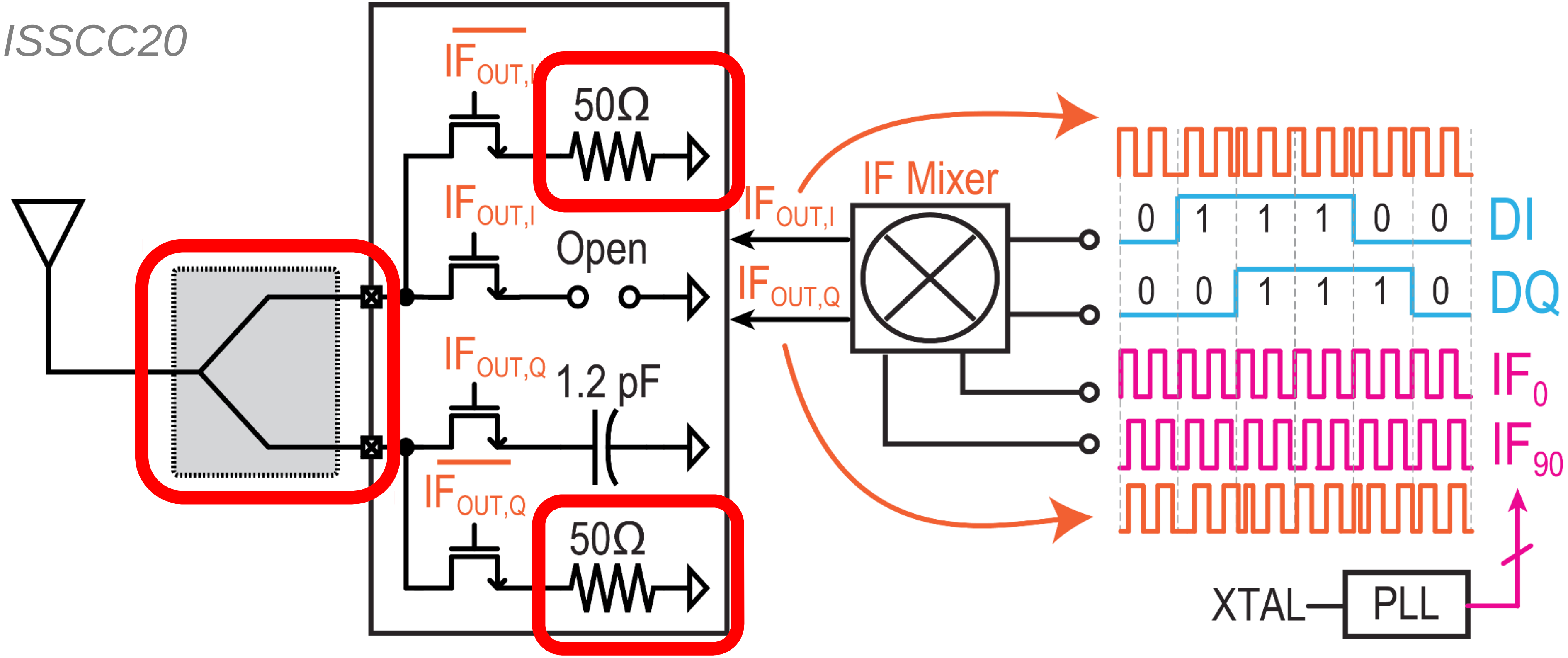


Quadrature IF modulates quadrature loads ㅂ SSB

SSB QPSK backscatter with absorptive component

P.-H. P. Wang et al., *ISSCC20*

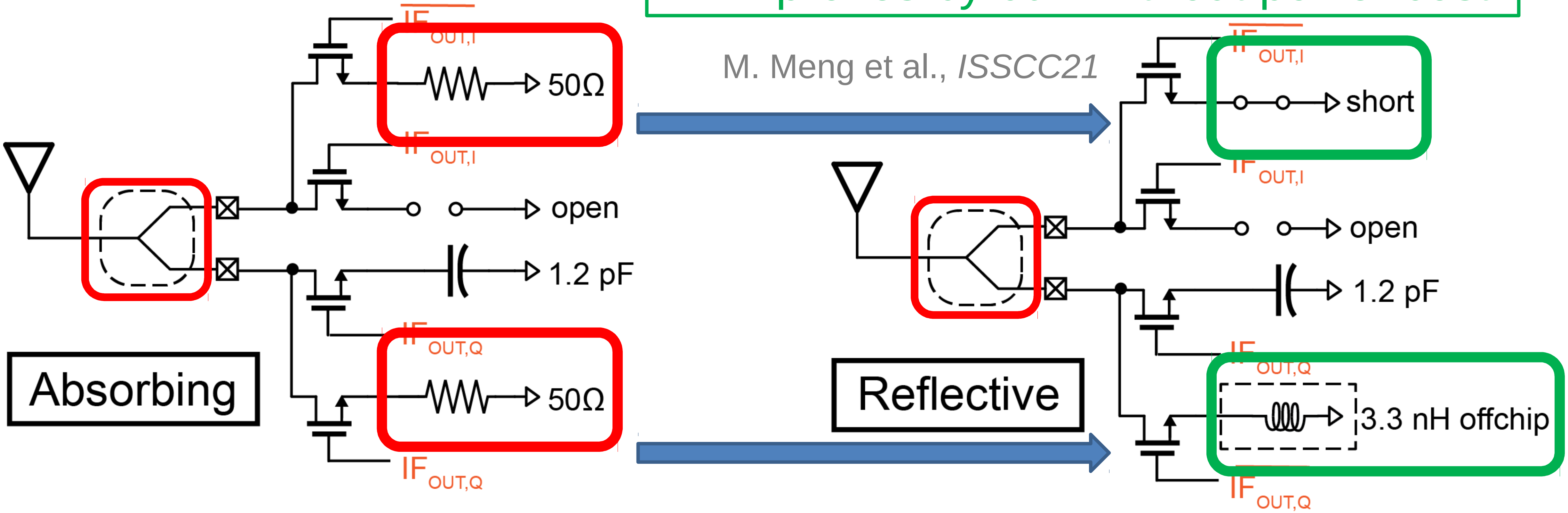




Power combiner & absorbing termination → less reflected power
→ AP-to-AP range is limited to 21m with tag in the middle

Fully-reflective SSB QPSK backscatter with power splitter/combiner

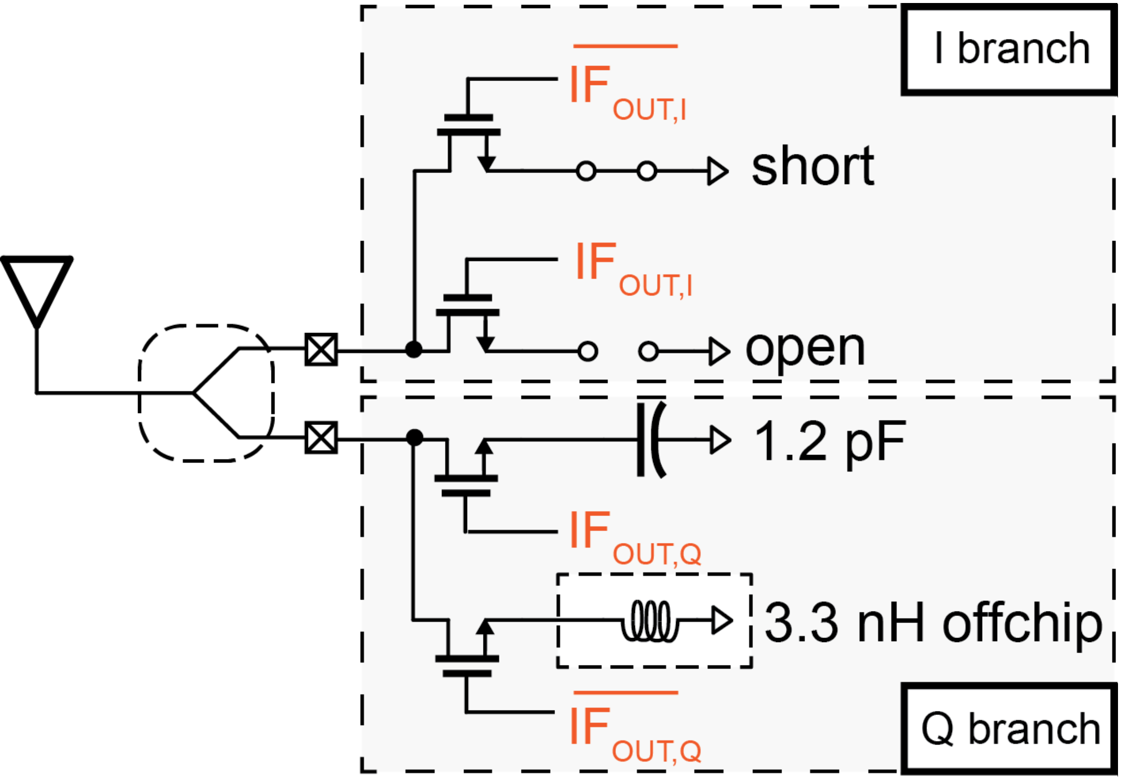
IL improves by 6dB without power cost



Power splitter still required

→ AP-to-AP range limited to 26m with tag in the middle

Is power splitter/combiner required?



Function of power splitter

Isolate and combine I/Q paths to achieve SSB backscatter

Essentially it is combing I/Q loads over 4 permutations

$(IF_{OUT,I}, IF_{OUT,Q}) = (0,0) \rightarrow \Gamma_{effective} = 0.707\angle{-45°}$

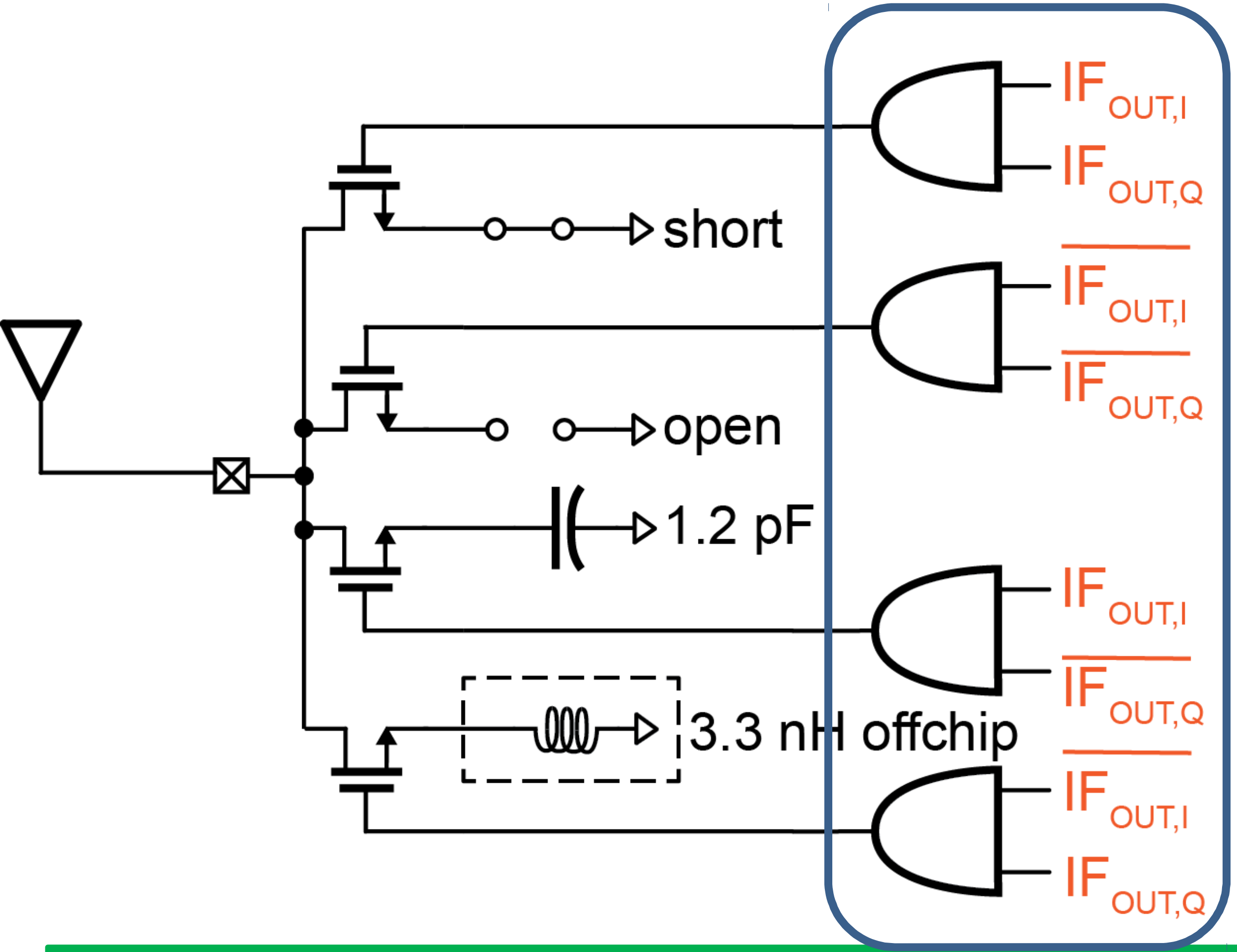
$(IF_{OUT,I}, IF_{OUT,Q}) = (0,1) \rightarrow \Gamma_{effective} = 0.707\angle{+45°}$

$(IF_{OUT,I}, IF_{OUT,Q}) = (1,0) \rightarrow \Gamma_{effective} = 0.707\angle{-135°}$

$(IF_{OUT,I}, IF_{OUT,Q}) = (1,1) \rightarrow \Gamma_{effective} = 0.707\angle{+135°}$

Is it possible to re-create the effective loads directly w/o power splitter?

Power splitter/combiner removal



Eliminating I/Q paths but instead driving the loads with a SP4T switch

$(IF_{OUT,I}, IF_{OUT,Q}) = (0,0) \rightarrow \Gamma_{effective} = 1\angle 0°$

$(IF_{OUT,I}, IF_{OUT,Q}) = (0,1) \rightarrow \Gamma_{effective} = 1\angle +90°$

$(IF_{OUT,I}, IF_{OUT,Q}) = (1,0) \rightarrow \Gamma_{effective} = 1\angle -90°$

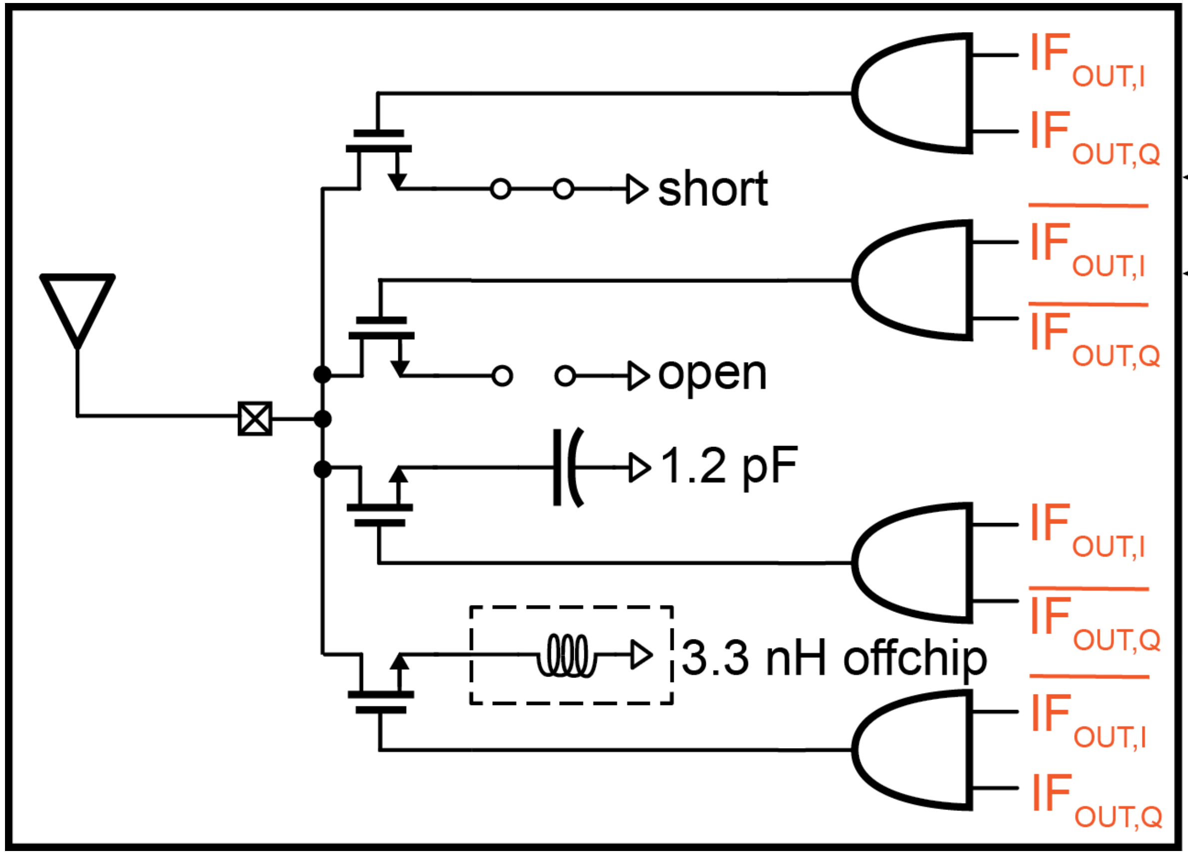
$(IF_{OUT,I}, IF_{OUT,Q}) = (1,1) \rightarrow \Gamma_{effective} = 1\angle +180°$

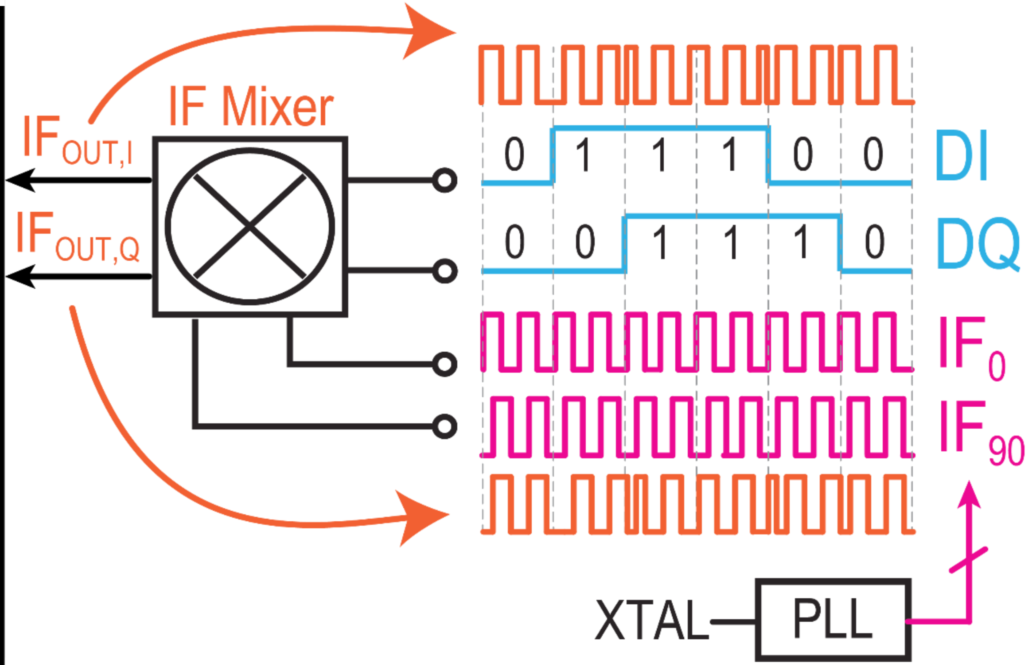
By directly selecting loads, power splitter can be removed, and |Γ| can be 1 instead of 0.707, which improves IL by 3dB

Proposed t-line-less fully-reflective SSB QPSK backscatter

Quadrature IF clocks further drive SP4T reflector

IQ tag data is first up-converted to IF via SSB digital mixer





3dB IL improvement without power cost, but there is no MIMO gain.

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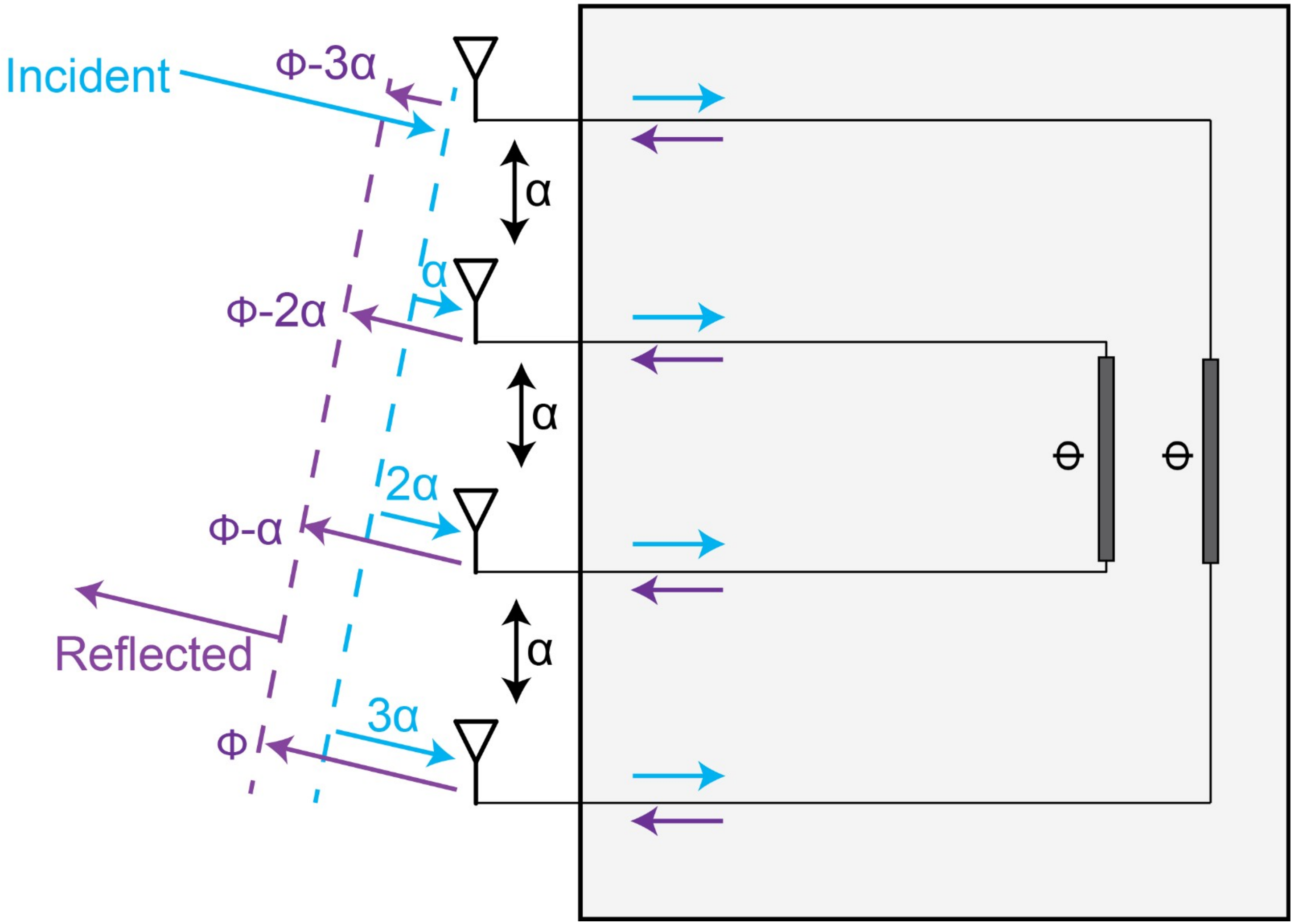
Van-Atta retro-reflective backscatter



Passively steer the incident beam back to the source with MIMO gain

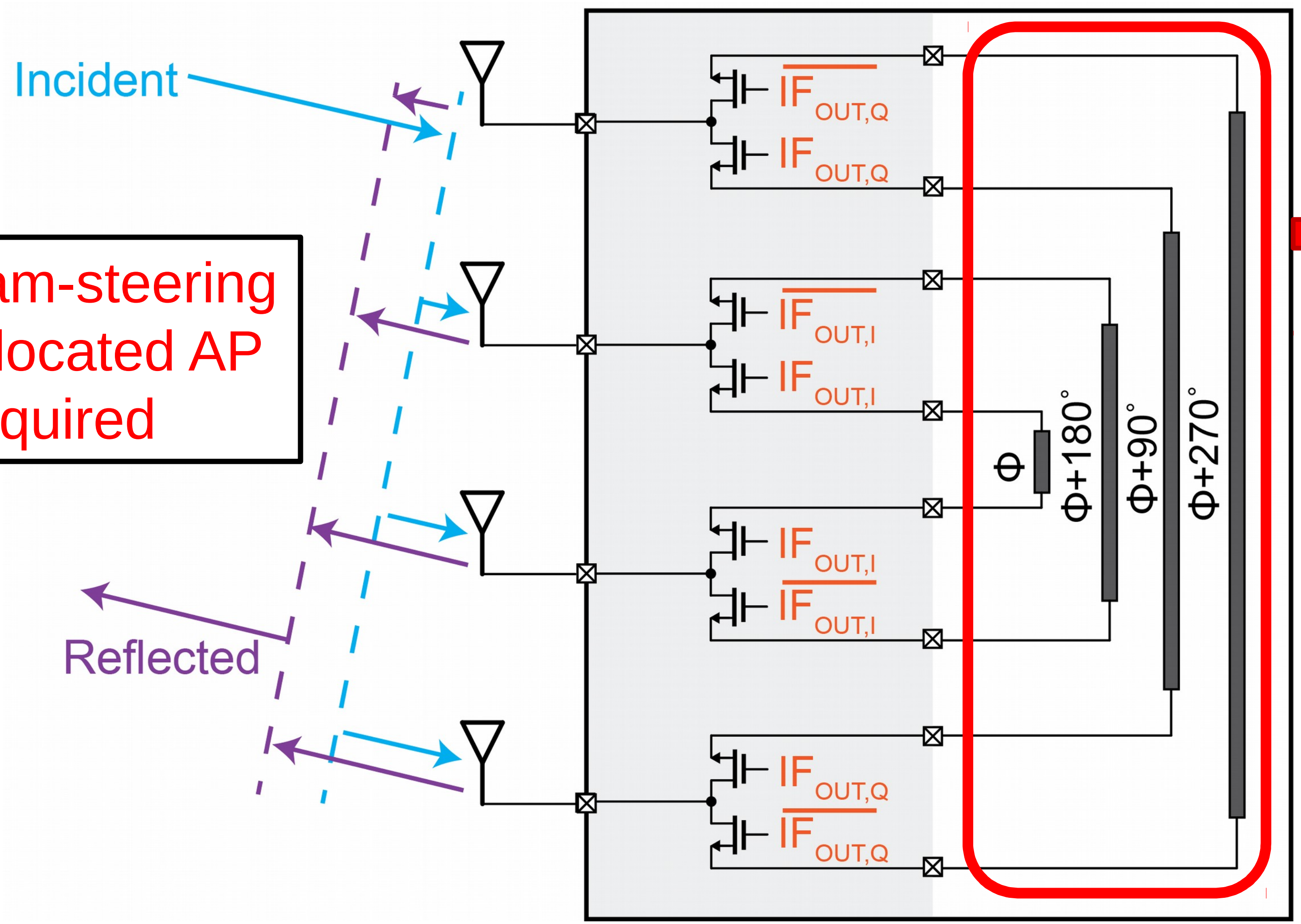
No data is modulated onto reflected signal

L.V. Atta, "Electromagnetic reflector," *U.S. patent 514040, 1959*

Van-Atta SSB QPSK backscatter

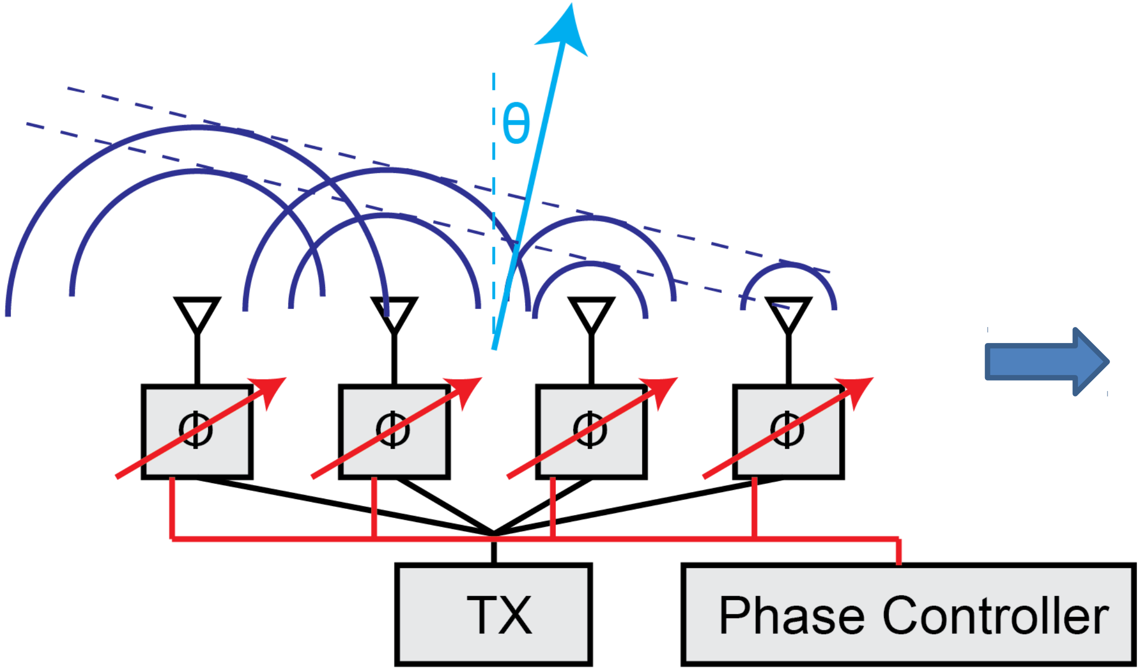
M. Meng et al., *ISSCC21*

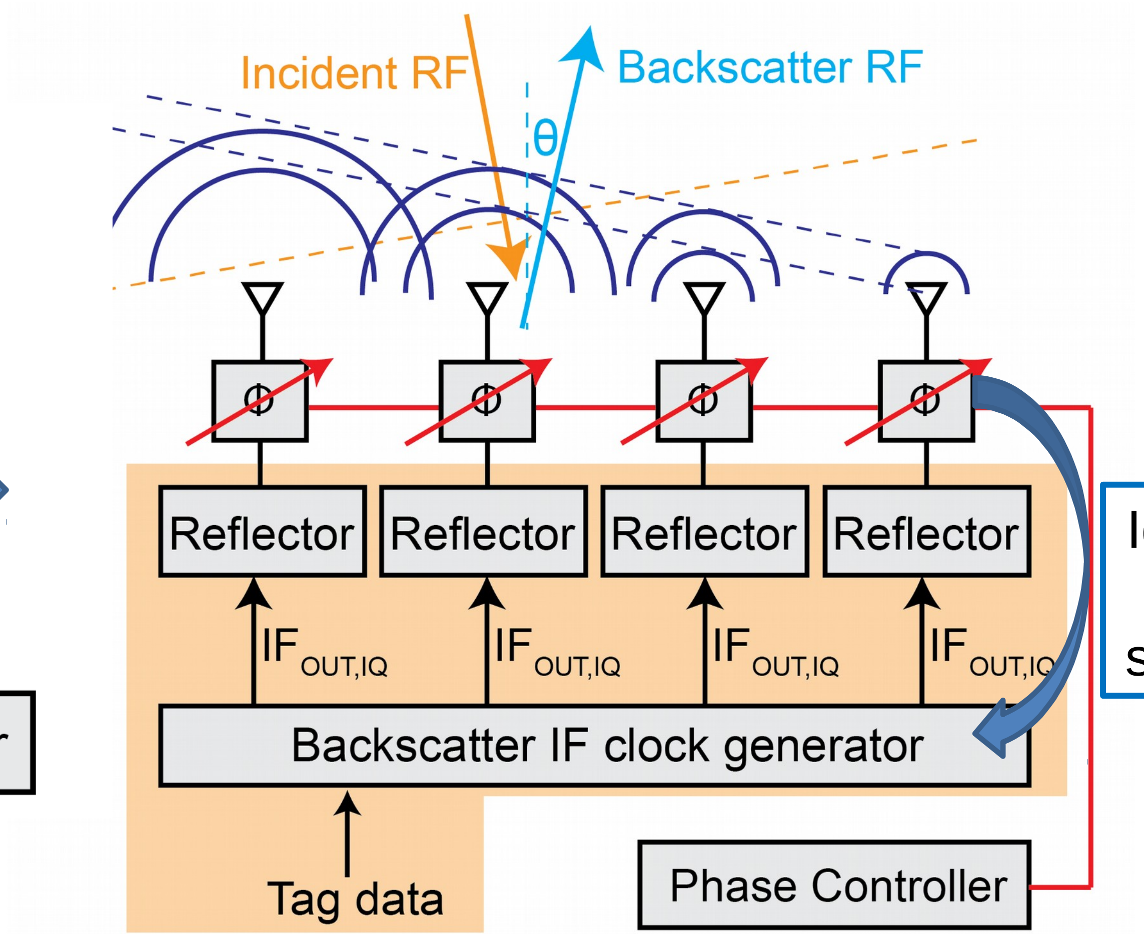
No beam-steering ▯ co-located AP required



Fixed-delay transmission lines w/o tunability occupy large board area

Phased array ⇒ Beam-steering backscatter





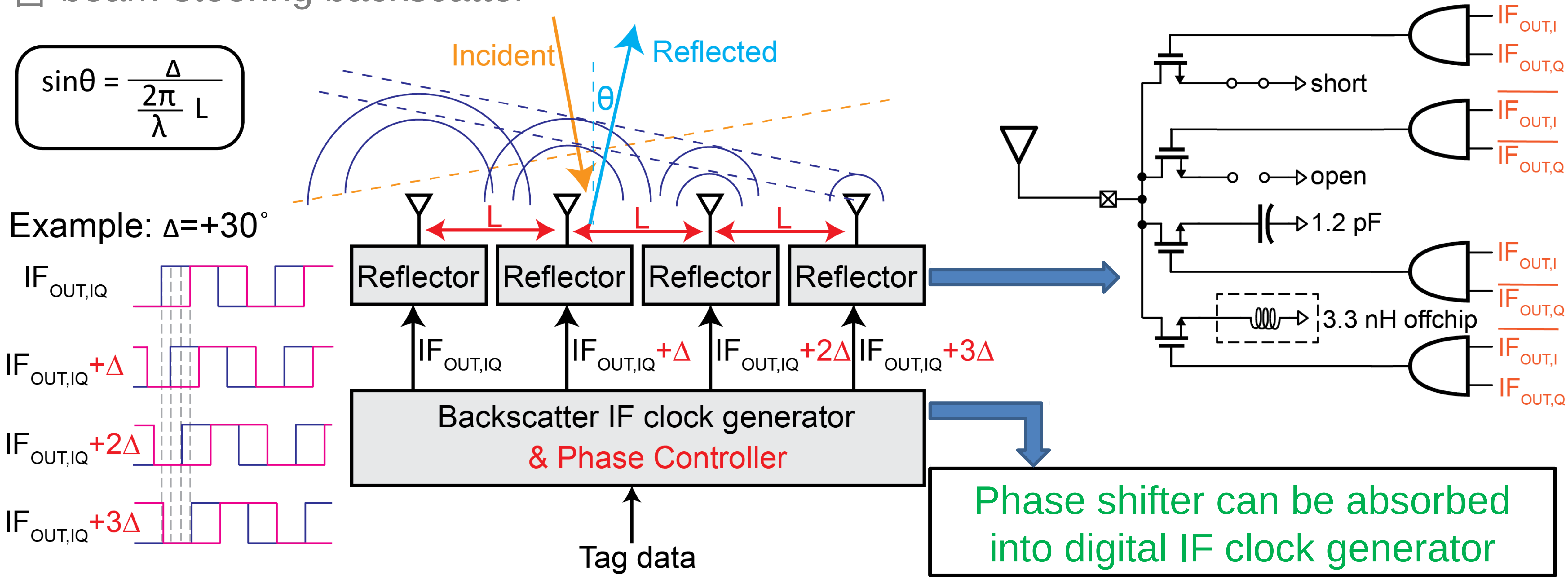
Idea: move phase shifter to IF

RF phase shifter is still required, which is not easily tunable with low power

Proposed MIMO beam-steering SSB QPSK backscatter

Multiple SP4T reflectors + phased-controlled IF clocks

- beam-steering backscatter



MIMO enables directional gain and compatible with mesh network

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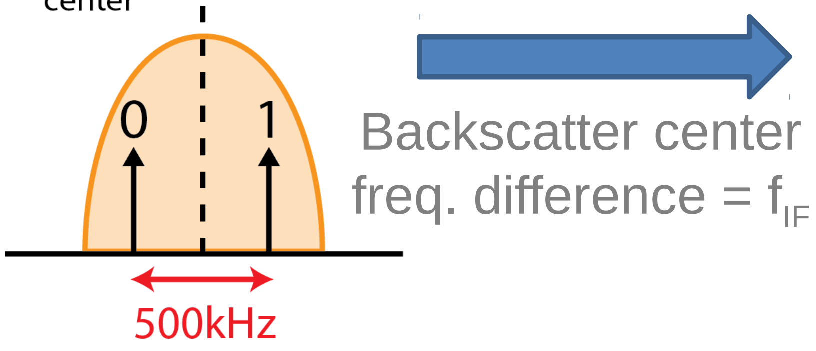
BLE backscatter scheme

BLE uses FSK with 500kHz tone separation

BLE channel
(Ex. Ch.37)
f_{center} = 2402 MHz

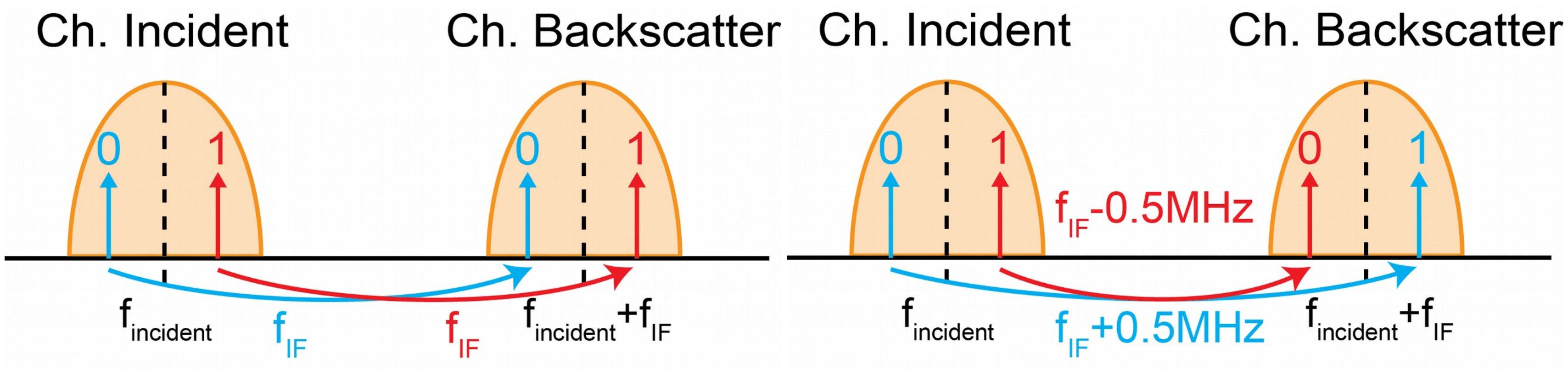


When tag data = 0

Do only freq. translation

When tag data = 1

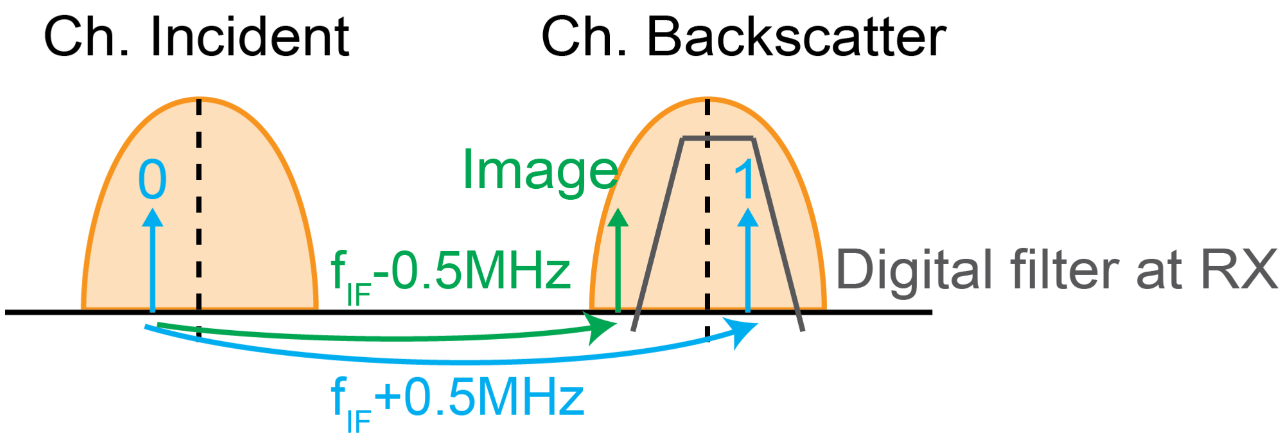
Do freq. translation and interchange the BLE symbol



When tag data=1, $f_{Backscatter}$ can be either f_{IF} + 0.5MHz or f_{IF} - 0.5MHz depending on the incident signal

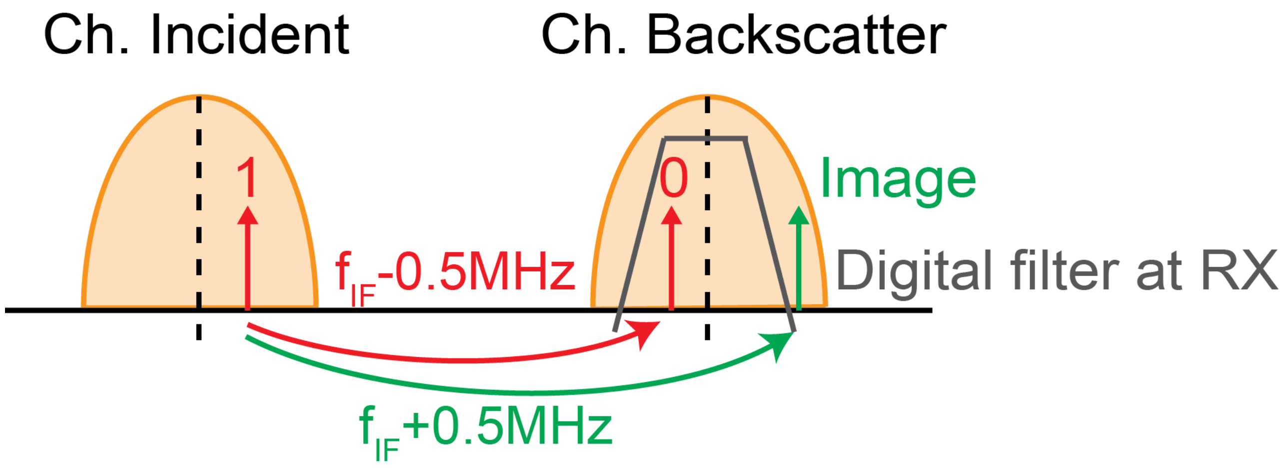
But incident data is unknown!

BLE backscatter scheme



<u>When tag data = 1</u>

Do freq. translation and interchange the BLE symbol



Solution: Mix 0.5MHz with f_{IF} to generate two freqs. by XOR gate. Image landed 1MHz away can be filtered out by RX.

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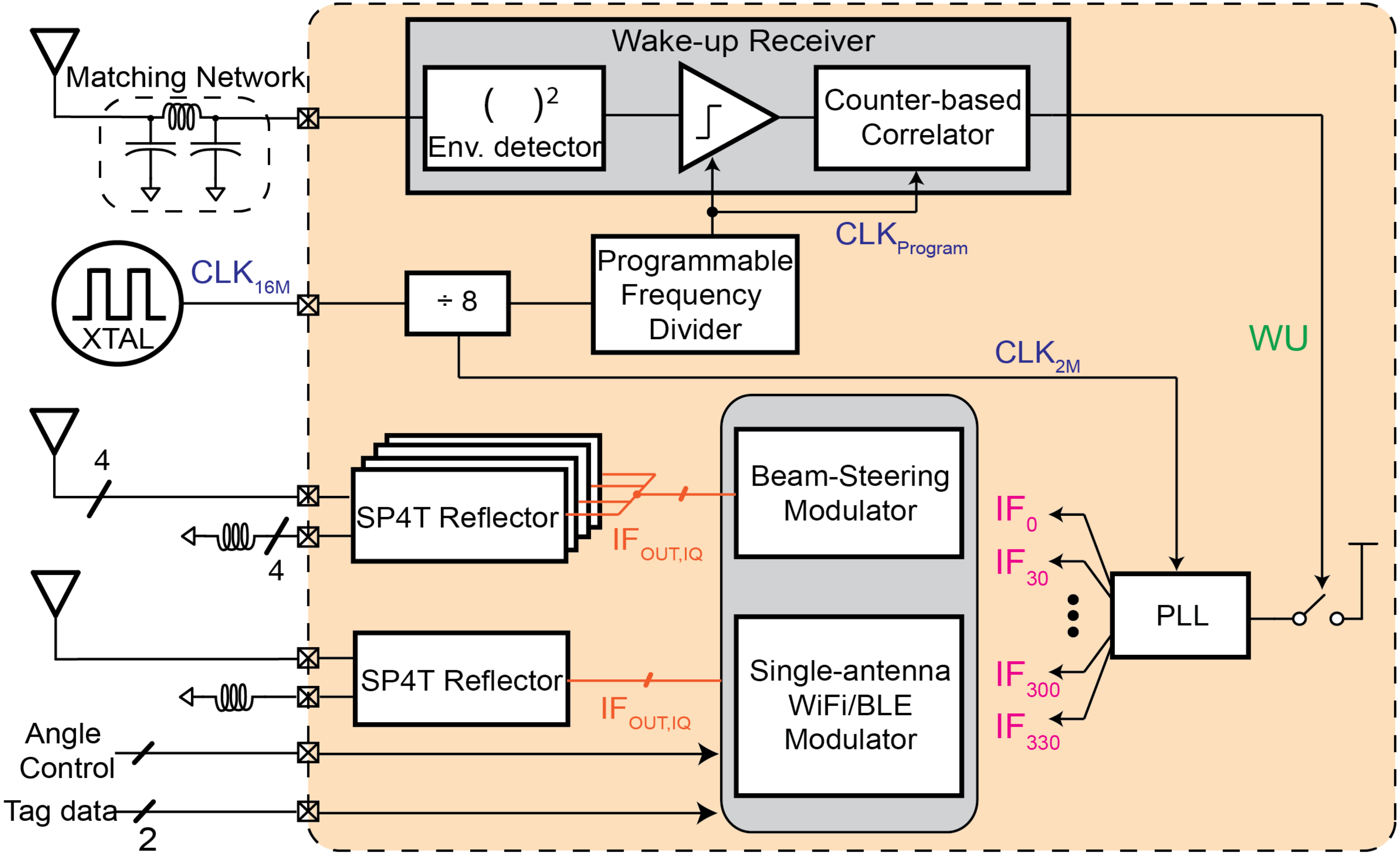
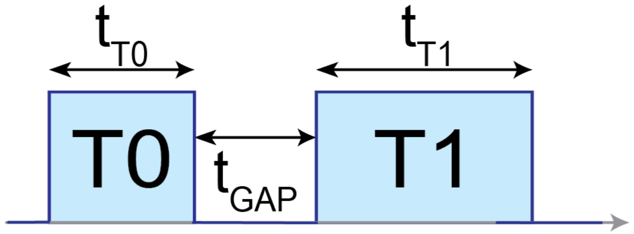
Block diagram of proposed WiFi/BLE combo tag



Block diagram of downlink

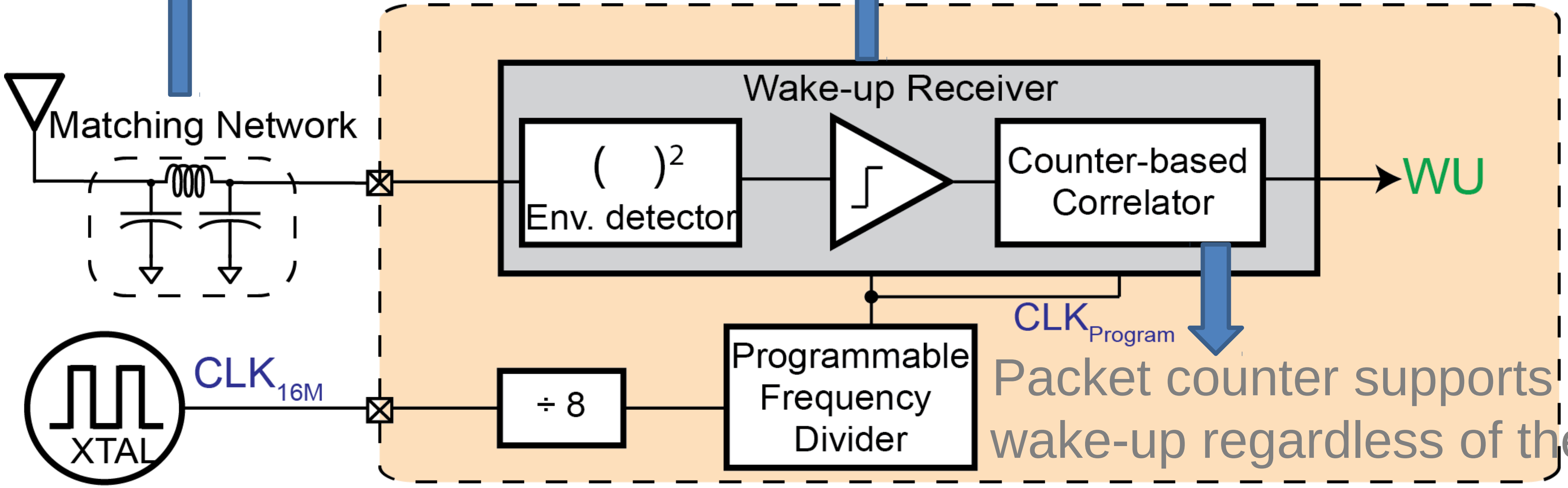


Wake-up structure

Two consecutive WiFi/BLE packets with an uncertain gap in between

8dB passive voltage gain from input matching network

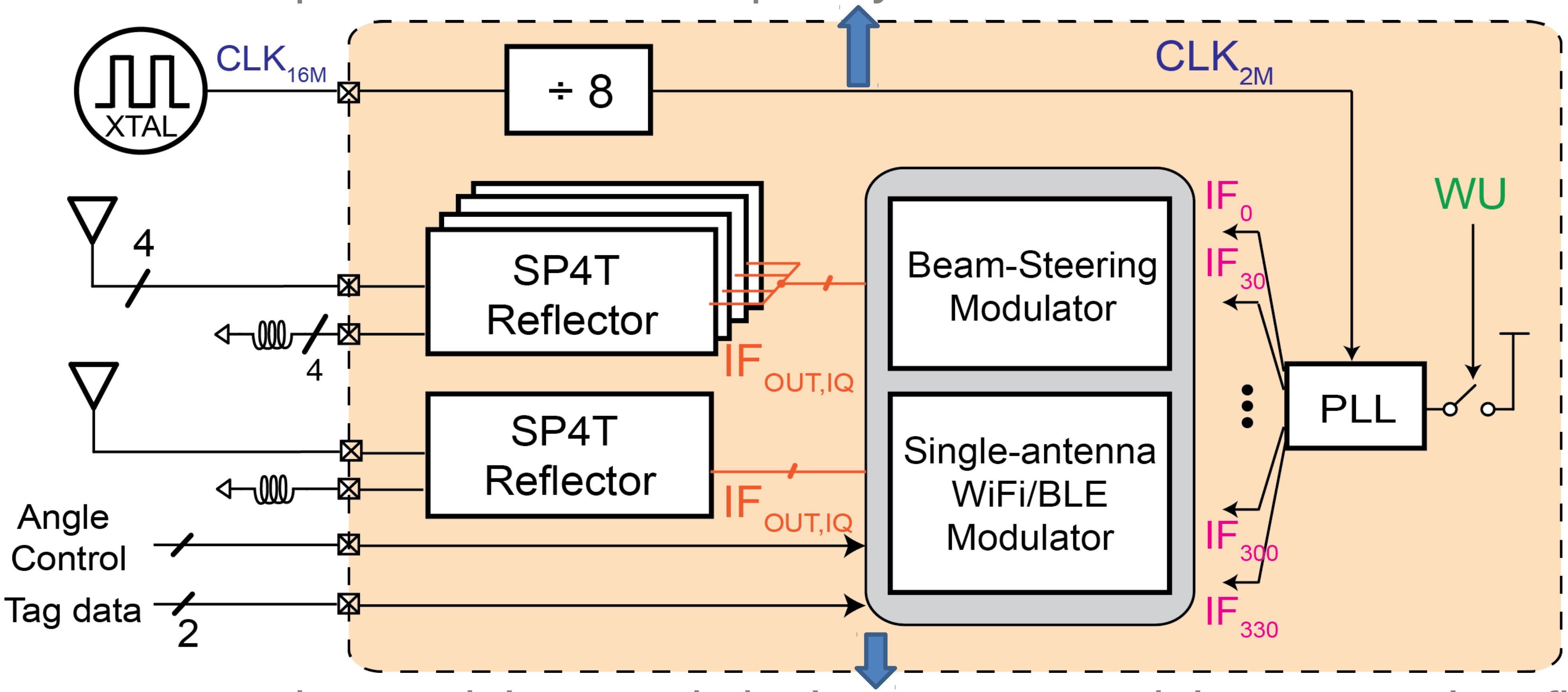
Direct envelope detection architecture for low standby power



Packet counter supports robust WiFi/BLE wake-up regardless of the length of gaps

Block diagram of uplink

- A PLL-based IF clock generator enabled by wake-up signal
- PLL provides flexible frequency translation for WiFi/BLE backscatter



Beam-steering modulator and single-antenna modulator controls reflector impedance loading based on tag data modulation

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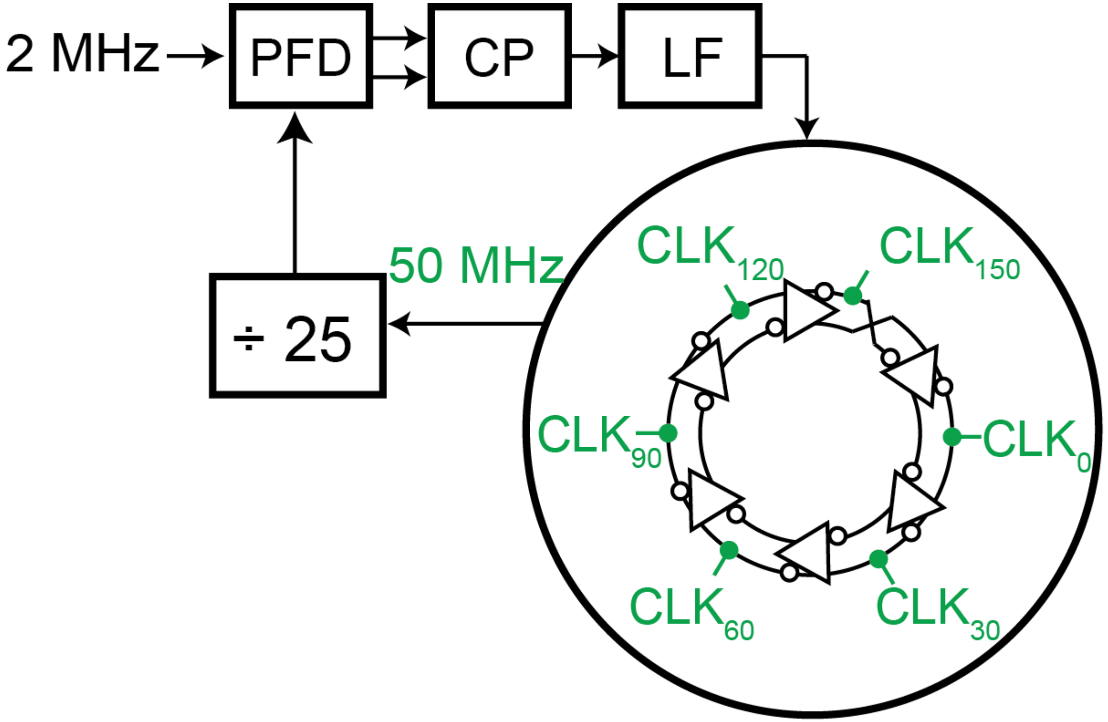
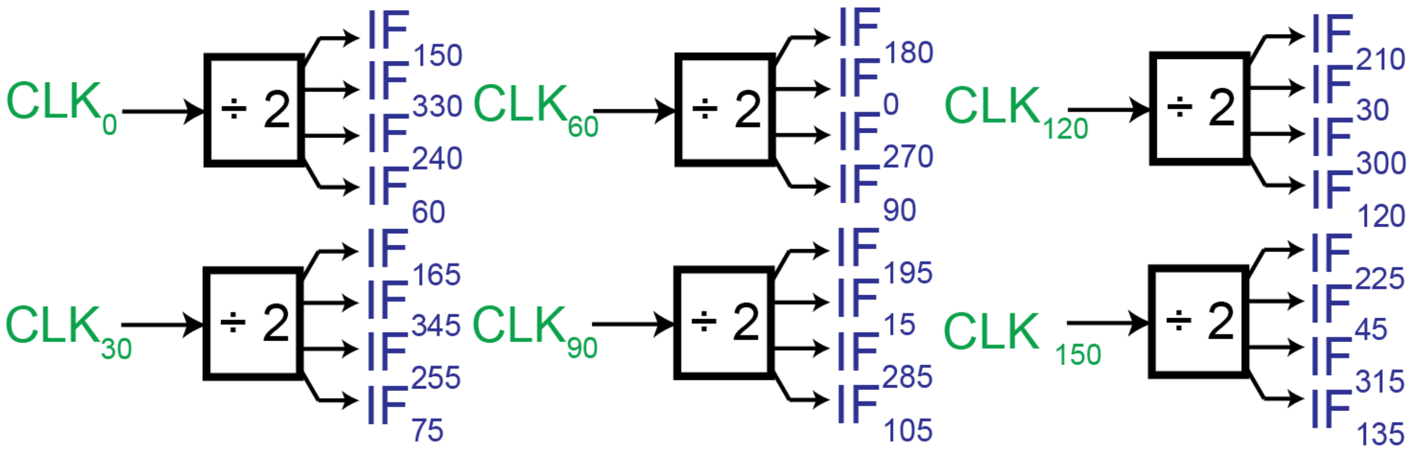
IF clock generator

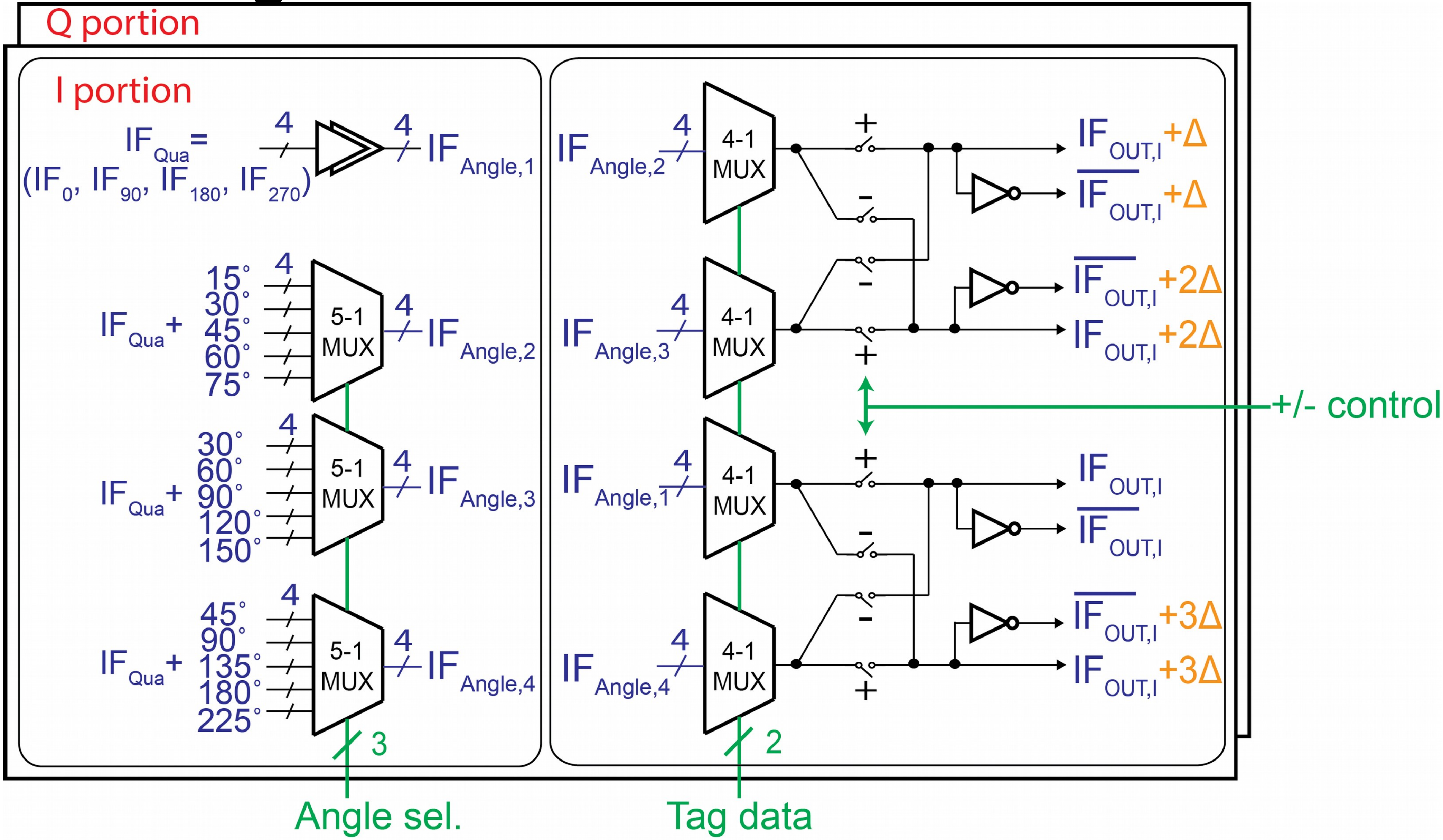


Ring oscillator-based integer-*N* PLL generates 6-phase of outputs



24-phase IF clocks are further generated by divide-by-2 blocks

Beam-steering modulator



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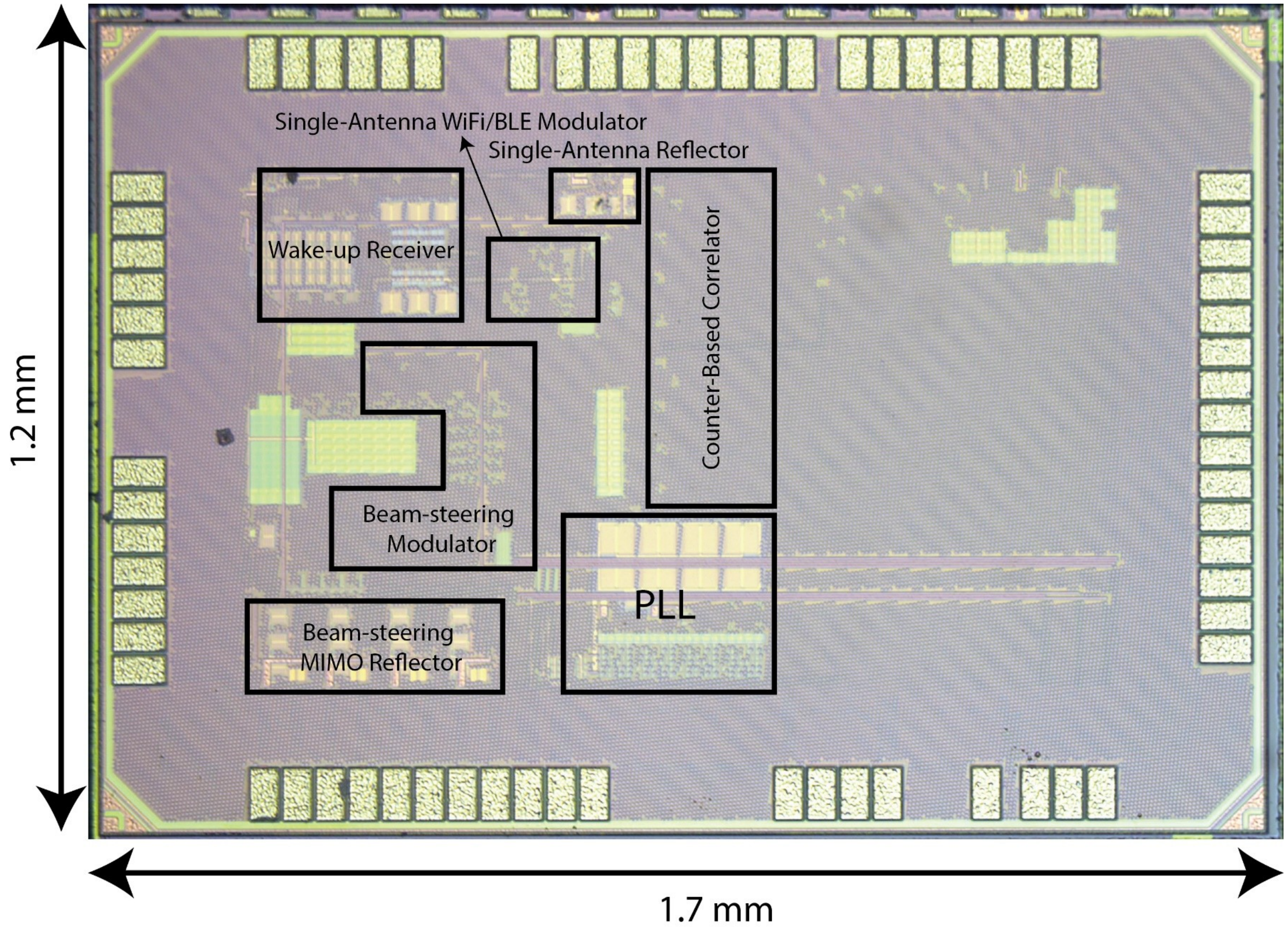
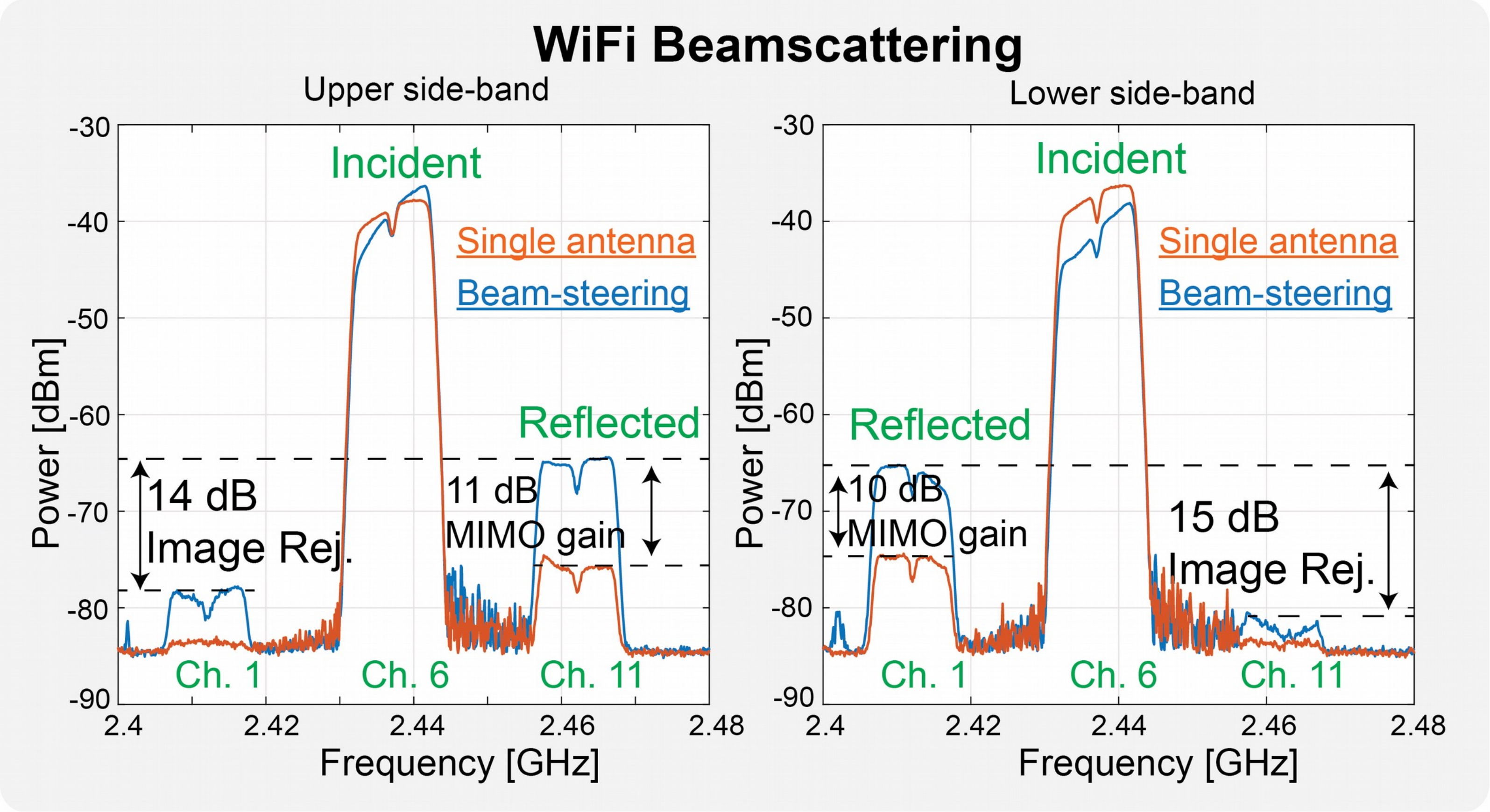
Die micrograph

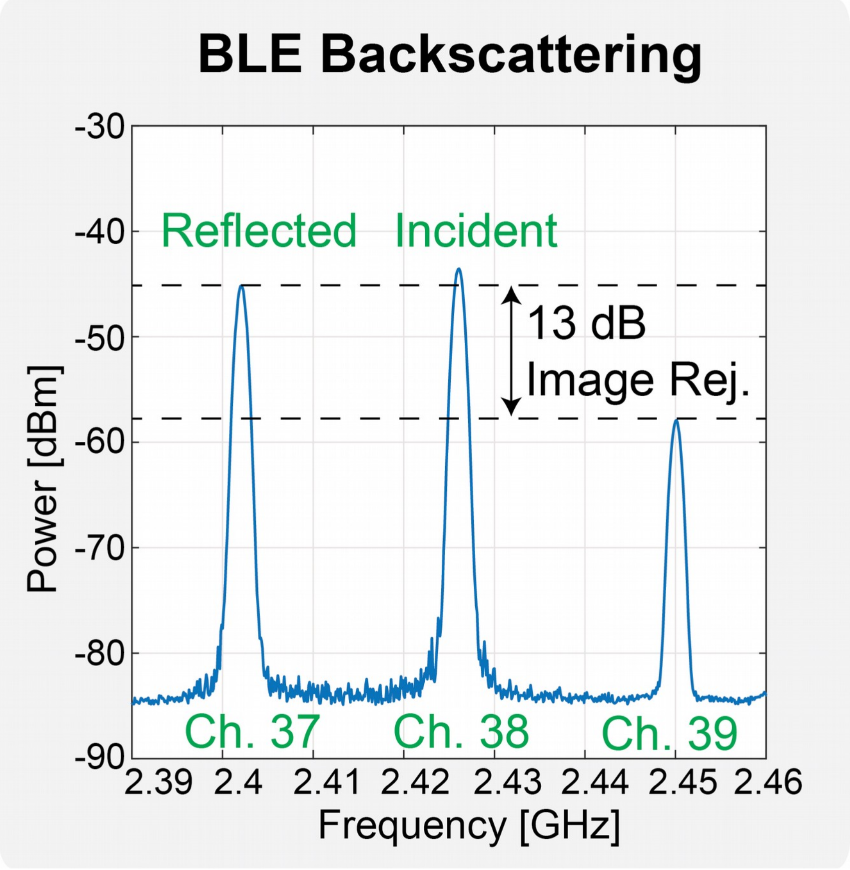


- 65nm CMOS
- 0.42mm^2 active area

WiFi/BLE SSB backscatter spectra

Incident signal appears due to finite circulator isolation and close TX-RX distance for testing purpose

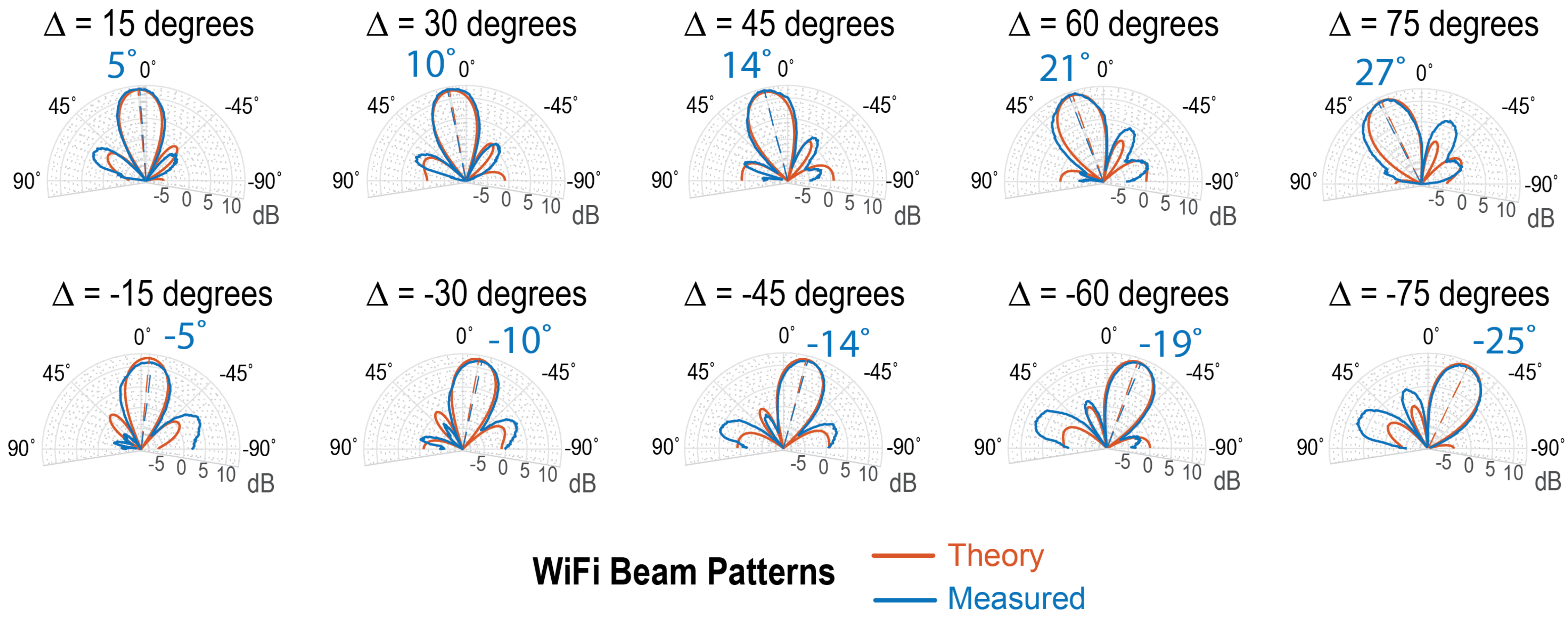




- Incident signal at WiFi CH6 reflected to either CH1 or CH11 with ~15dB image rejection
- WiFi beam-steering shows ~10dB MIMO gain improvement compared to single-antenna case
- BLE backscatter shows 13dB image rej. when incident signal at CH38 and reflected signal at CH37

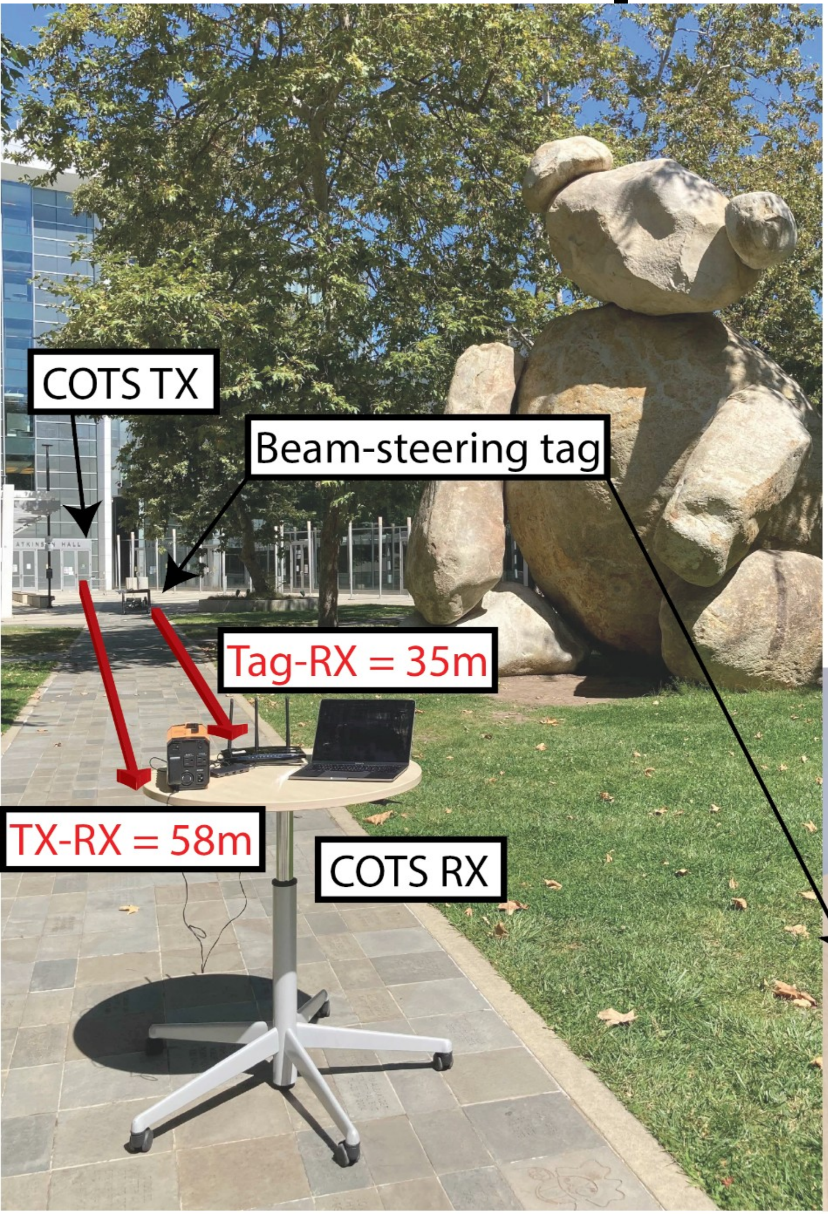
WiFi beam-scattered pattern

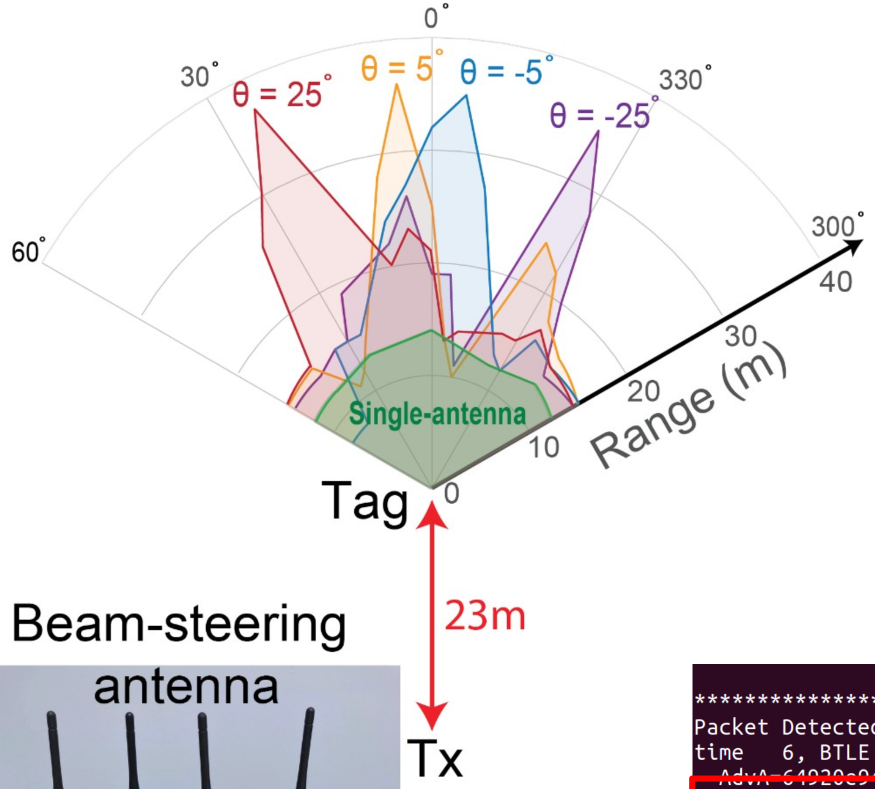
M. Dunna et al., *Arxiv 2021*



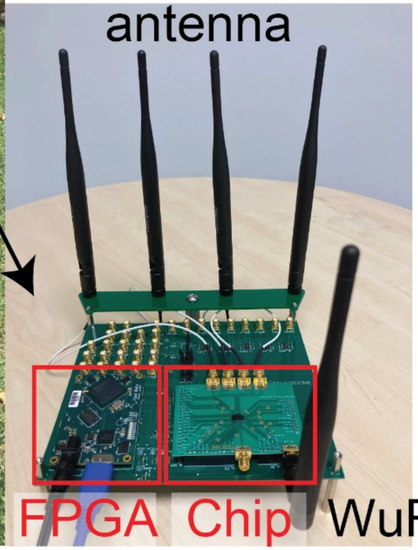
Measured WiFi beam-scattered pattern matches theoretical results with different Δ settings

Wireless experiment





Beam-steering antenna



Effective AP-to-AP range with tag in the middle: Beam steering = 56m vs. single antenna 35m

Decoded BLE packet with BER=2e-4

Comparison to prior art

	ISSCC 2020	ISSCC 2021		VLSI 2021	This Work	
Technology	65 nm	65 nm		180 nm	65 nm	
Core Area (mm^2)	0.34	0.41		1.62	0.42	
Backscatter Scheme	Partially Absorbing QPSK	Fully Reflective QPSK	Retro-reflective MIMO QPSK	DBPSK	**QPSK Fully-reflective MIMO Beam-steering for WiFi** **SSB FSK for BLE**	
Single Side Band?	Yes	Yes	Yes	No	**Yes**	
AP-to-AP Range with tag in the middle (m) (TX peak power = 30dBm)	21	26 (Single-antenna)	46 (MIMO)	16	Single antenna	**35**
					Beam-steering	**56**
Compatible with commodity WiFi/BLE hardware	Yes	Yes	Partial	No - tone generator needed	**Yes**	
OOK Wake-up Power (µW)	2.8	4.5		0.15	5.5	
Backscatter Communication Power (µW)	28	32	38	2.5	WiFi/BLE w/ single antenna	39
					WiFi Beam-steering	88

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Conclusion

A transmission-line-less WiFi/BLE combo backscatter IC with improved range (35m for single antenna & 56m for MIMO) and MIMO beam-steering ability towards pragmatic adoption in large inter-AP environments

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Thanks for your attention!