Place for Speaker's video (5cm x 3.5cm)

# Improving the Range of WiFi Backscatter Via a Passive Retro-Reflective Single-Side-Band-Modulating MIMO Array and Non-Absorbing Termination

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UCSD

# Miniature and ubiquitous IoT devices

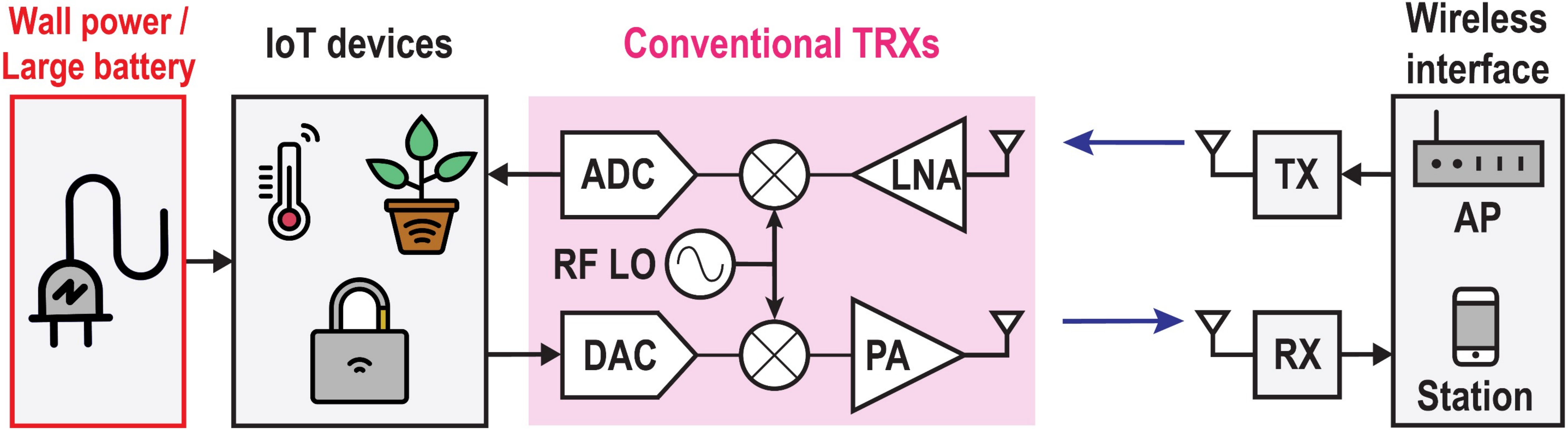
Place for Speaker’s video (5cm x 3.5cm)




- Enable new class of applications
- Require miniature size, long lifetime, wireless standard-compliant

# Conventional wireless transmission

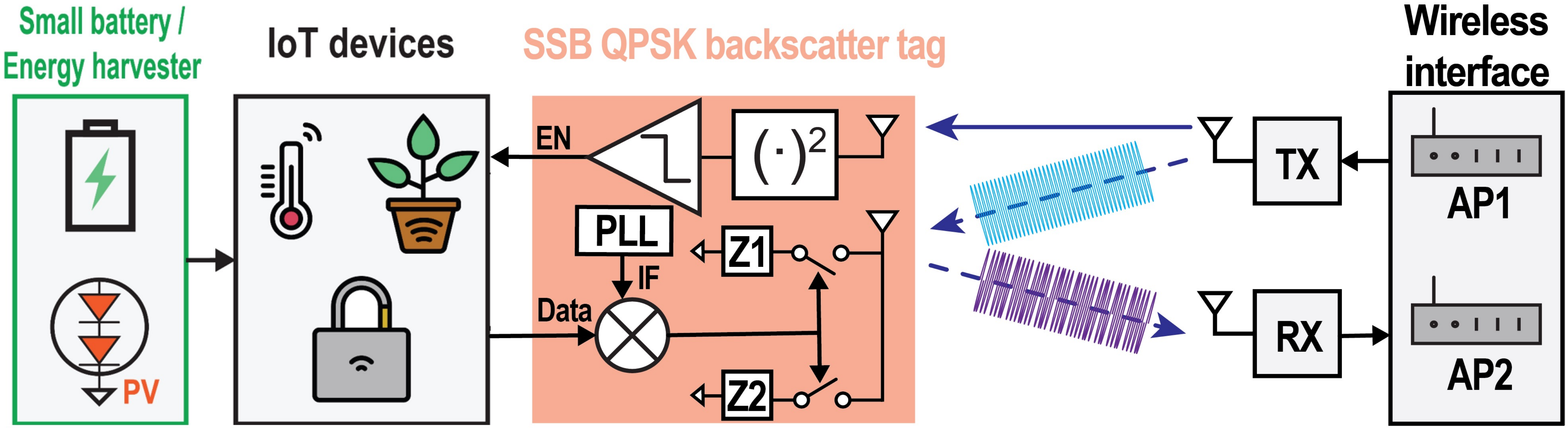
Place for Speaker's video (5cm x 3.5cm)




- ☒ Conventional WiFi TRXs require 10s~100s mW active power
- ☒ Size of IoT devices is limited by power consumption
- ☑ Higher order modulation is achievable but trades-off with power

# WiFi compatible backscatter communication

Place for Speaker's video (5cm x 3.5cm)

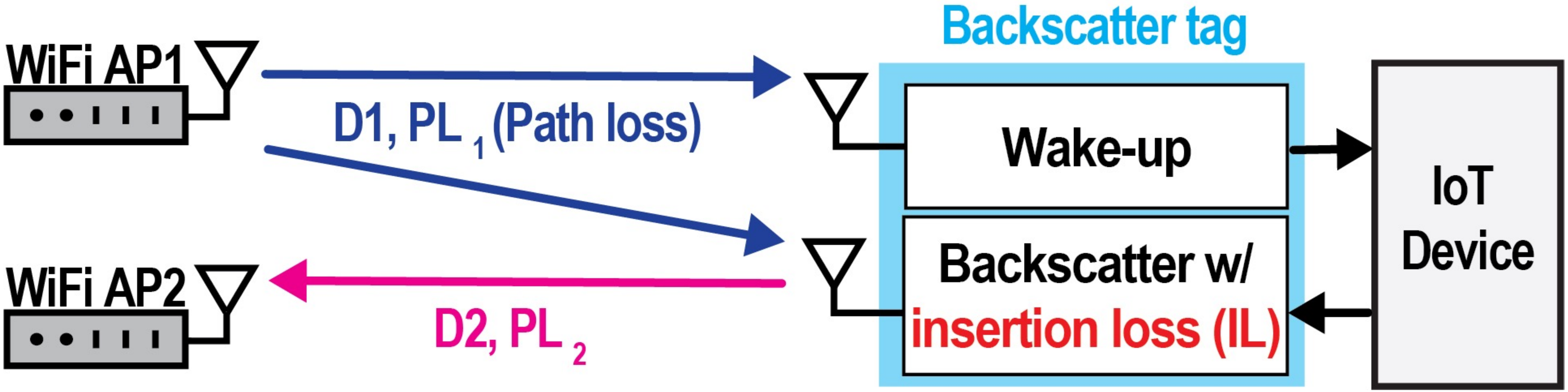



- ☑ Elimination of active RF circuit enables low power consumption
- ☑ Recent work showed compatibility with existing standards
- ☑ Higher order modulation is achievable by implementing IF switches
- ☒ Range is limited due to passive nature

# Backscatter - range calculation

Place for Speaker's video (5cm x 3.5cm)

**Downlink:** $P_{sens,wu} \leq P_{TX,AP} - PL_1$

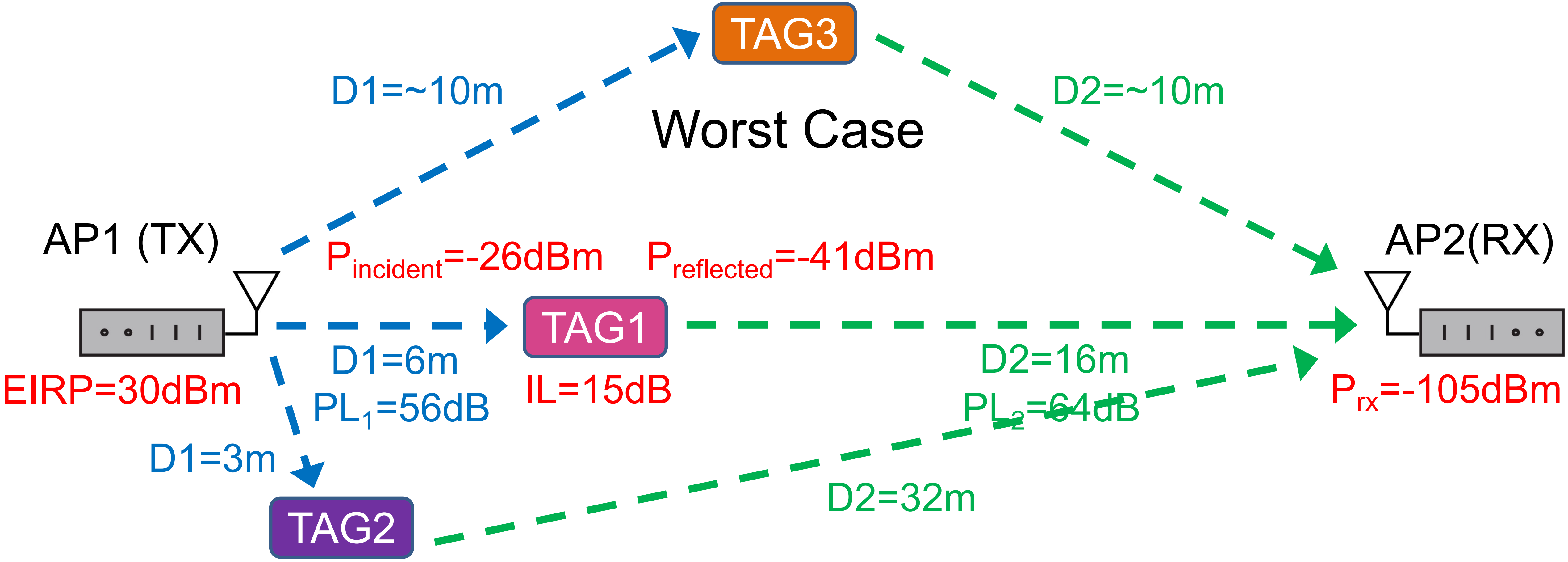



**Uplink:** $P_{sens,AP} \leq P_{TX,TAP} - PL_1 - PL_2 - IL_{TAG}$

- PL1 and PL2 are determined by D1 and D2
- D1 × D2 is limited by system parameters

# Link budget - Meshed network

Place for Speaker's video (5cm x 3.5cm)

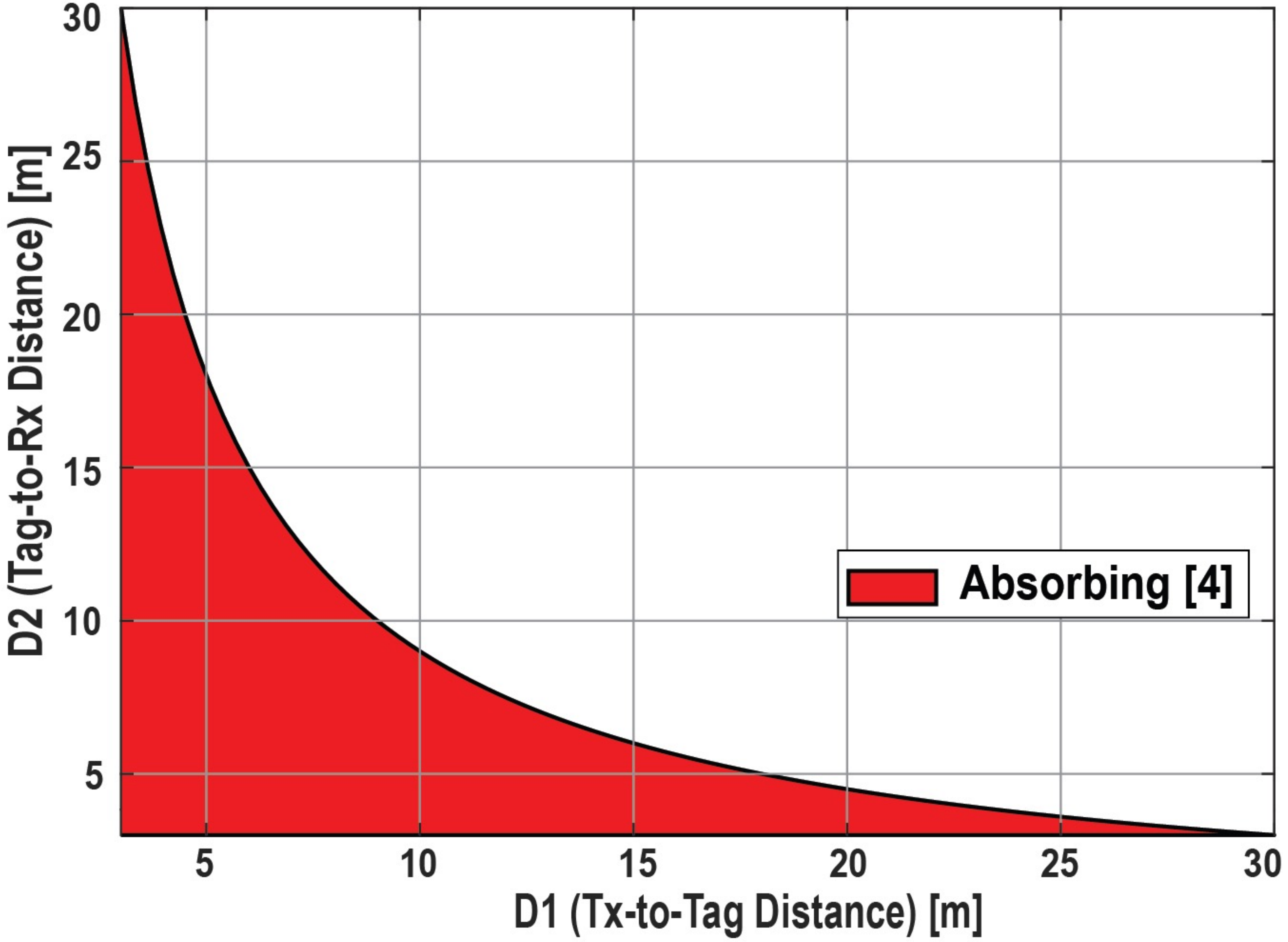



$$D1 \times D2 = 96\text{mm}^2$$

Wang et al., *ISSCC20*

# Tag in meshed network

Place for Speaker's video (5cm x 3.5cm)

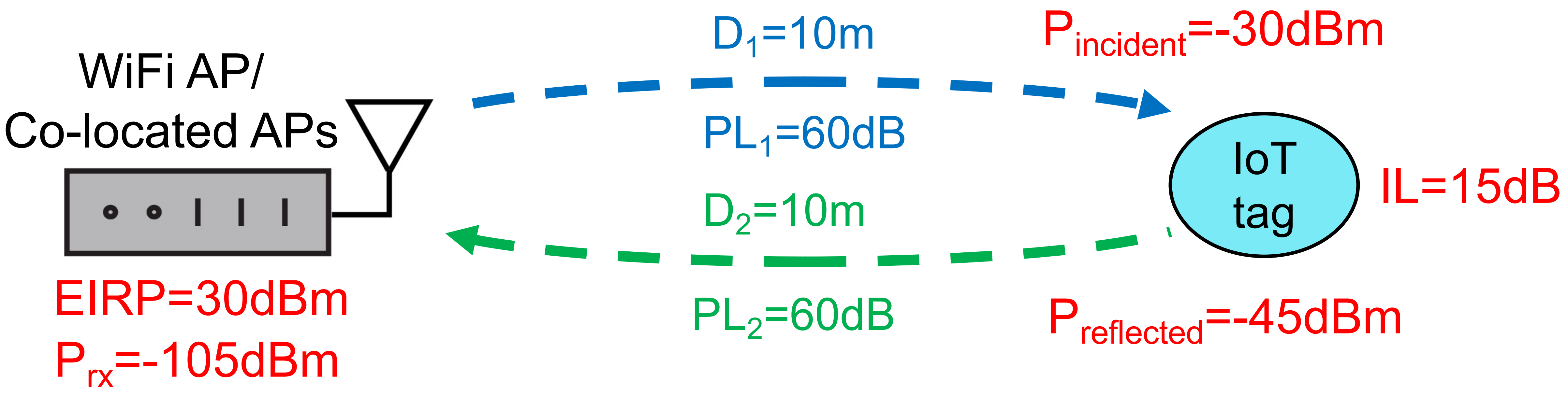



- Tags can work if placed anywhere in the shaded area

Wang et al., *ISSCC20*

# Link budget – single AP or co-located APs

Place for Speaker's video (5cm x 3.5cm)




- Always in the worst-case scenario
- Range improvement is needed for pragmatic adoption in homes and offices with single AP or co-located APs

# Range improvement

Place for Speaker's video (5cm x 3.5cm)

- TX power: can not be increased, standard in commodity WiFi APs and FDA limits to maximum of 30dBm
- RX Sensitivity: ~-100dBm is the standard for commodity WiFi APs
- D1×D2: cannot be improved due to the passive nature of backscatter communication

Improve the insertion loss or apply MIMO gain to improve the covered range

# Outline

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- Motivation
- Prior-art and proposed SSB QPSK backscatter with retro-reflective MIMO array and non-absorbing termination
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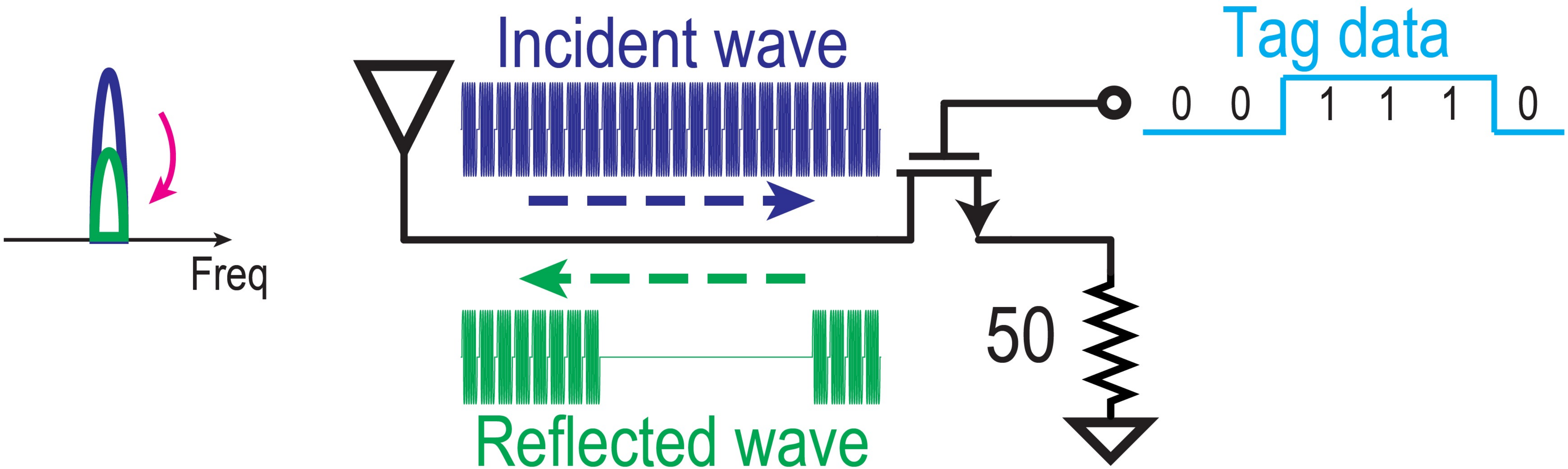
# Conventional OOK backscatter

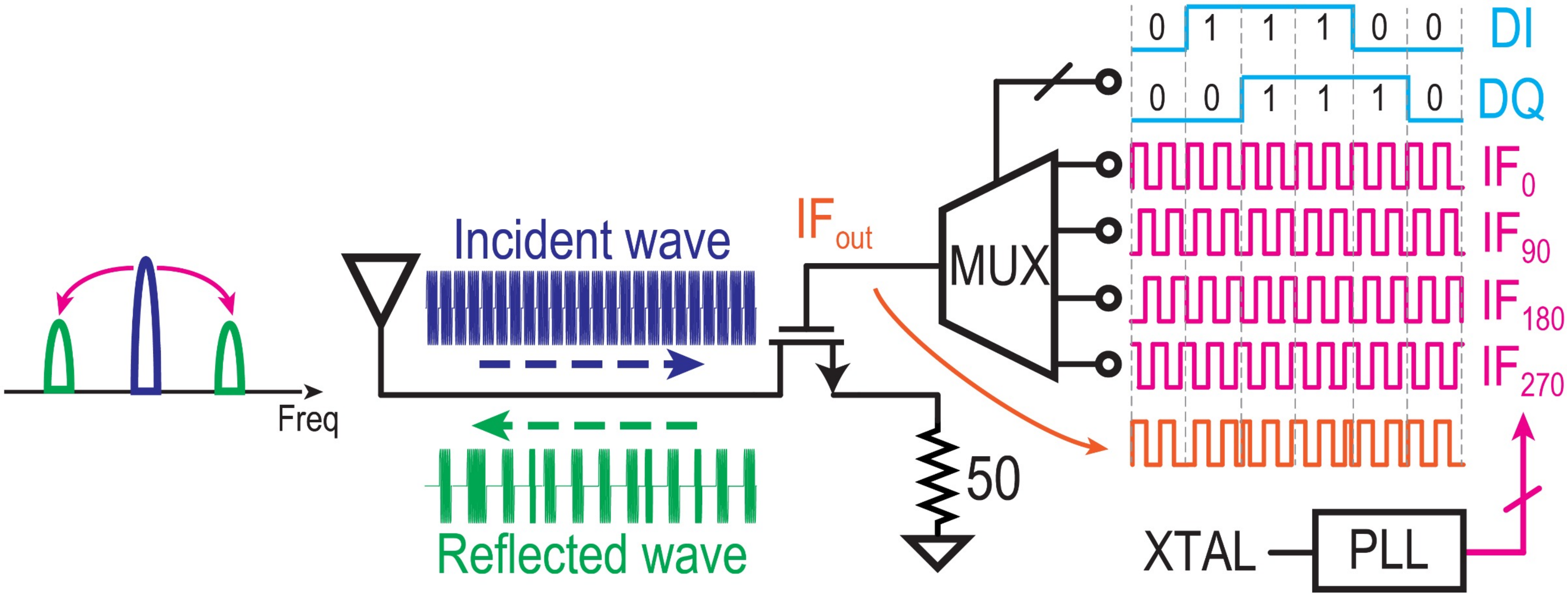
Place for Speaker's video (5cm x 3.5cm)




- Tag data modulates the input impedance via a single switch directly
- ☒ OOK modulation only
- ☒ Reflected wave spectrum overlaps with incident wave

# QPSK frequency translation backscatter

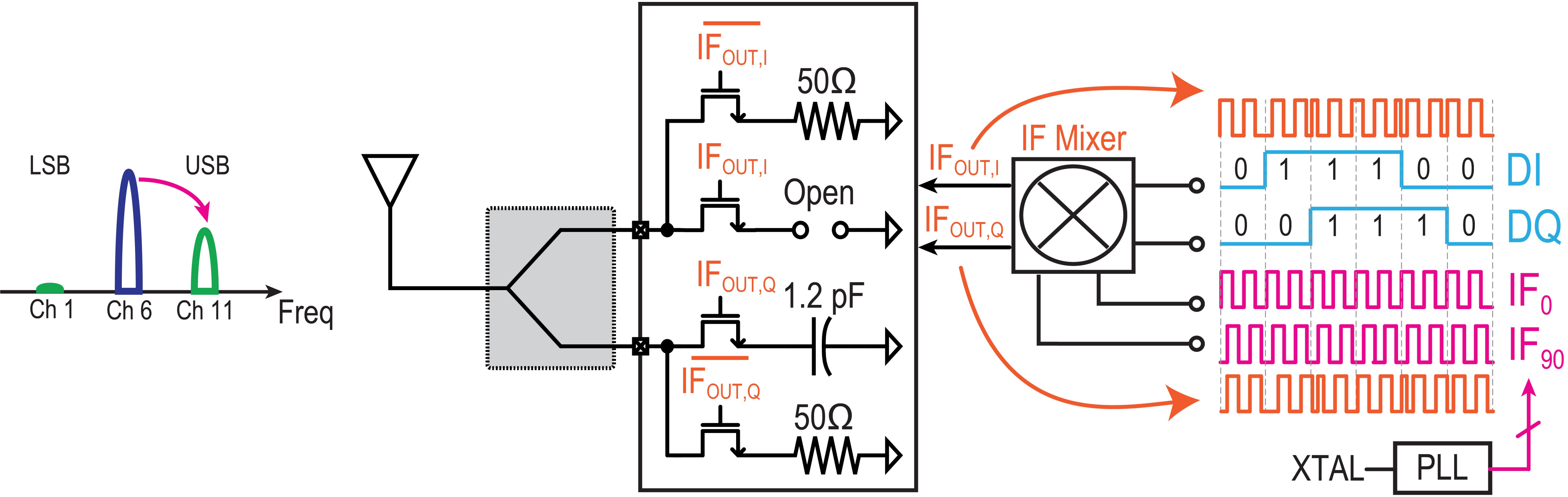
Place for Speaker's video (5cm x 3.5cm)




- 4 phase of IF clock is selected by IQ tag data and mixed with incident signal via a single switch
- ☑ QPSK modulation
- ☒ Double-side-band modulation occupies 2 adjacent channels

# SSB QPSK backscatter

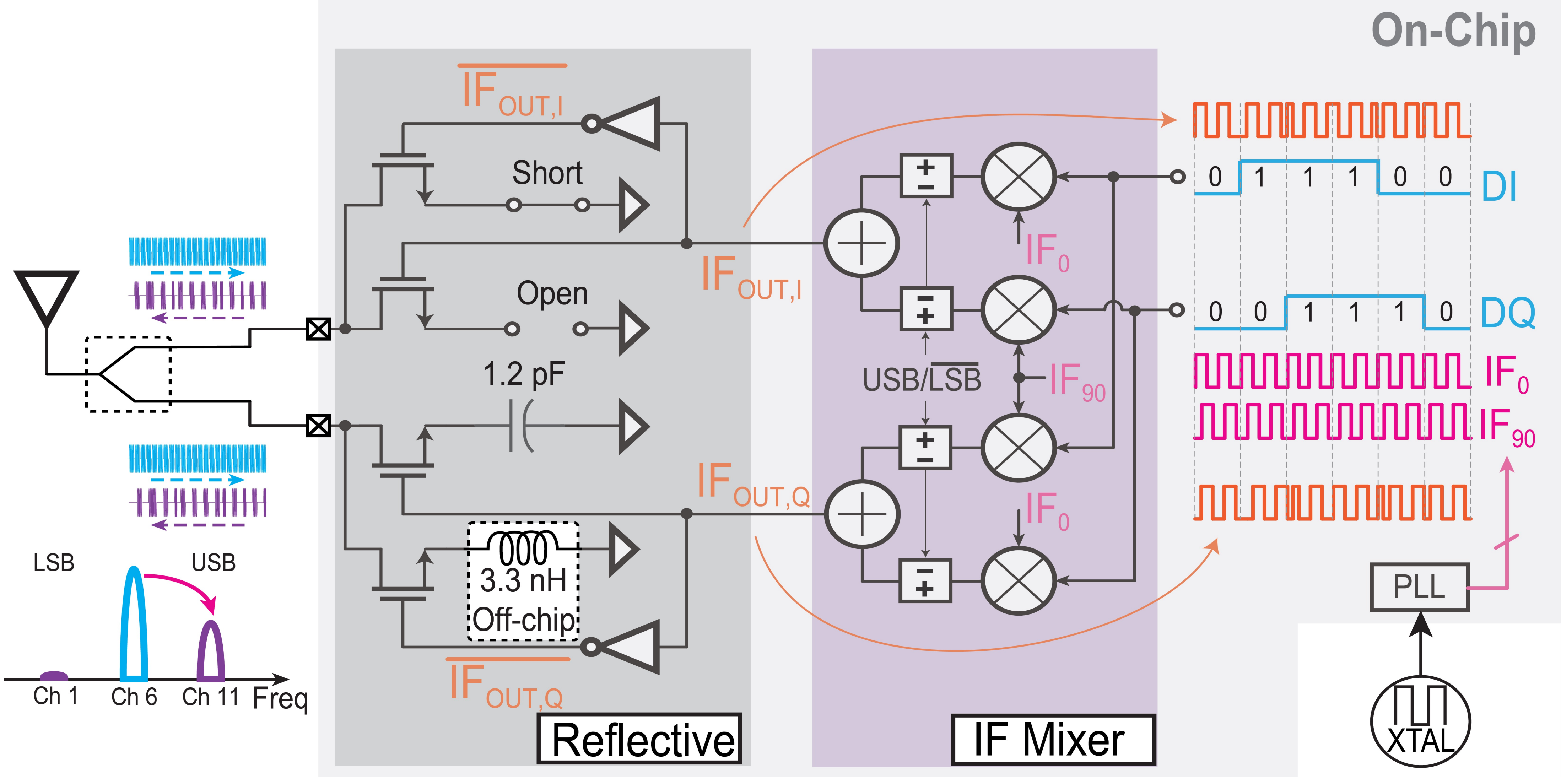
Place for Speaker's video (5cm x 3.5cm)




- ☑ QPSK modulation
- ☑ Single-side-band modulation occupies only one adjacent channel
- ☒ Range is limited to 10m with co-located APs

# Proposed fully-reflective SSB QPSK backscatter

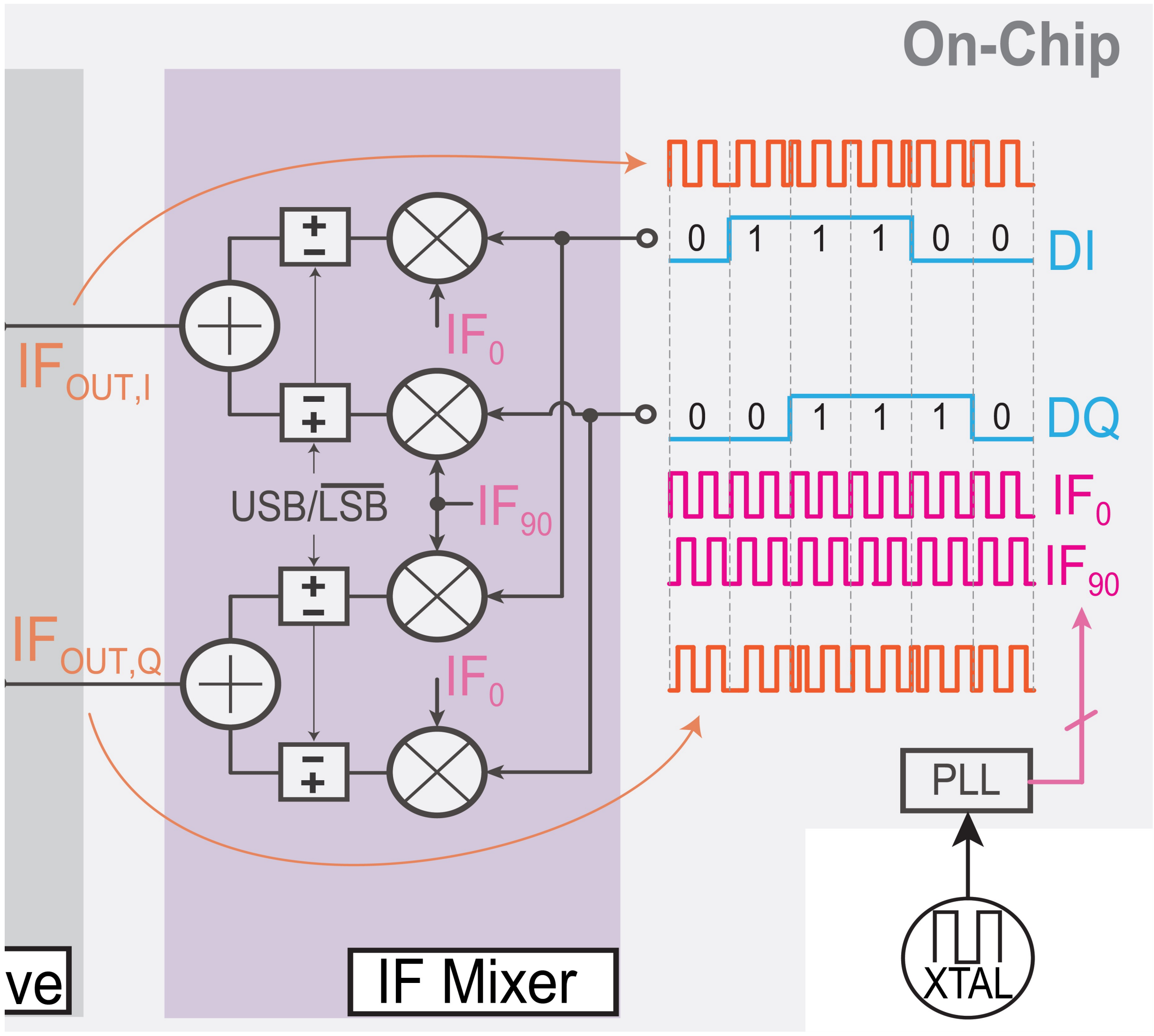
Place for Speaker's video (5cm x 3.5cm)



# Proposed fully-reflective SSB QPSK backscatter

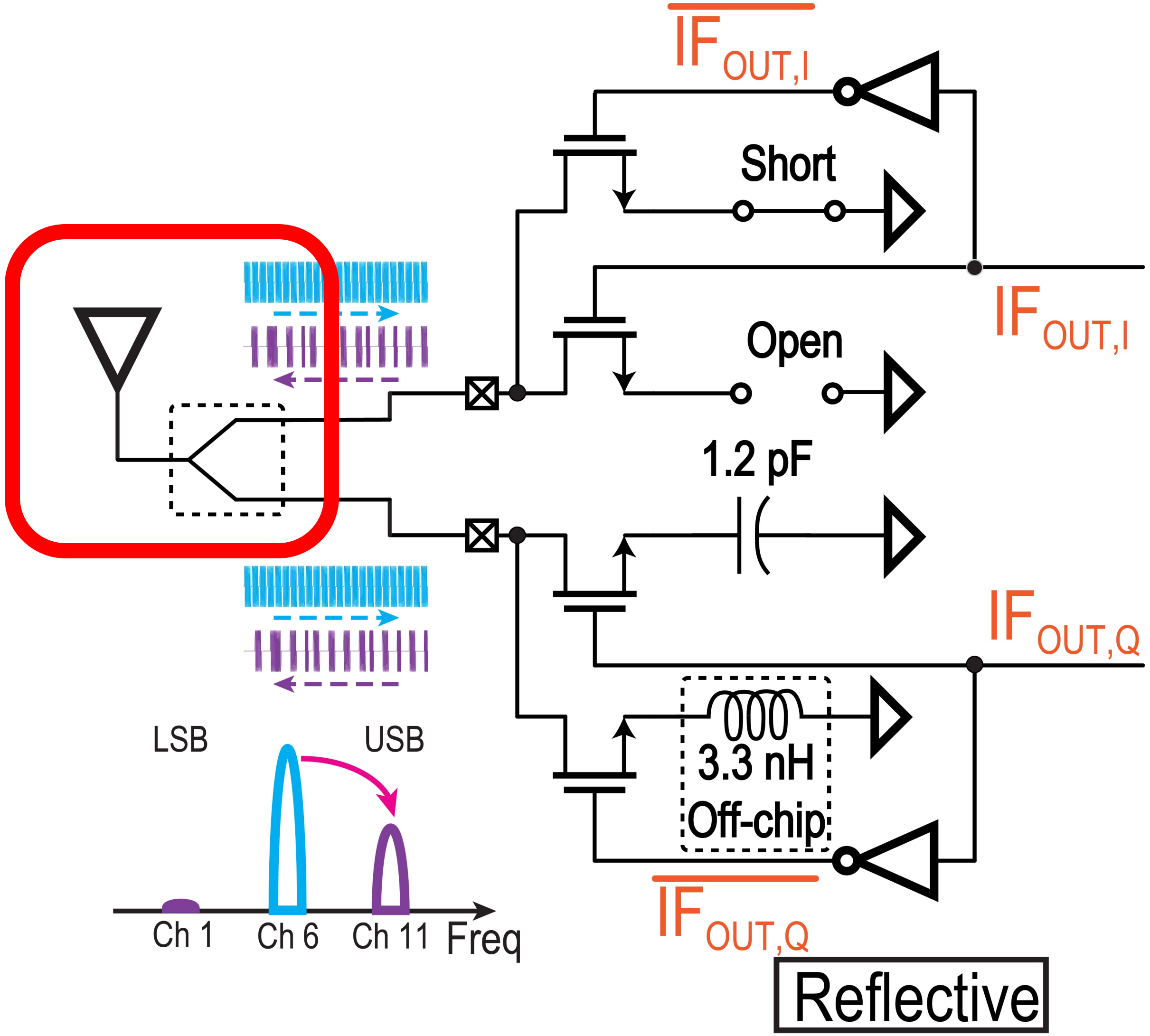
Place for Speaker's video (5cm x 3.5cm)

- IQ tag data is first upconverted to IF via a SSB digital mixer



# Proposed fully-reflective SSB QPSK backscatter

Place for Speaker's video (5cm x 3.5cm)




- Two 90° separated loads provide 90° rotated reflection coefficients

- $Z_{L,0}$= open; $\Gamma_{L,0}$ = 1= $e^{j\times 0°}$
- $Z_{L,}$ … = -j= $e^{j\times -90°}$

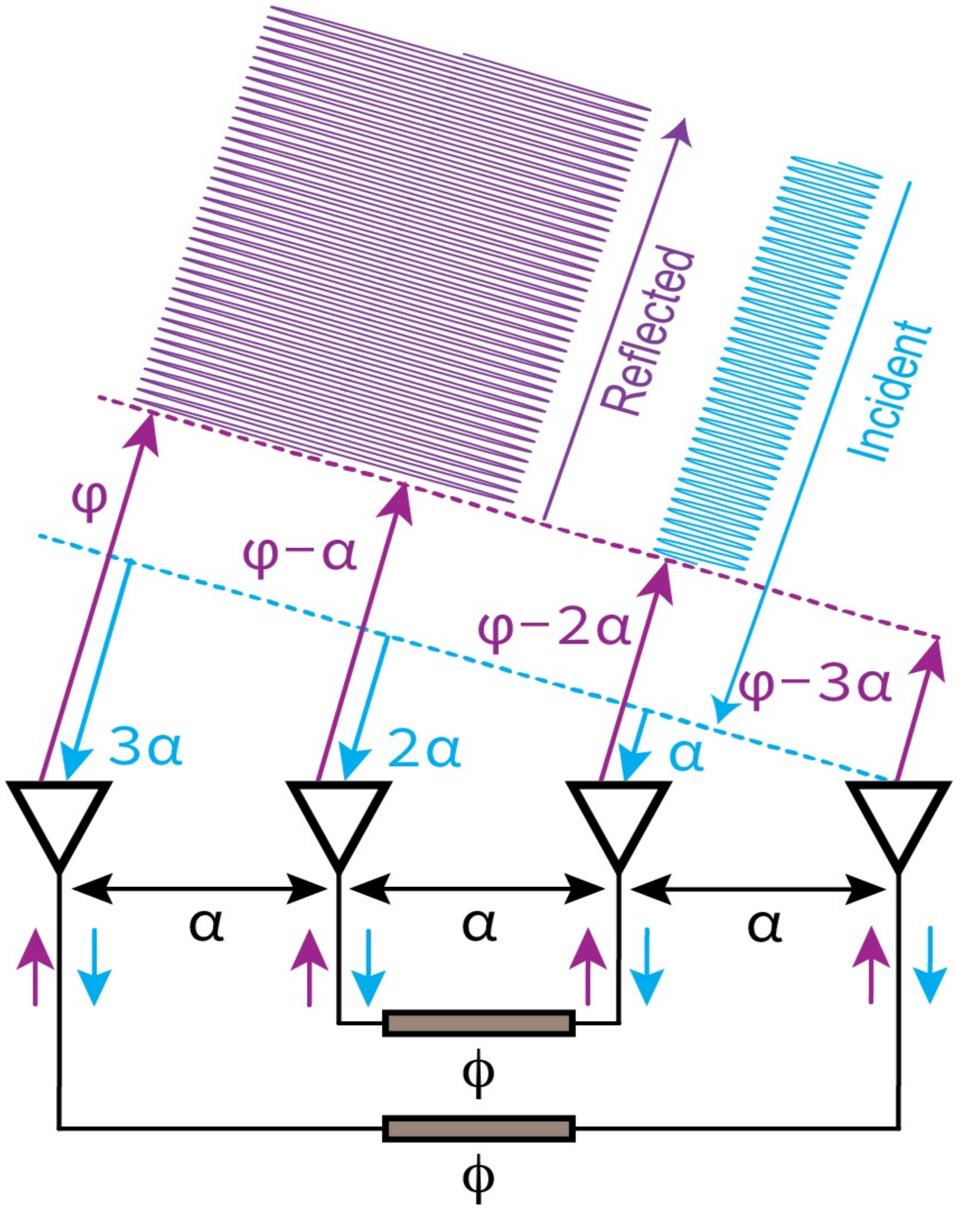
**Improve insertion loss by 6dB without power cost!**

- $Z_{L,180}$= short; $\Gamma_{L,180}$ = -1= $e^{j}$…
- $Z_{L,90}$= j×50 = 3.3nH@2.4GHz; $\Gamma_{L,90}$= -j= $e^{j\times 90°}$

- Quadrature IF signal modulates quadrature RF loading => SSB backscattering
- ☒ Power splitter => Insertion loss
- ☒ Single antenna => No gain

# Passive MIMO – Van Atta antenna array

Place for Speaker's video (5cm x 3.5cm)



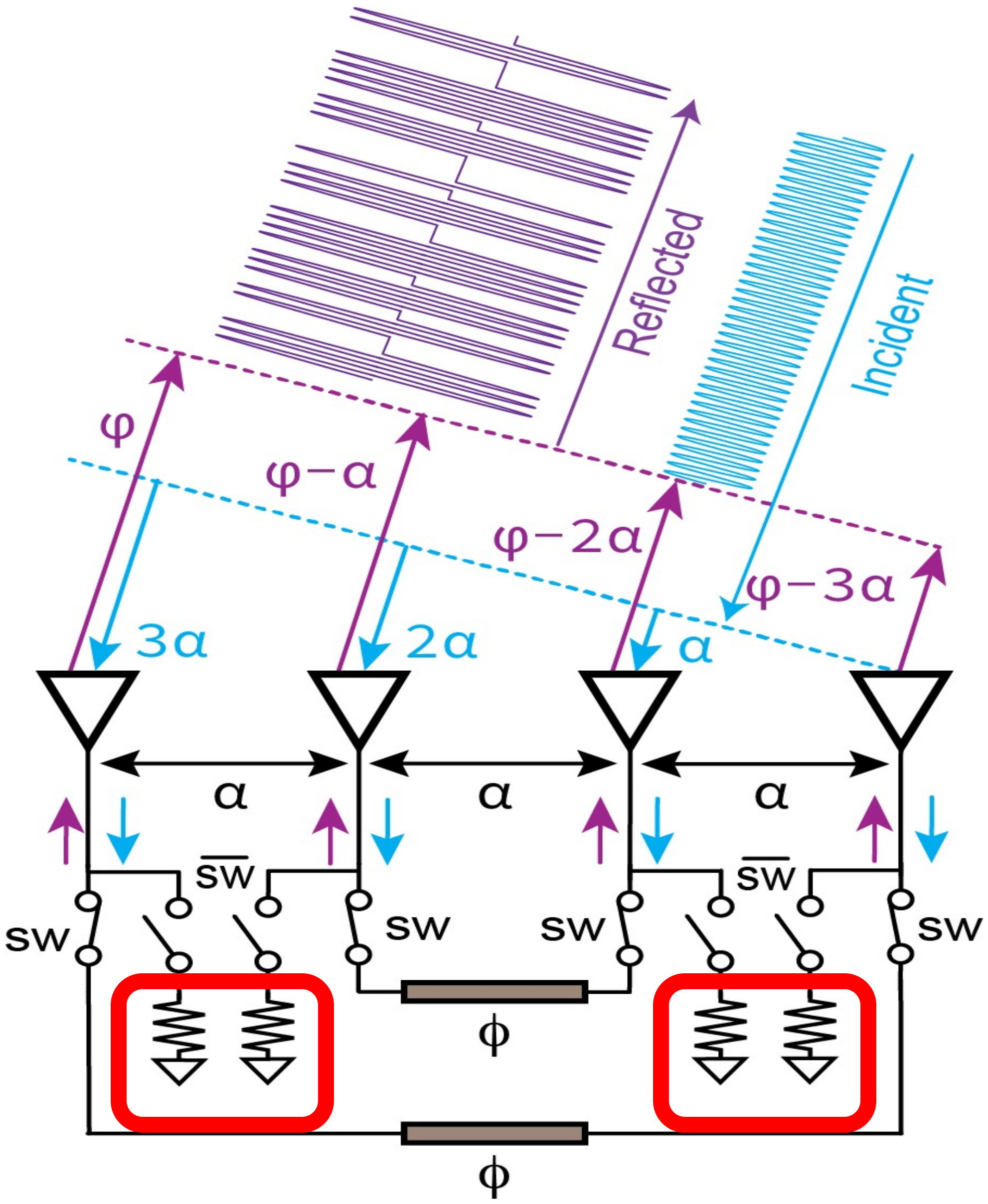

- Passively steers an incident beam back to its source with MIMO gain

- ☑ Reflected signal power is increased

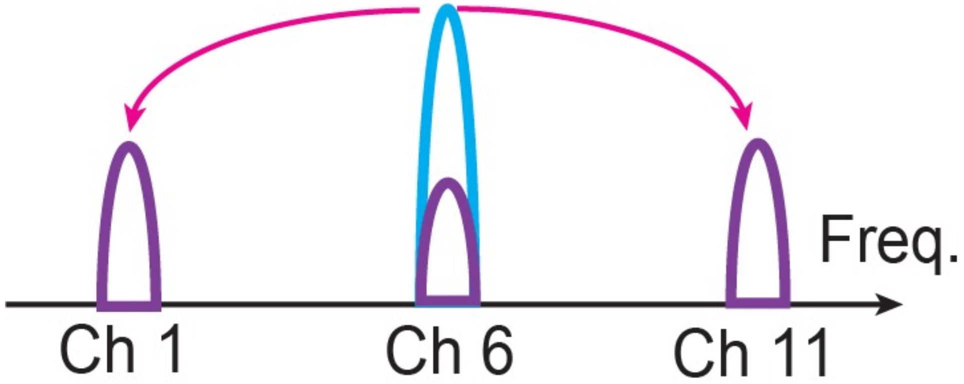
- ☒ No data can be modulated onto reflected signal

# Passive MIMO: one possible implementation

Place for Speaker's video (5cm x 3.5cm)

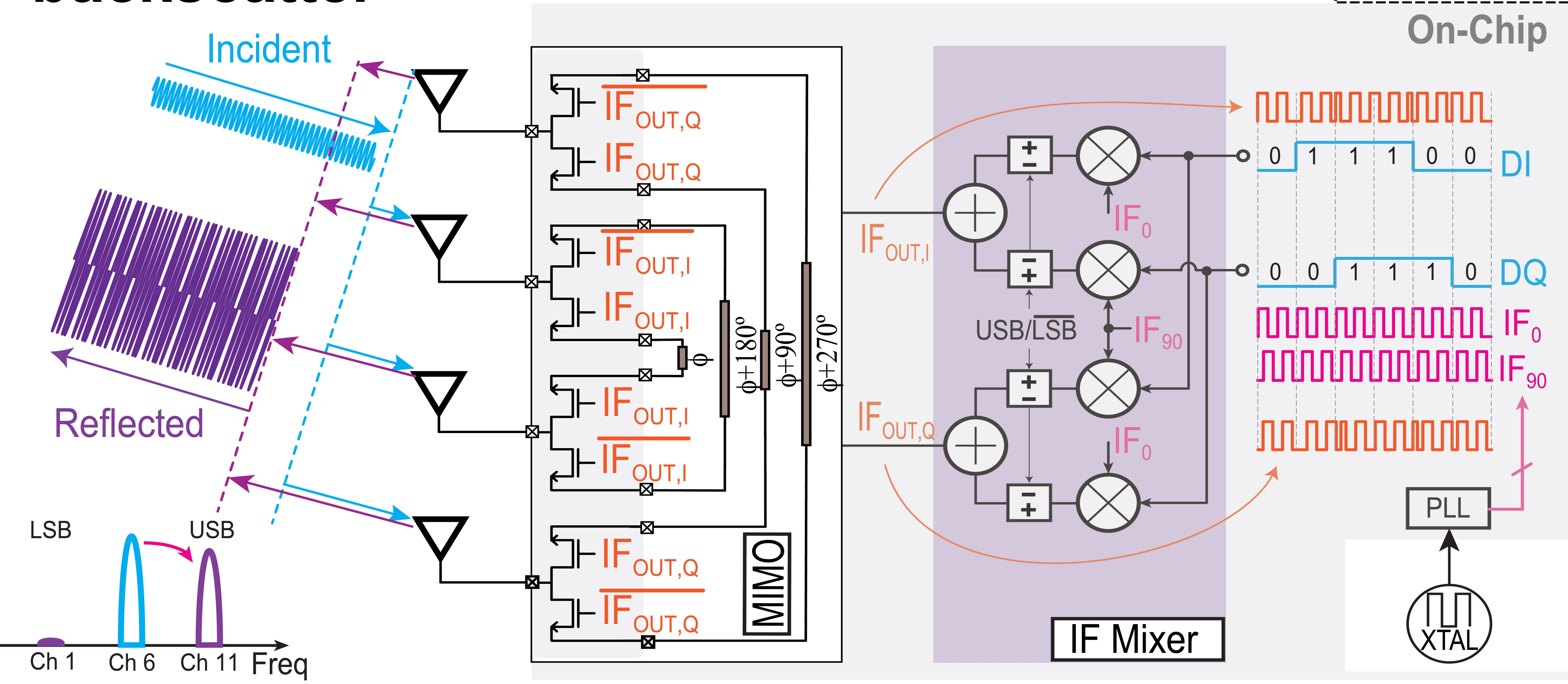



- ☑ Modulated data is reflected with increased signal power
- ☒ Absorbing termination decreases signal power
- ☒ Double-side-band modulation occupies 2 adjacent channels



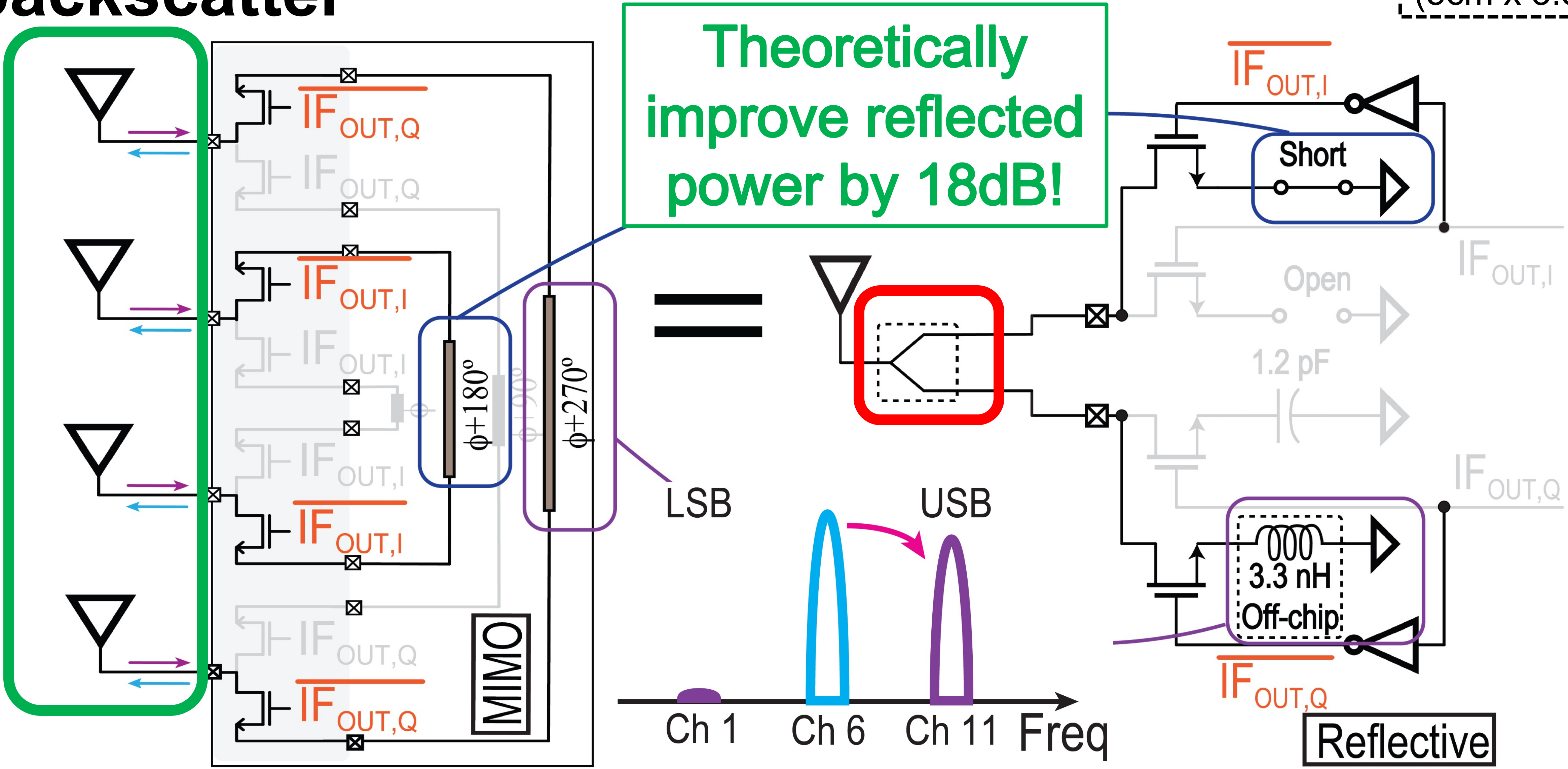
# Proposed retro-reflective SSB MIMO QPSK backscatter

Place for Speaker's video (5cm x 3.5cm)



# Proposed retro-reflective SSB MIMO QPSK backscatter

Place for Speaker's video (5cm x 3.5cm)



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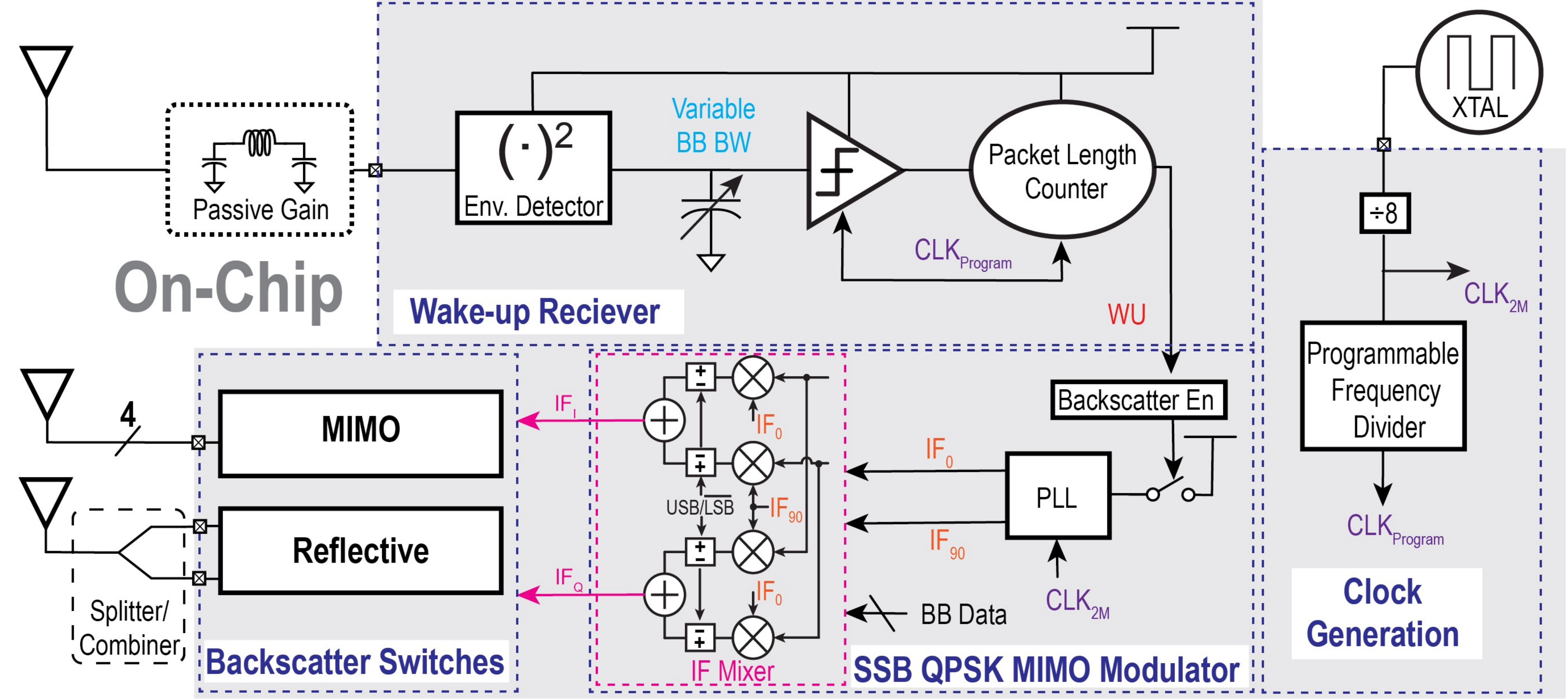
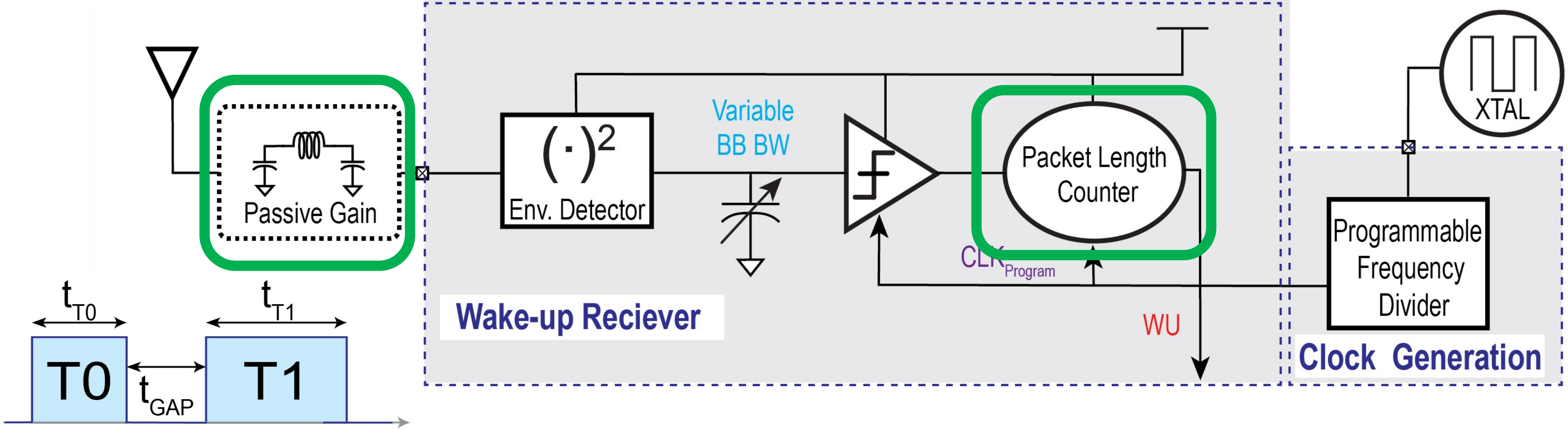
# Block diagram of proposed IoT tag

Place for Speaker's video (5cm x 3.5cm)



# Block diagram of downlink

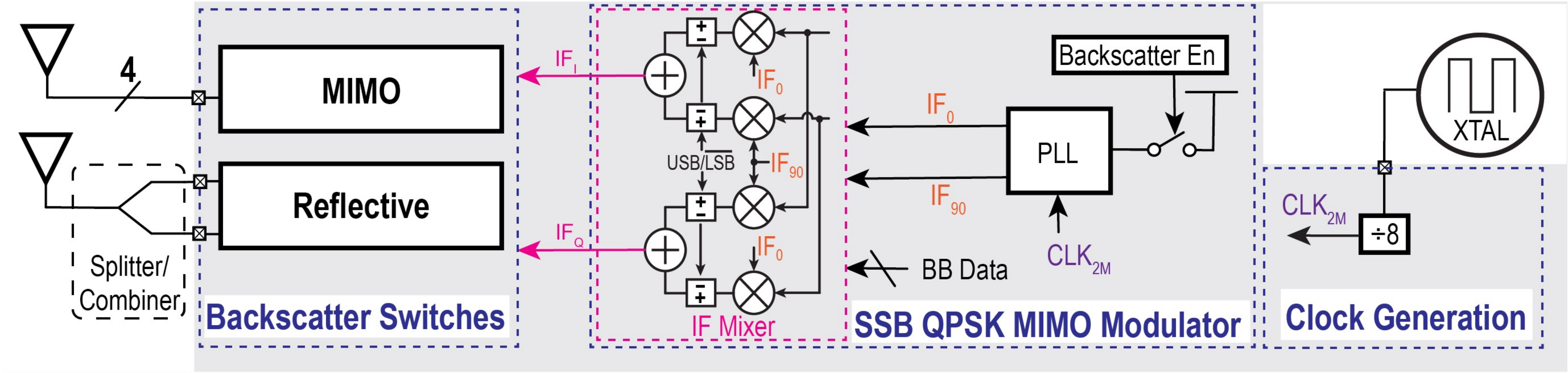
Place for Speaker's video (5cm x 3.5cm)




- Direct envelope detection architecture for low standby power
- 8dB passive voltage gain from input matching network
- WiFi packets counter supports robust WiFi compatible wake-up and multi-tag wake-up regardless of the length of inter-packet gaps

# Block diagram of uplink

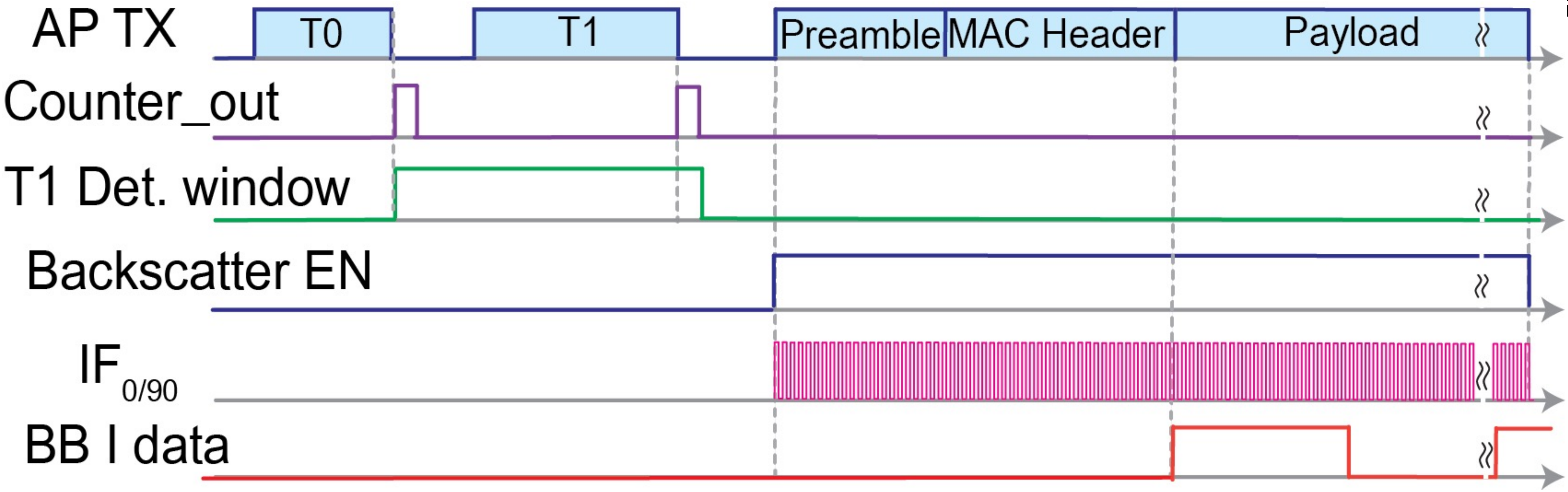
Place for Speaker's video (5cm x 3.5cm)




- A PLL based backscatter modulator enabled by wake-up signal
- PLL provides 25/50MHz frequency translation for backscatter
- IF mixer controls impedance loading for tag data modulation

# Wake up and backscatter timing

Place for Speaker's video (5cm x 3.5cm)




- Robust WiFi-compatible wake-up regardless of the length of gaps between T0 and T1
- A PLL based backscatter modulator enabled by wake-up signal
- PLL provides 25/50MHz frequency translation for backscatter
- IF mixer controls impedance loading for tag data modulation

# Outline

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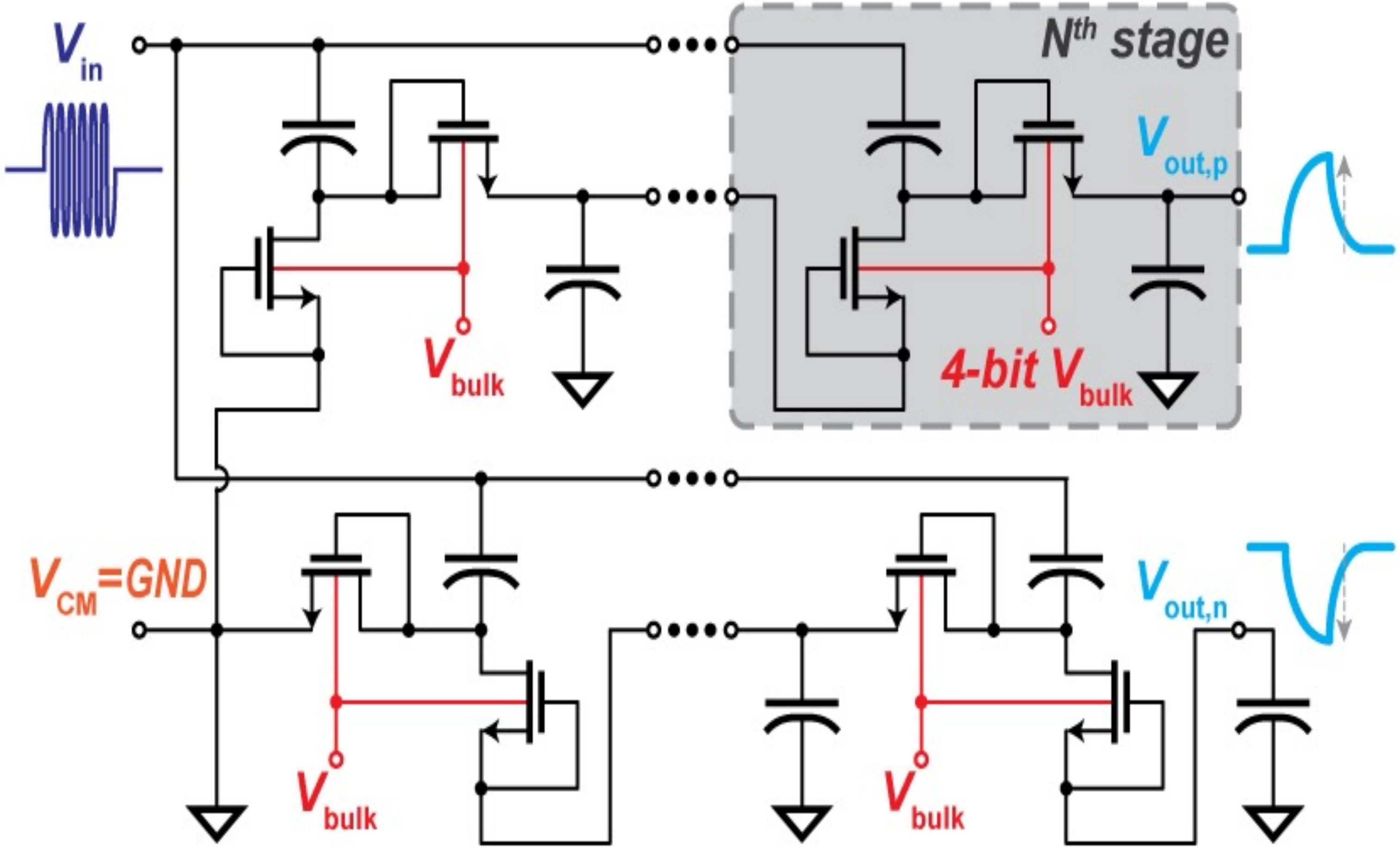
# Passive pseudo-balun envelop detector

Place for Speaker's video (5cm x 3.5cm)

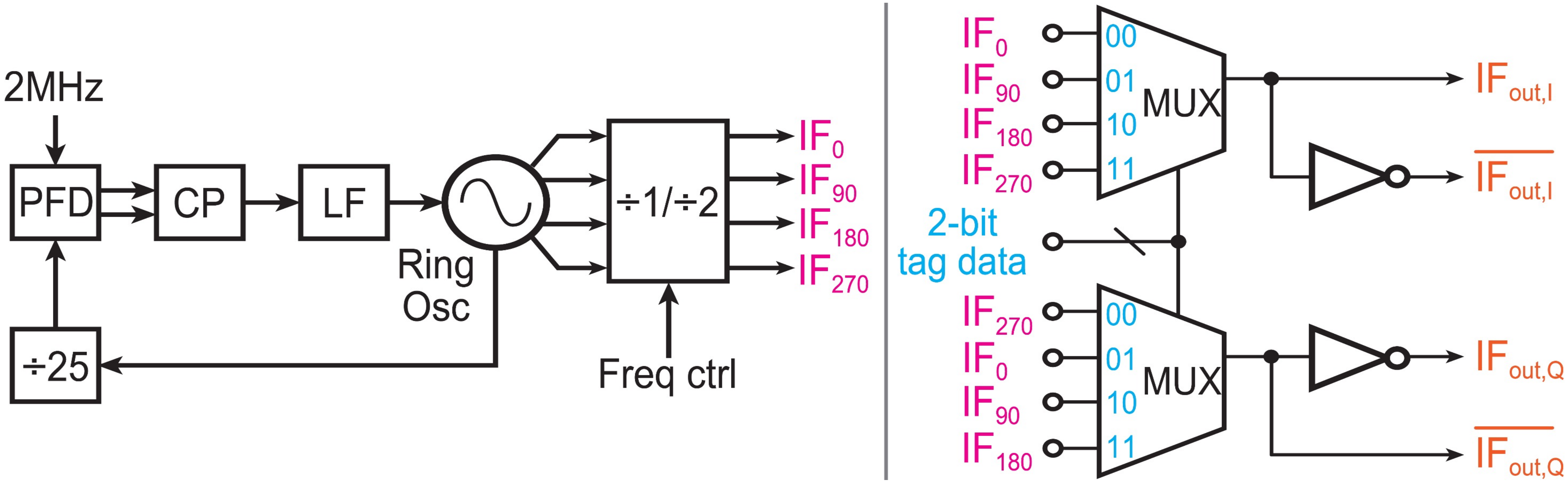



Wang et al., *SSCL'18*

- Single-ended input RF to differential output BB signal
- 2× conversion gain w/o output BW penalty
- 1.5dB sensitivity improvement
- Tunable $V_{th}$ via DNW device bulk control for PVT

# PLL and digital SSB IF mixer

Place for Speaker's video (5cm x 3.5cm)




- Ring oscillator based integer-*N* PLL: 4-phase of output
- Digital SSB IF mixer

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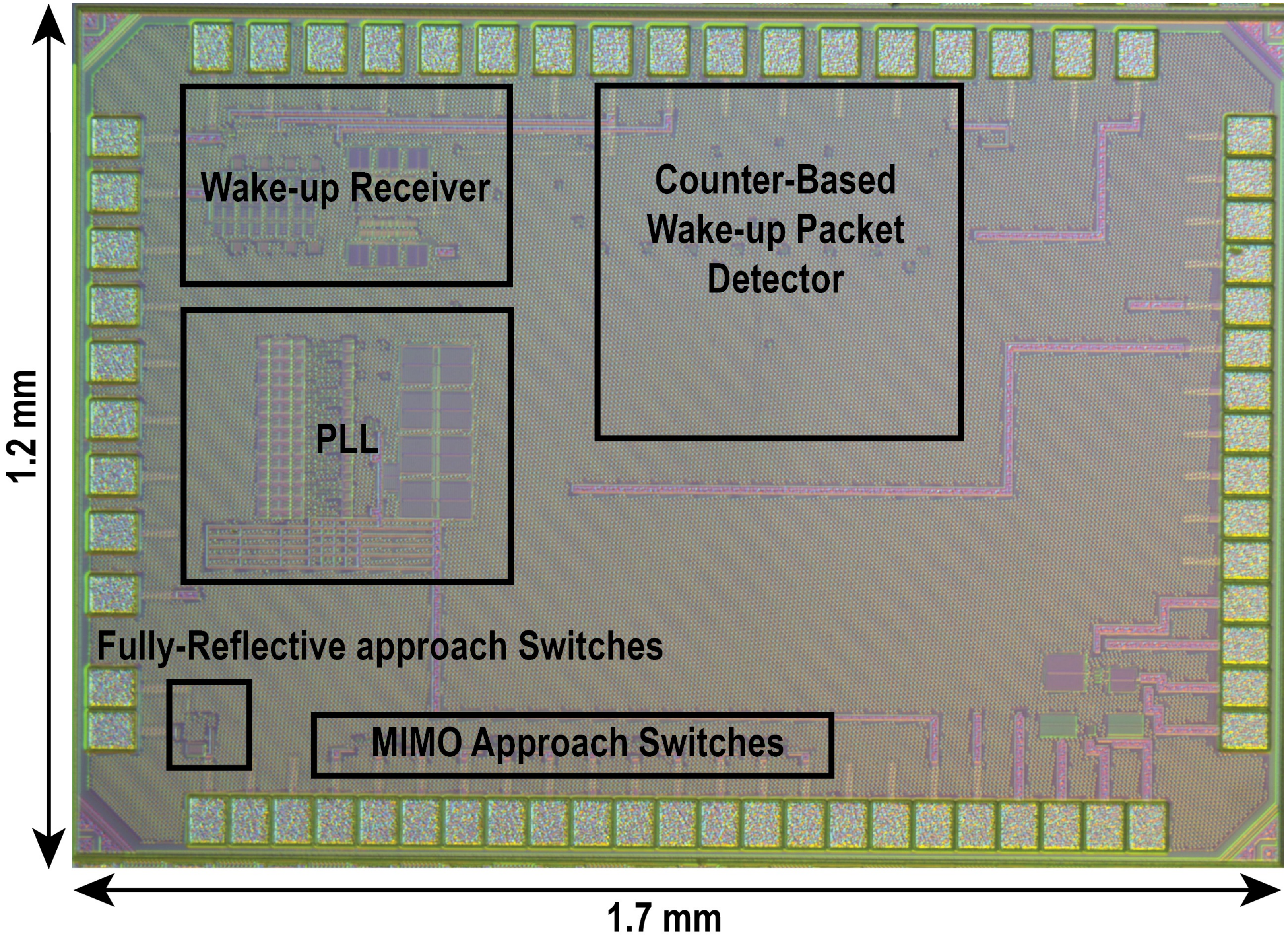
# Die micrograph

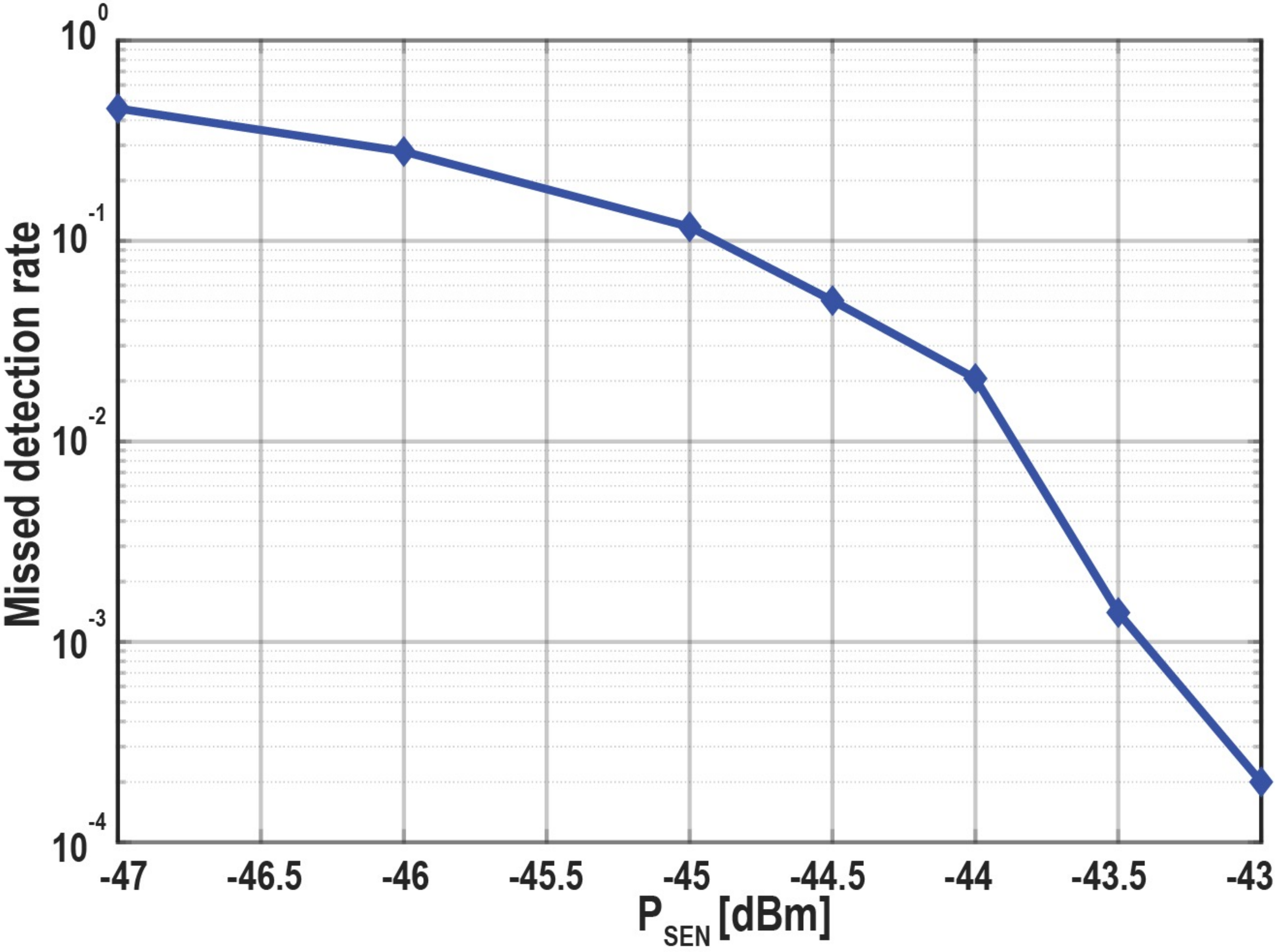
Place for Speaker's video (5cm x 3.5cm)




- 65nm CMOS
- 0.44mm$^2$ active area

# Downlink sensitivity

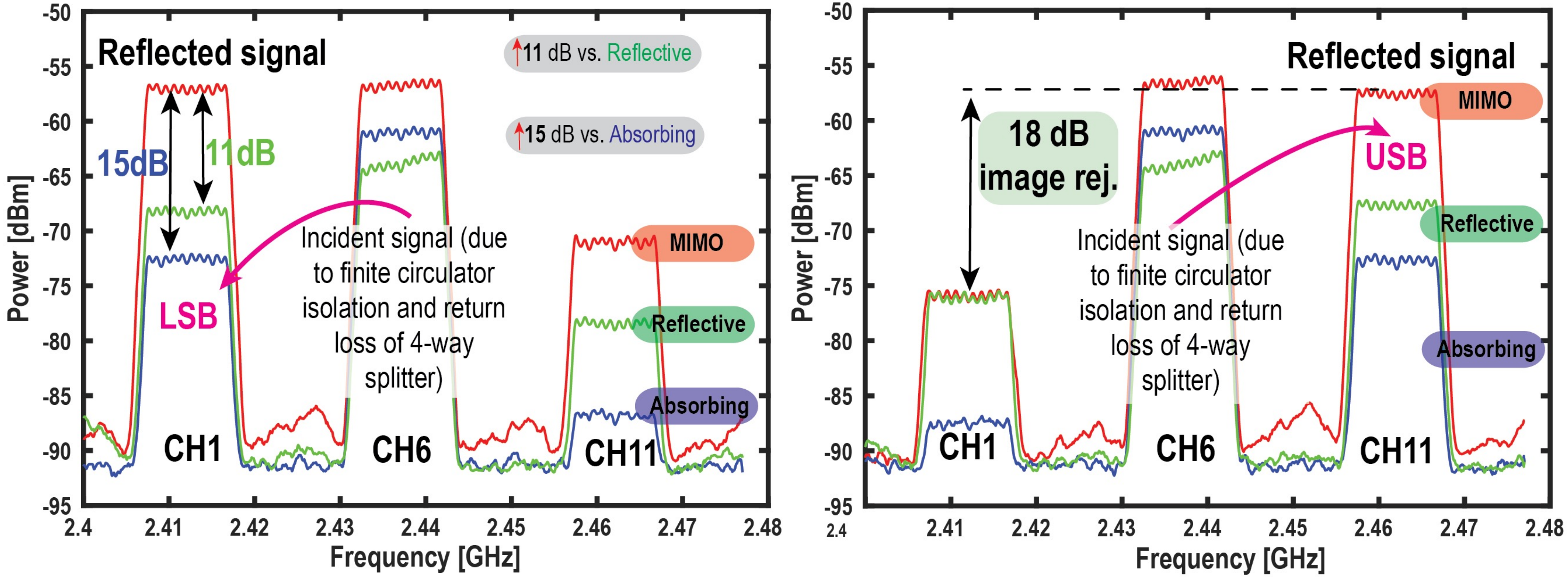
Place for Speaker's video (5cm x 3.5cm)




- -43.4dBm downlink sensitivity for 1e-3 wake-up event missed detection rate
- > 30m wake-up range

# SSB frequency translation

Place for Speaker's video (5cm x 3.5cm)




- Incident signal at CH6 reflected to either CH1 or CH11 based on logic setting with up to 18dB image rejection
- 11dB improvement of passive MIMO compared to reflective method and 15dB improvement over absorbing method

# Wake-up and backscatter transient measurement

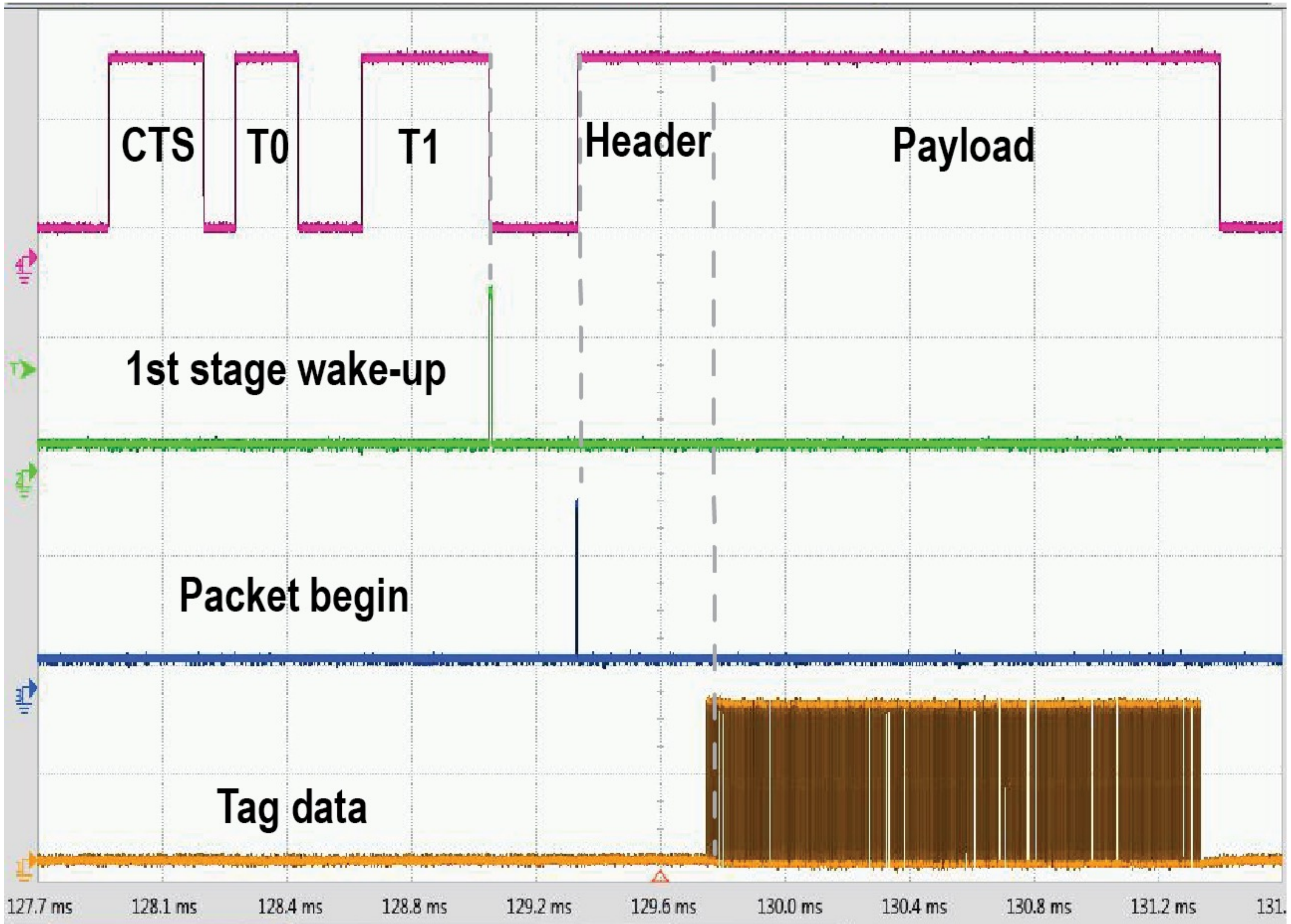
Place for Speaker's video (5cm x 3.5cm)

Packet envelope

Wake-up signal

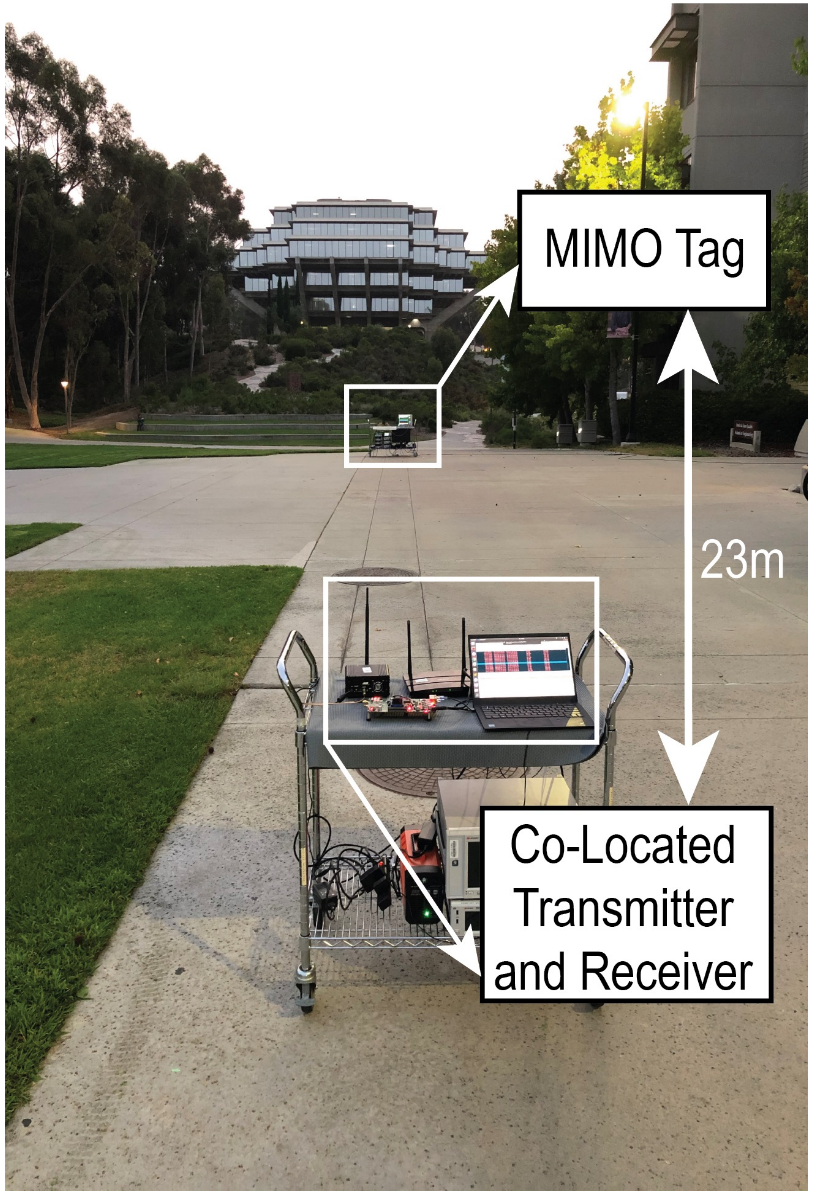
Backscatter En

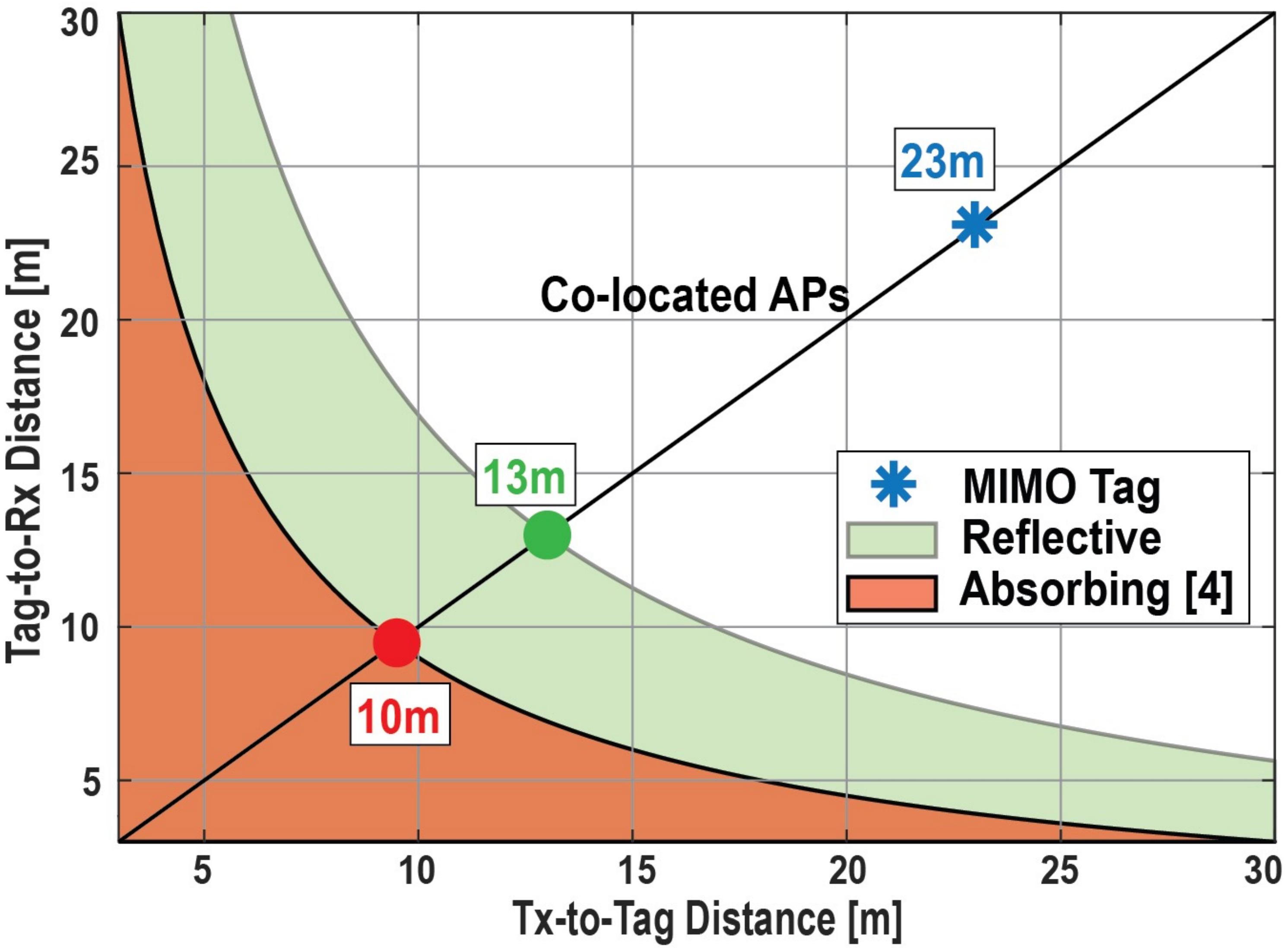
Tag data



# Wireless experiment - range

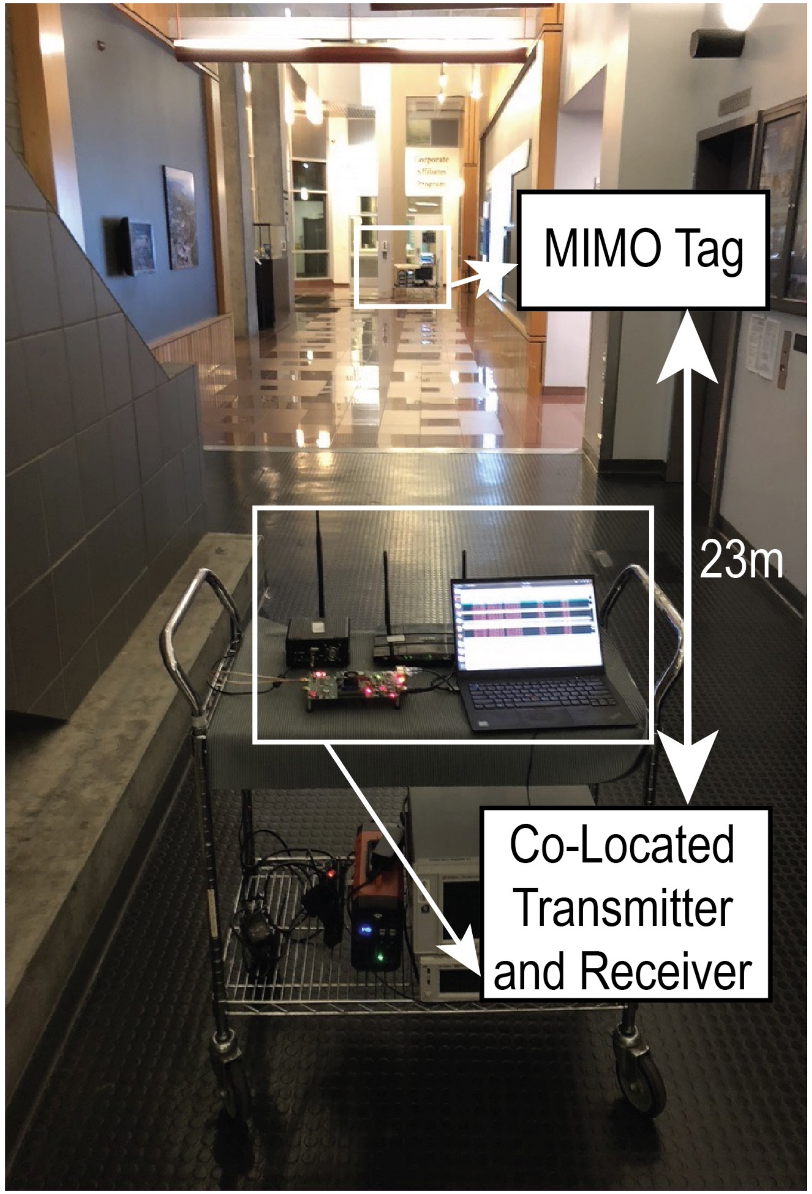
Place for Speaker's video (5cm x 3.5cm)

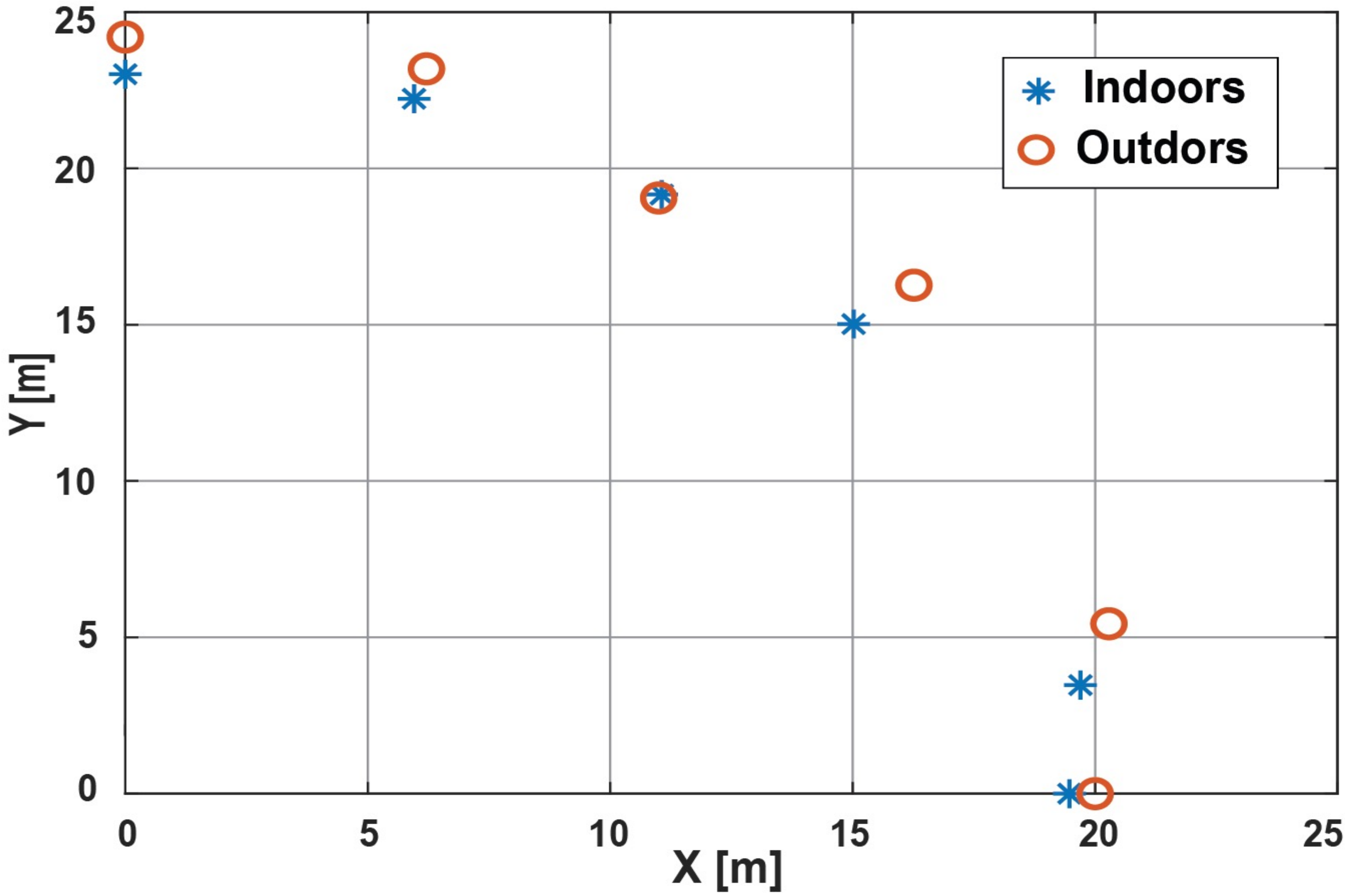


# Wireless experiment - angle

Place for Speaker's video (5cm x 3.5cm)



# Comparison to prior art

Place for Speaker's video (5cm x 3.5cm)

| | [1] | [2] | [3] | [4] | This work | |
|---|---|---|---|---|---|---|
| | | | | | Fully-Reflective | MIMO |
| Technology (nm) | 65 | NA | NA | 65 | 65 | |
| Scheme | Backscatter | Backscatter | SSB WiFi Backscatter | SSB Partially Absorbing WiFi Backscatter | SSB Fully Reflective WiFi Backscatter | SSB Passive Retro-Reflective MIMO WiFi Backscatter |
| Frequency (GHz) | 5.8 | 2.4 | 2.4 | 2.4 | 2.4 | |
| Incident signal source | Tone Transmitter | Tone Transmitter | WiFi | WiFi | WiFi | |
| Wake-up power (μW) | 8.2 | 18 (COTS) | NA | 2.8 | 4.5 | |
| Backscatter communication power (μW) | 113 | 59.2** | 33** | 28 | 32 | 38 |
| Range: equidistance TX and RX (m) | 0.1 | 4.6 | 6 | 10.5 | 13 | >23 |

*Simulated

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# Conclusion

Place for Speaker's video (5cm x 3.5cm)

- The first IC demonstrating WiFi-compatible passive MIMO backscatter communication to cover >1600 $m^2$ area towards pragmatic adoption in home and office environment
- A fully-reflective backscatter communication with ~13 m communication range for device-area-restricted applications
- Low power: A 4.5μW standby power, 32μW for fully reflective and 38μW for passive MIMO
- Acknowledgement: This work was supported in part by the National Science Foundation (NSF) under Grant No. 1923902.