A 28μW IoT Tag That Can Communicate with Commodity WiFi Transceivers via a Single-Side-Band QPSK Backscatter Communication Technique

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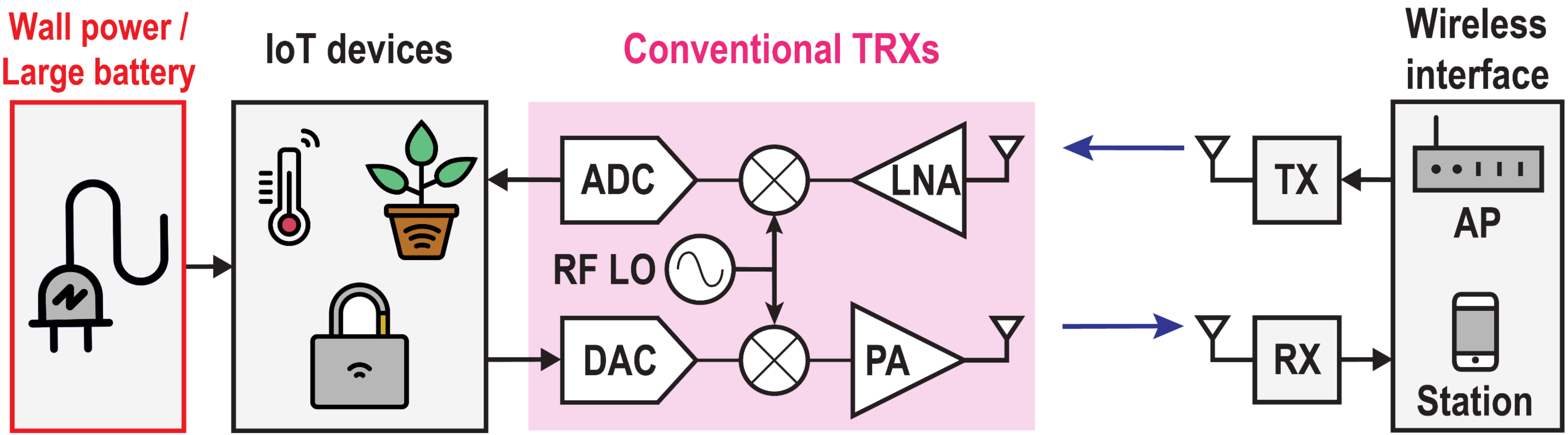
UCSD

Miniature and ubiquitous IoT devices

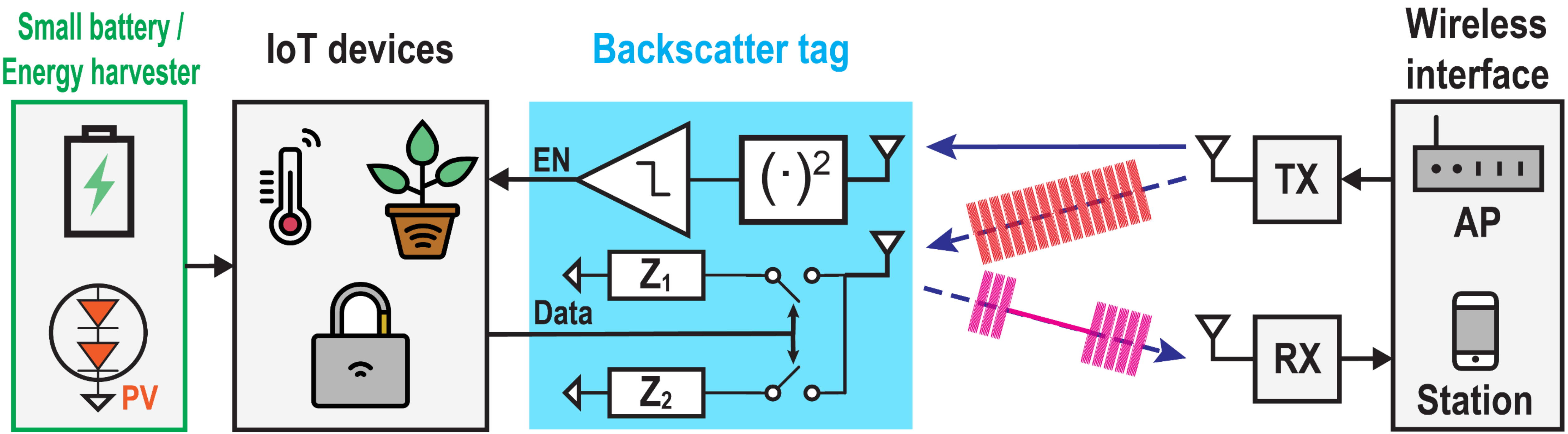
- Enable new class of applications
- Require miniature size, long lifetime, and wireless standard-compliant

Conventional wireless transmission



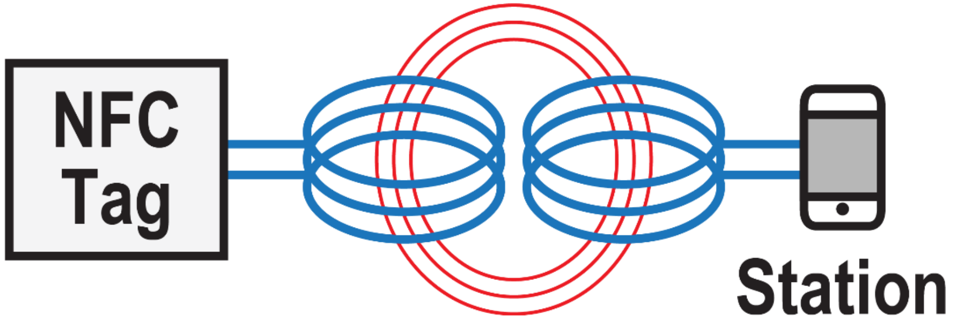
- ☒ Conventional WiFi TRXs require 10s~100s mW active power
- ☒ Size of IoT devices is limited by power consumption
- ☑ Higher order modulation is achievable but trades-off with power

Backscatter communication – basic concept

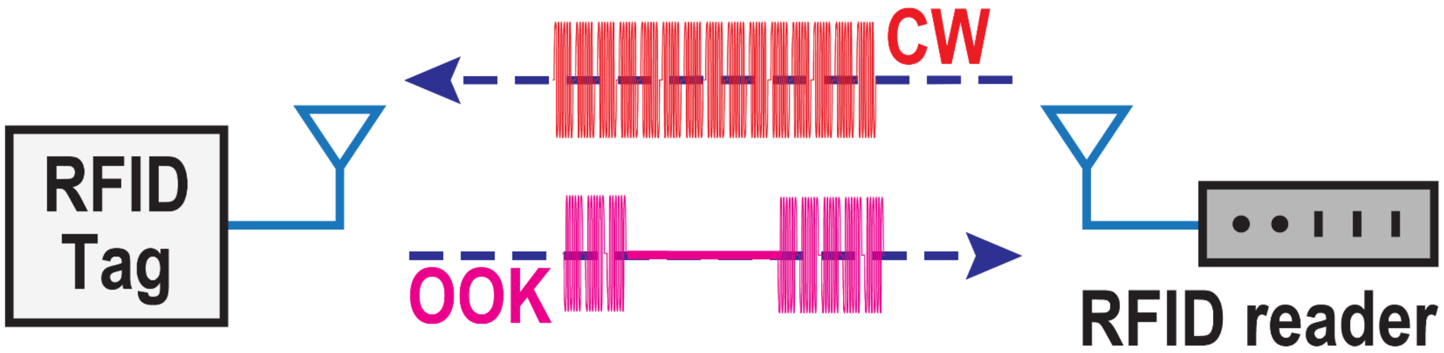


- ☑ Elimination of active RF circuit enables low power consumption
- ☒ Single-tone incident wave is not compatible with existing standards
- ☒ Modulation is limited to on-off-keying (OOK)

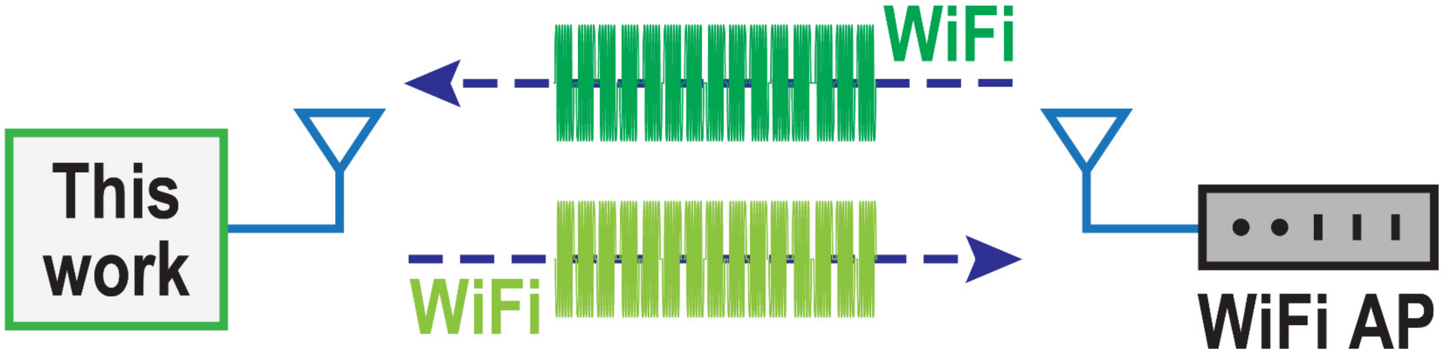
Backscatter communication – range/interference



- Near-field inductive coupling
- ☒10s of cm range; 13.56MHz
- ☑ No RF interference concern



- Far-field radiative coupling
- ☑10s of meter; 0.4~2.4GHz
- ☒ CW/OOK: susceptible to interference

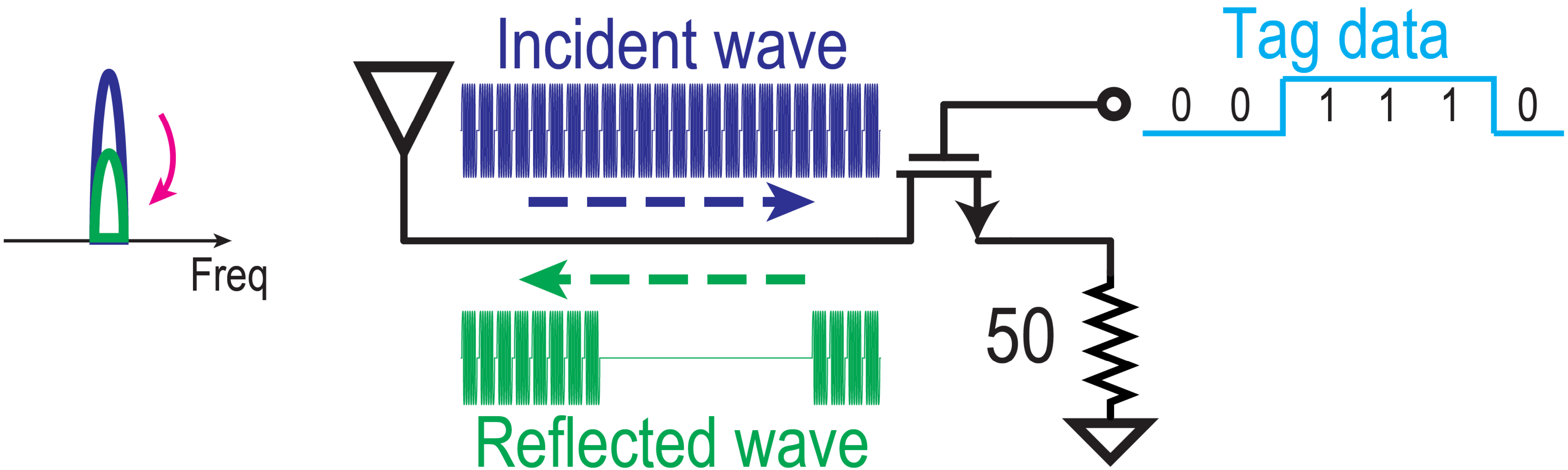


- ☑ 10s of meter range
- ☑ 2.4GHz WiFi compatible
- ☑ Modulation reduces interference (ex: PSK; DSSS)

Outline

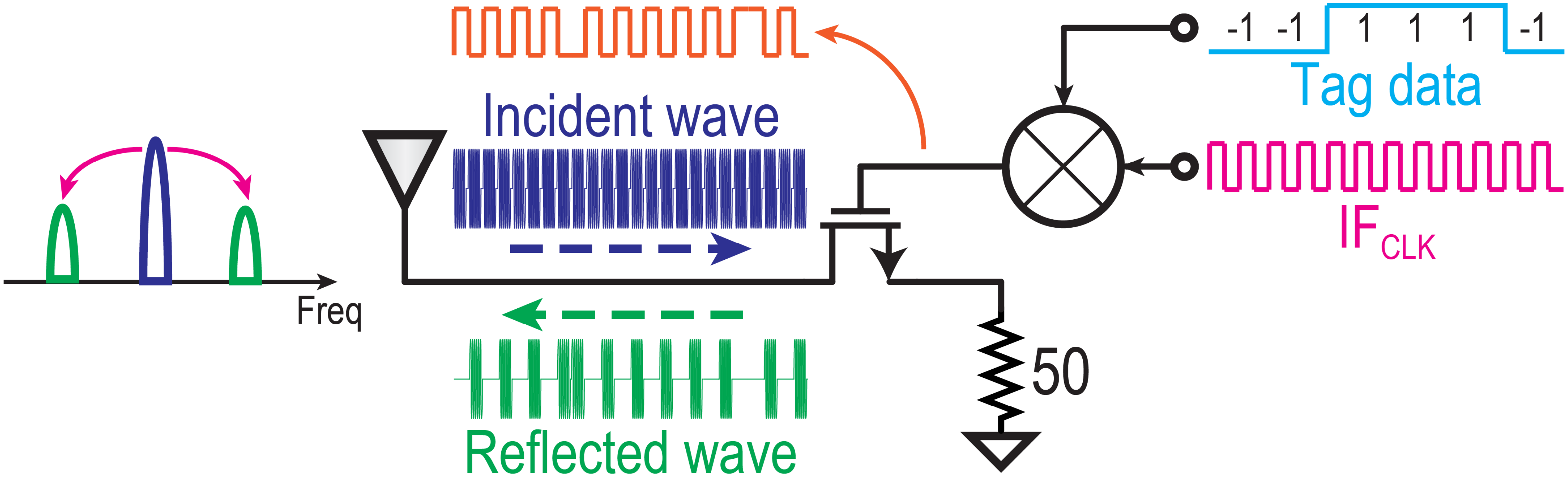
- Motivation
- Prior-art and proposed SSB QPSK backscatter modulation
- Prior-art and proposed WiFi-compliant backscatter solution
- Circuit implementation
- Measurement results
- Conclusion

Conventional OOK backscatter



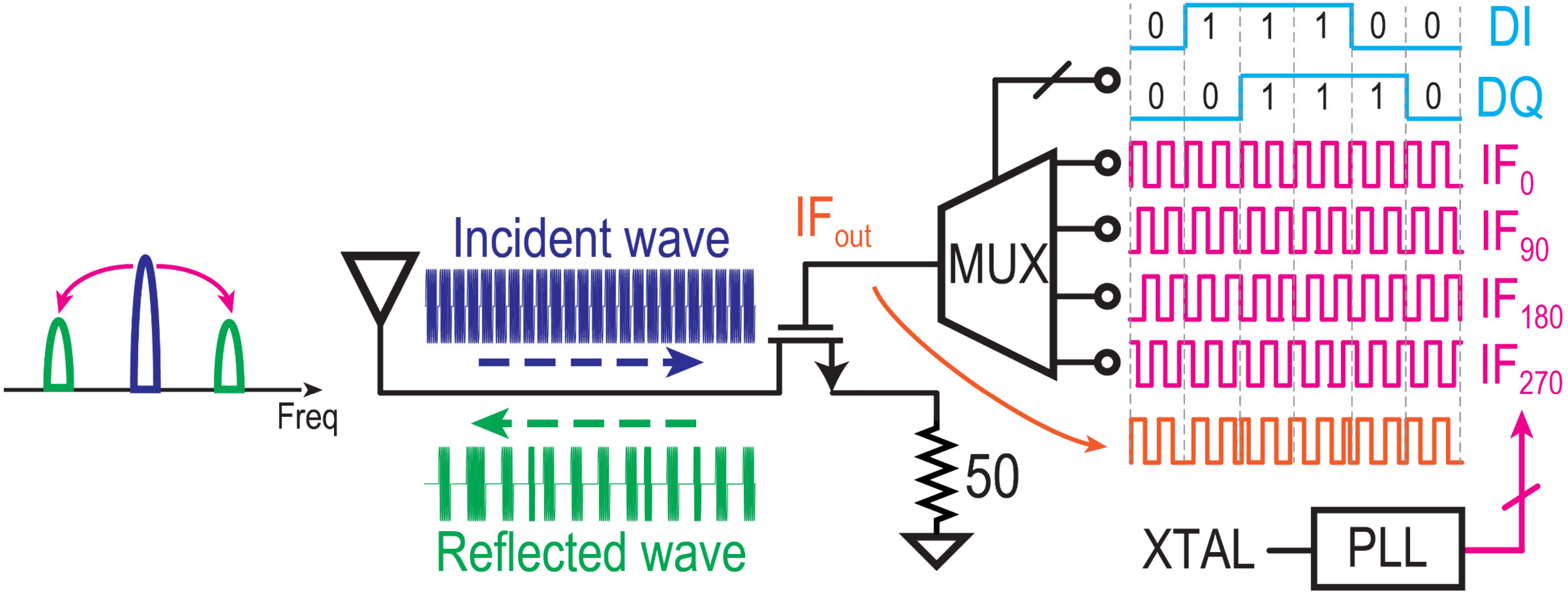
- Tag data modulates the input impedance via a single switch directly
- ☒ OOK modulation only
- ☒ Reflected wave spectrum overlaps with incident wave

Frequency translation backscatter



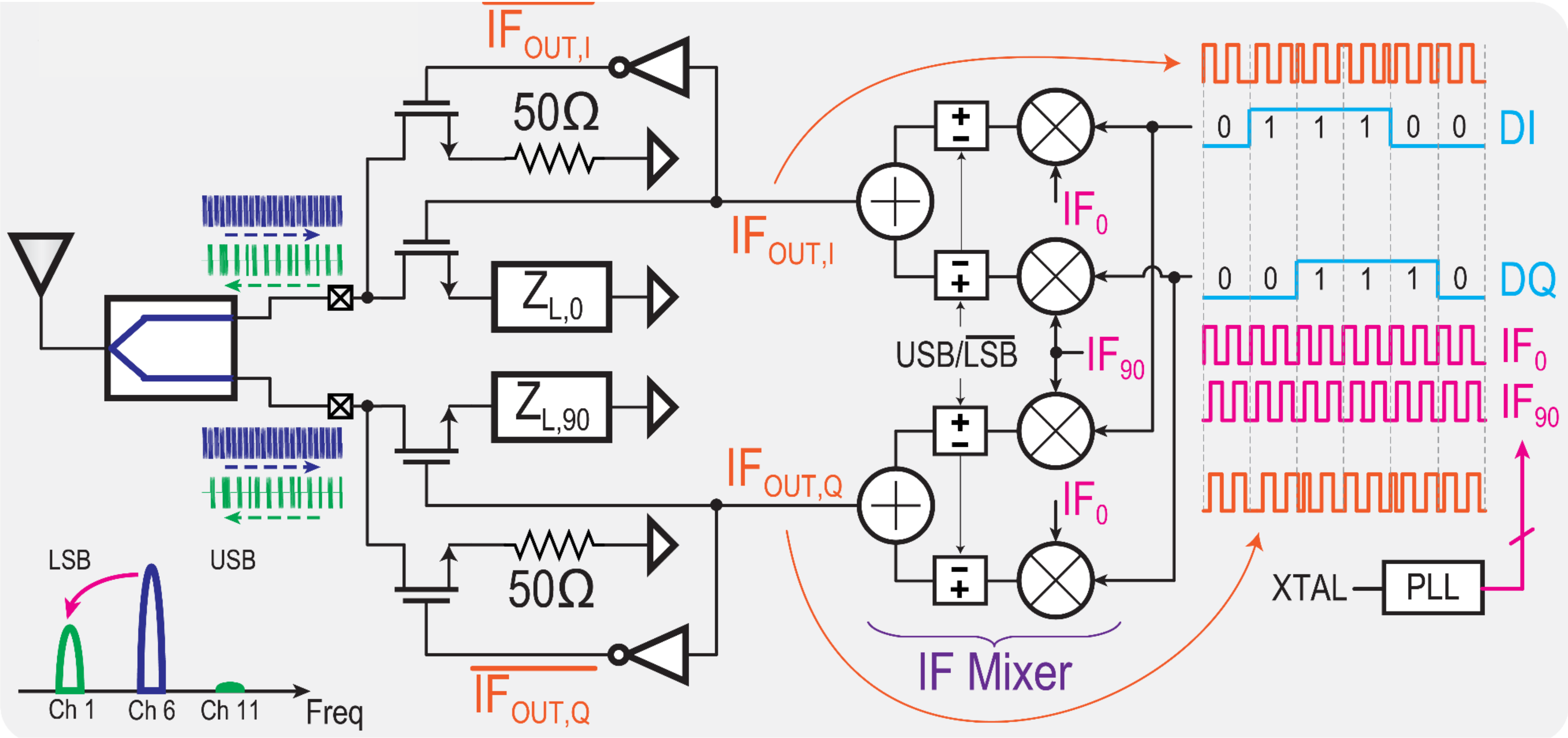
- Tag data is upconverted to IF first and mixed with incident signal
- ☑ Reflected wave spectrum is translated to adjacent channel
- ☒ Double-side-band modulation occupies 2 adjacent channels
- ☒ BPSK modulation only

QPSK frequency translation backscatter



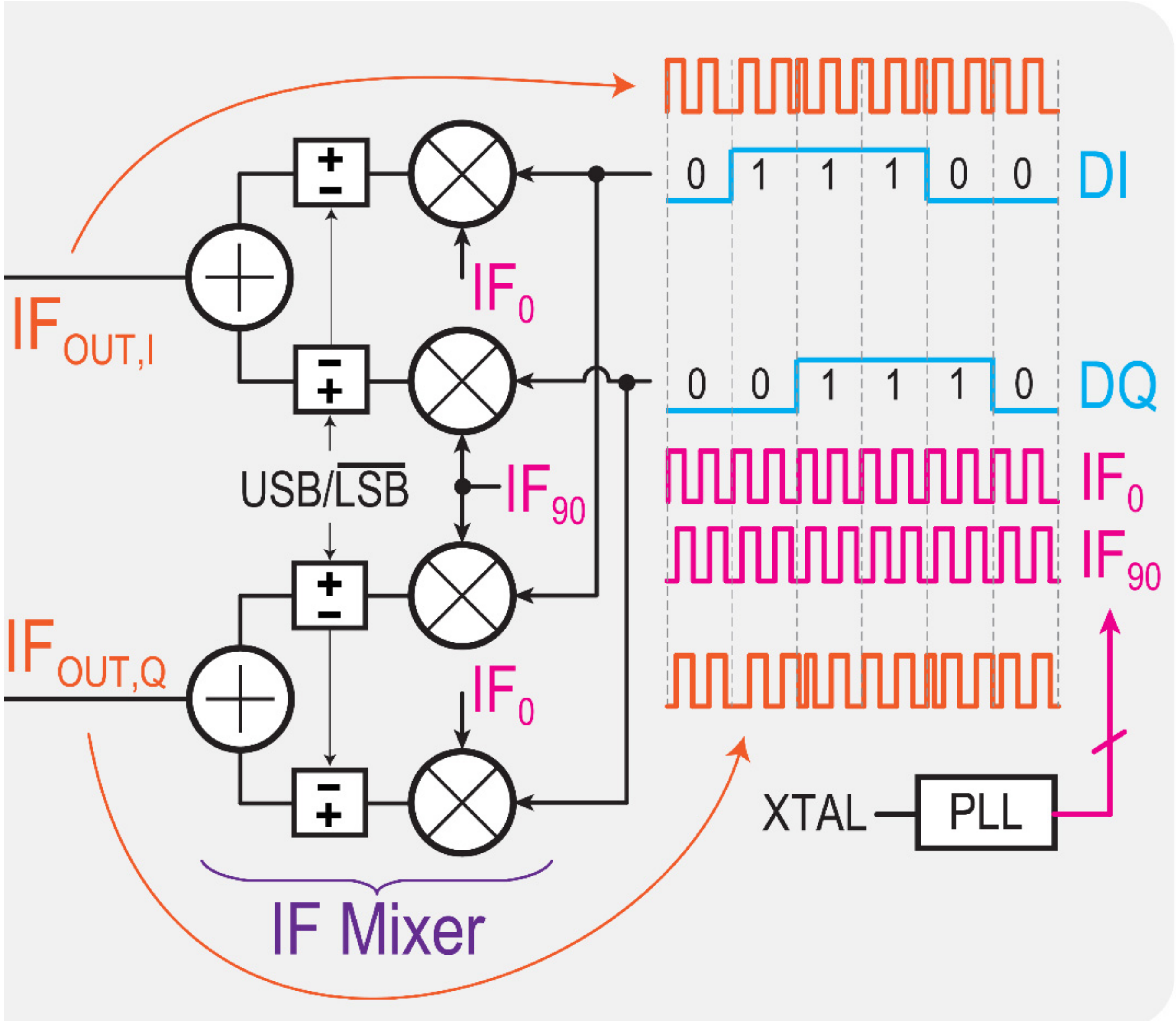
- 4 phase of IF clock is selected by IQ tag data and mixed with incident signal via a single switch
- ☑ QPSK modulation
- ☒ Double-side-band modulation occupies 2 adjacent channels

Proposed SSB QPSK backscatter

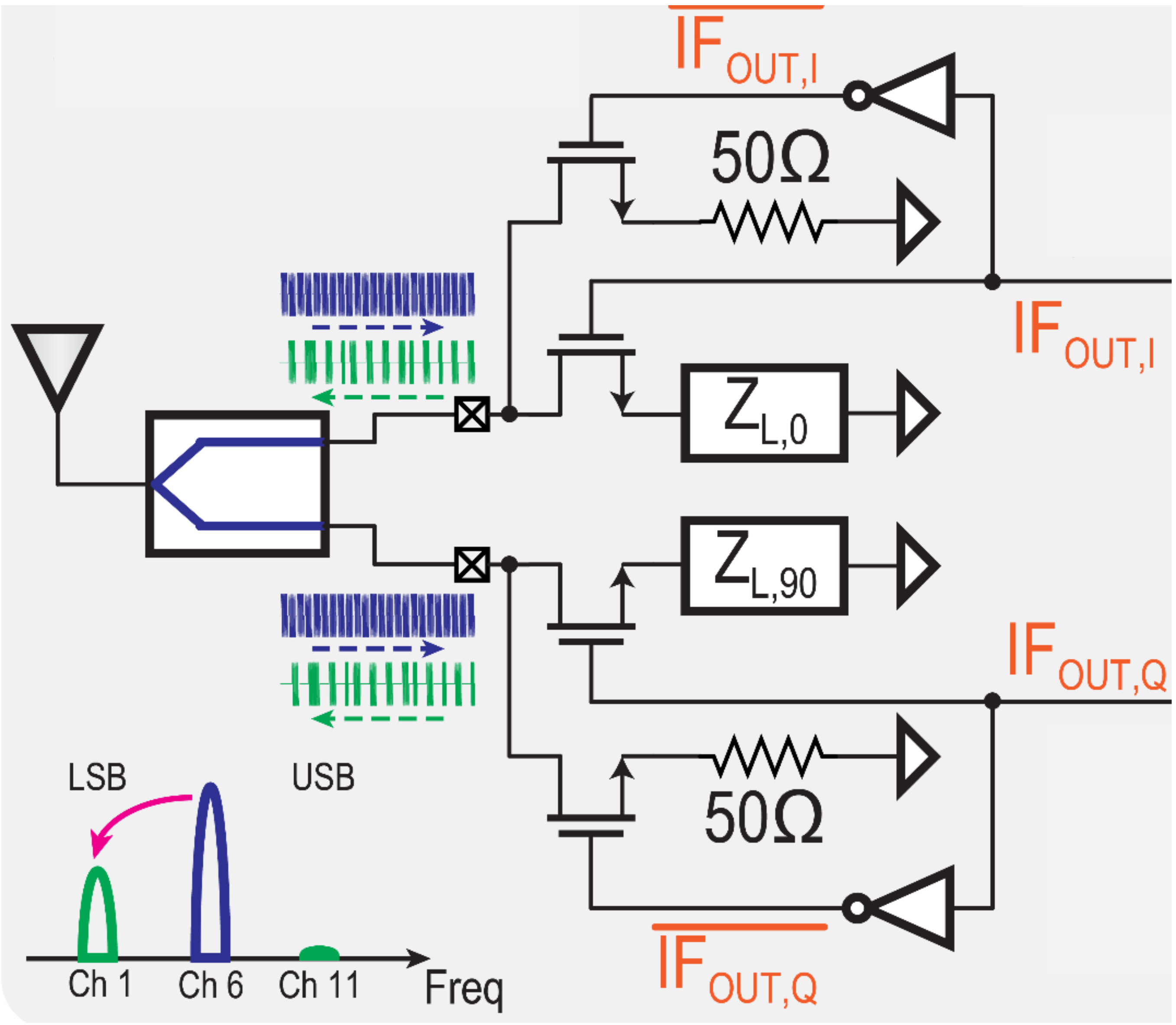


Proposed SSB QPSK backscatter

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



Proposed SSB QPSK backscatter



- Two separated loads provide 90° rotated reflection coefficients
- $Z_{L,0}$= open; $\Gamma_{L,0}$ = 1= $e^{j\times0°}$
- $Z_{L,90}$= -j×50 = 1.2pF@2.4GHz; $\Gamma_{L,90}$= -j= $e^{j\times-90°}$
- Quadrature IF signal modulates quadrature RF loading
  => SSB backscattering

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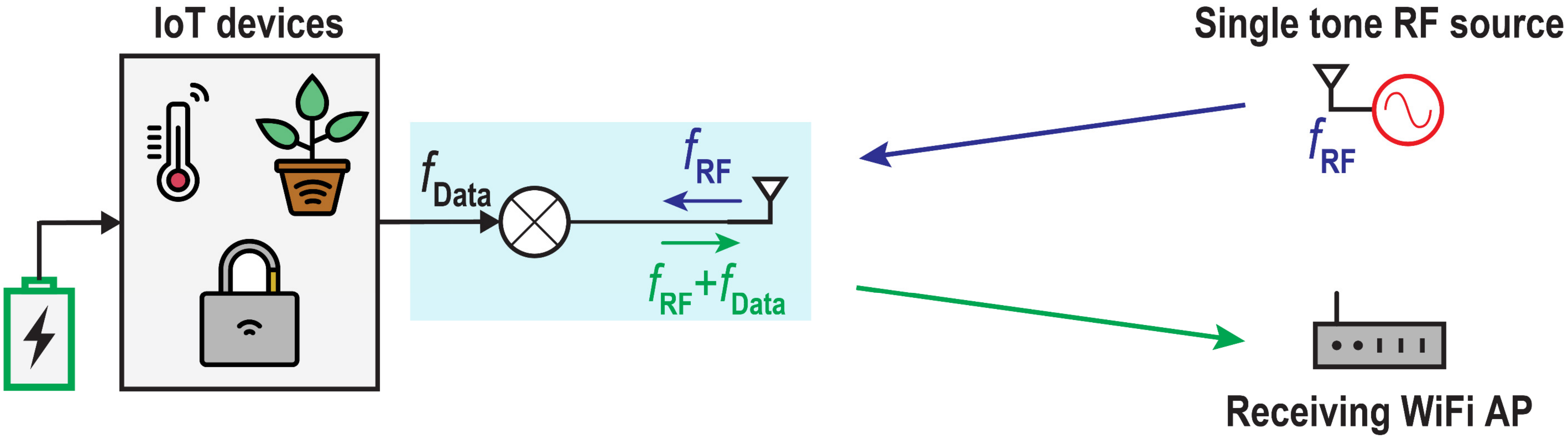
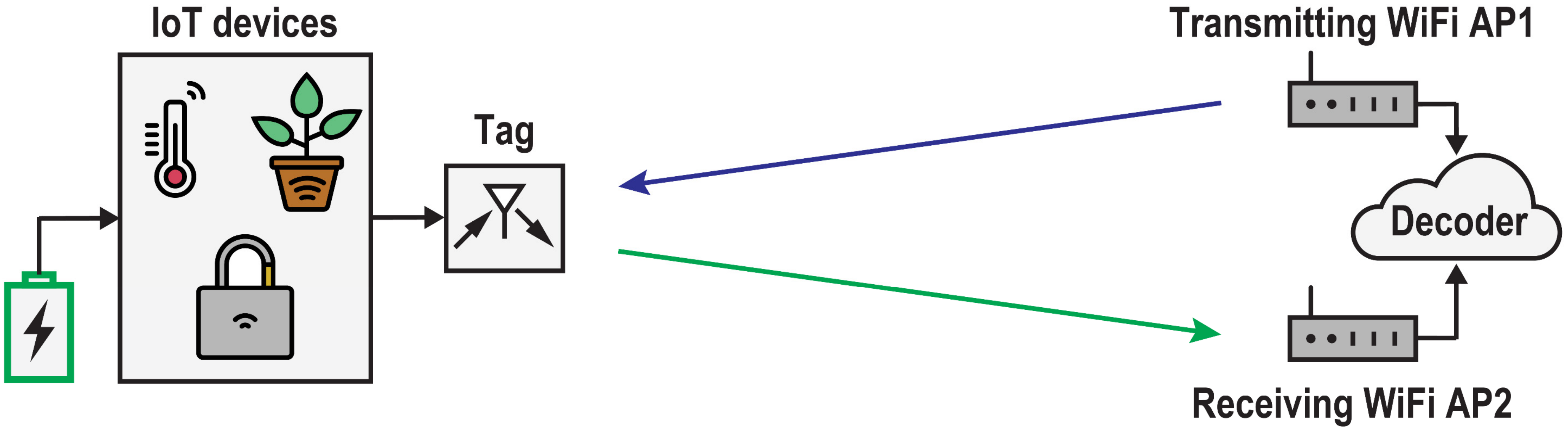
Passive Wi-Fi



Kellogg et al., *NSDI'16*

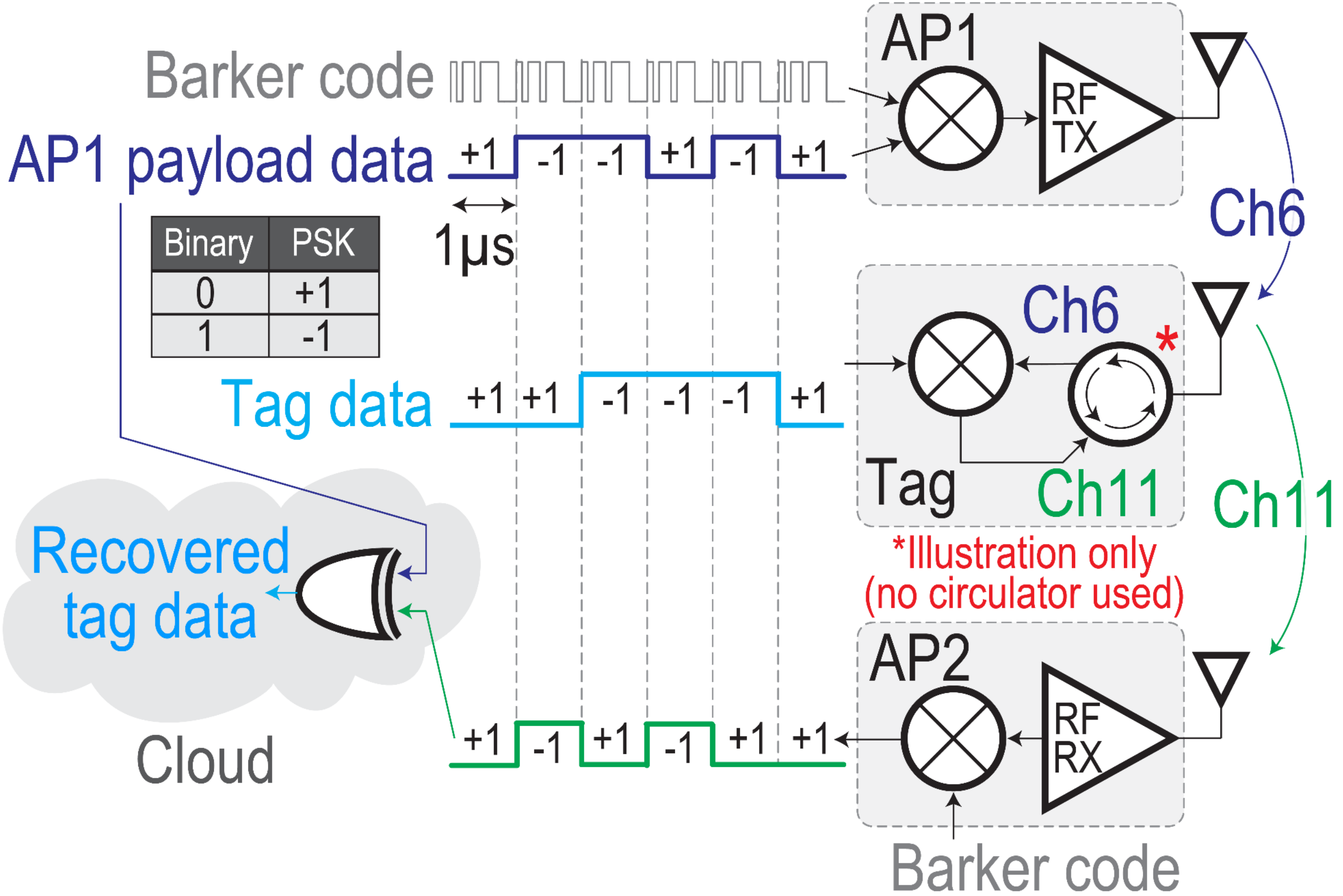
- ☑ Low power WiFi signal transmission via backscatter
- ☒ Require a custom single tone RF source, therefore not WiFi compatible for both downlink and uplink

Hitchhike – basic concept



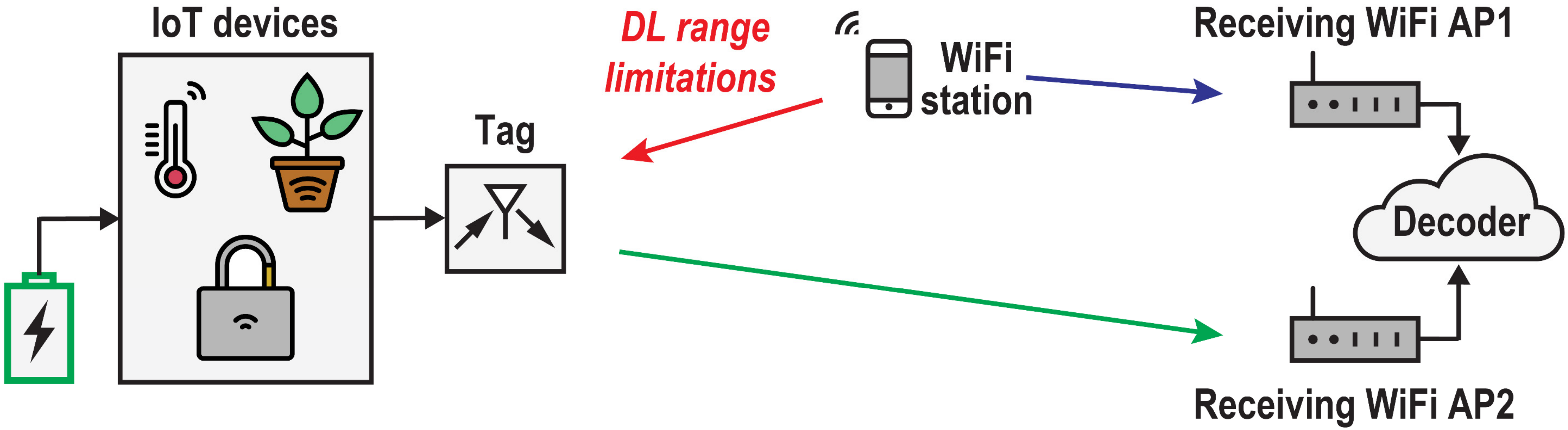
- WiFi AP1 sends data to Tag; Tag modulates and backscatters the incident signal to AP2
- A cloud decoder then decodes the tag data based on data from both AP1 and AP2

Hitchhike – codeword translation



- Ex: BPSK modulation
- For Tag data=0, phase of data is unchanged
- For Tag data=1, phase of data is inverse
- Tag data is recovered on cloud by XOR-ing AP1 and AP2 data

Hitchhike – required improvement



Zhang et al., *SenSys'16*

- ☒ Downlink (DL) range is limited by Tag RX sensitivity, which requires another dedicated WiFi station
- ☒ Board level demonstration only without low power IC solution

Downlink RX requirement

- Power: can not afford high power synchronization routine and needs to be always-on but low power

- Sensitivity: -40dBm is required for >30m receiving range

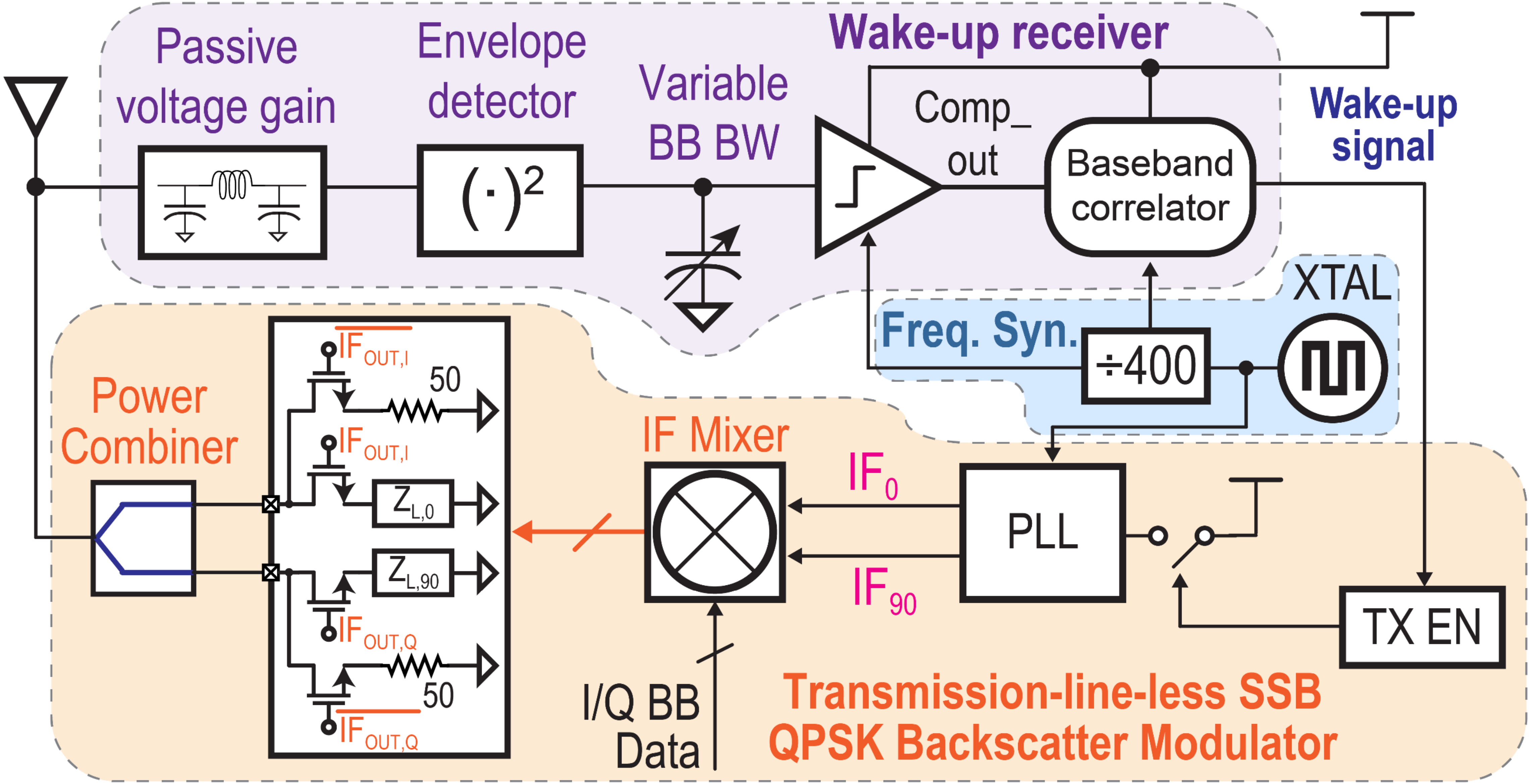
- WiFi standard-compliance: reuse the same incident AP to establish communication between Tag and APs

⇩

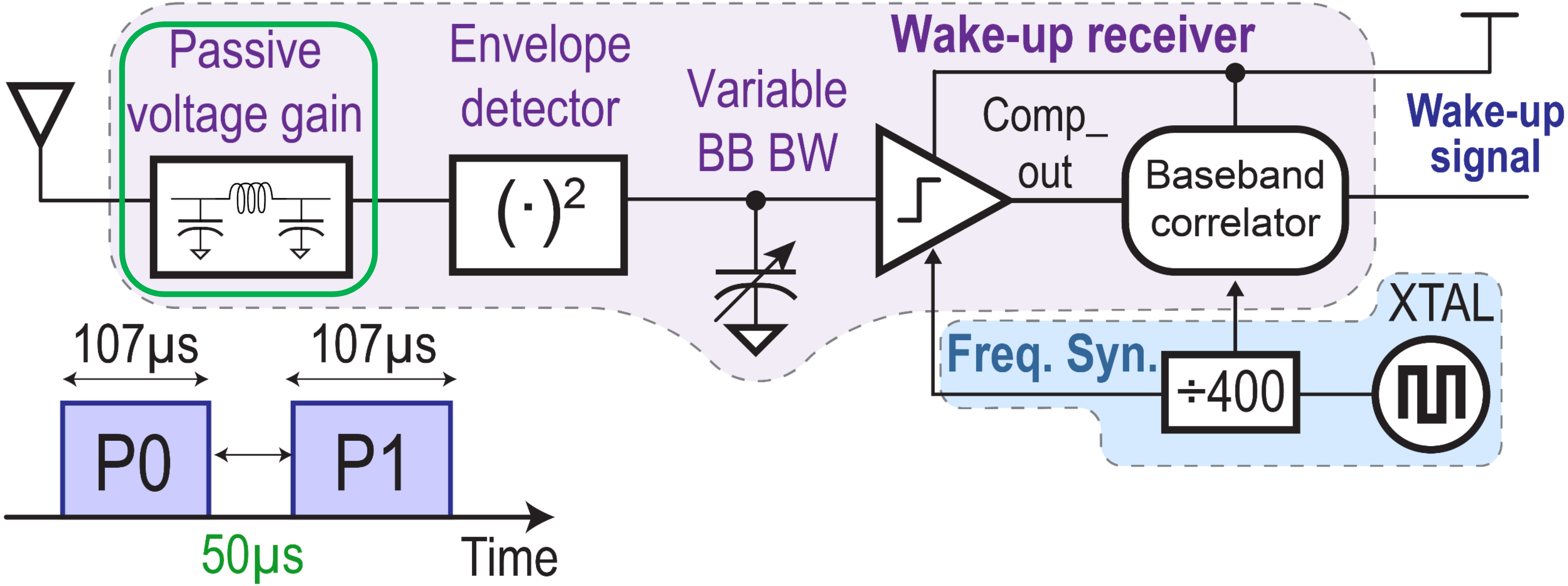
A WiFi-compliant wake-up receiver (WuRX) via Back-channel communication

N. E. Roberts et al., *ISSCC'16*

Block diagram of proposed IoT tag



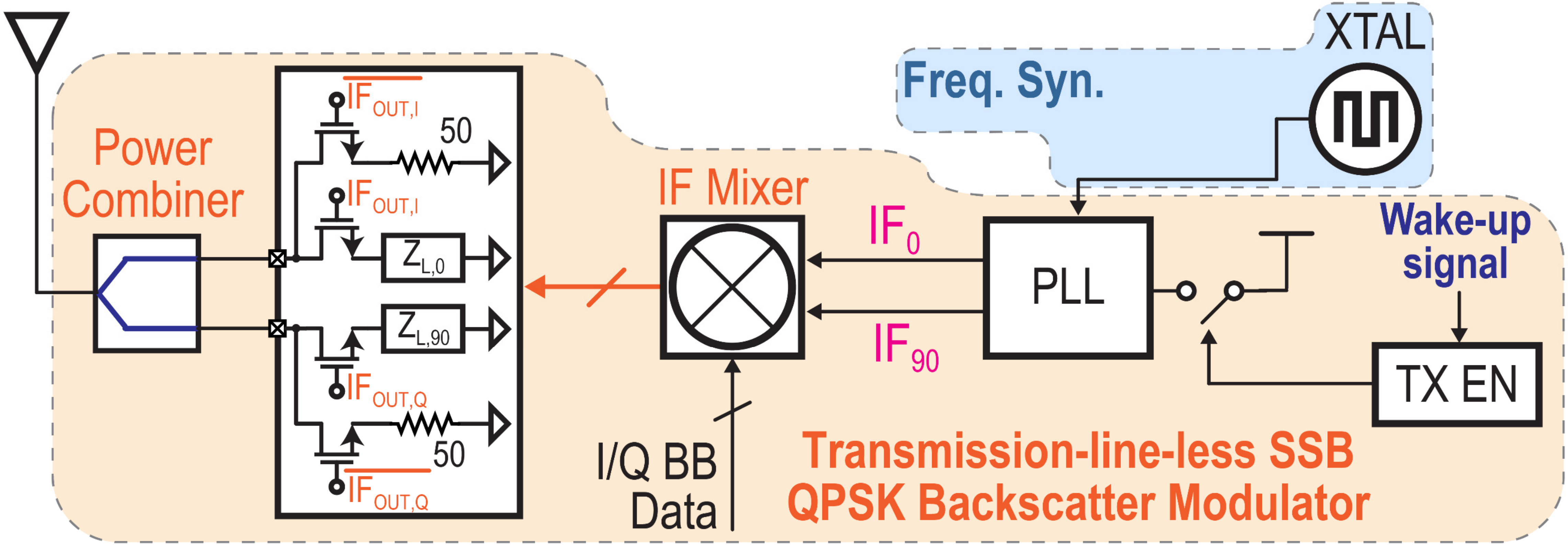
Block diagram of Downlink



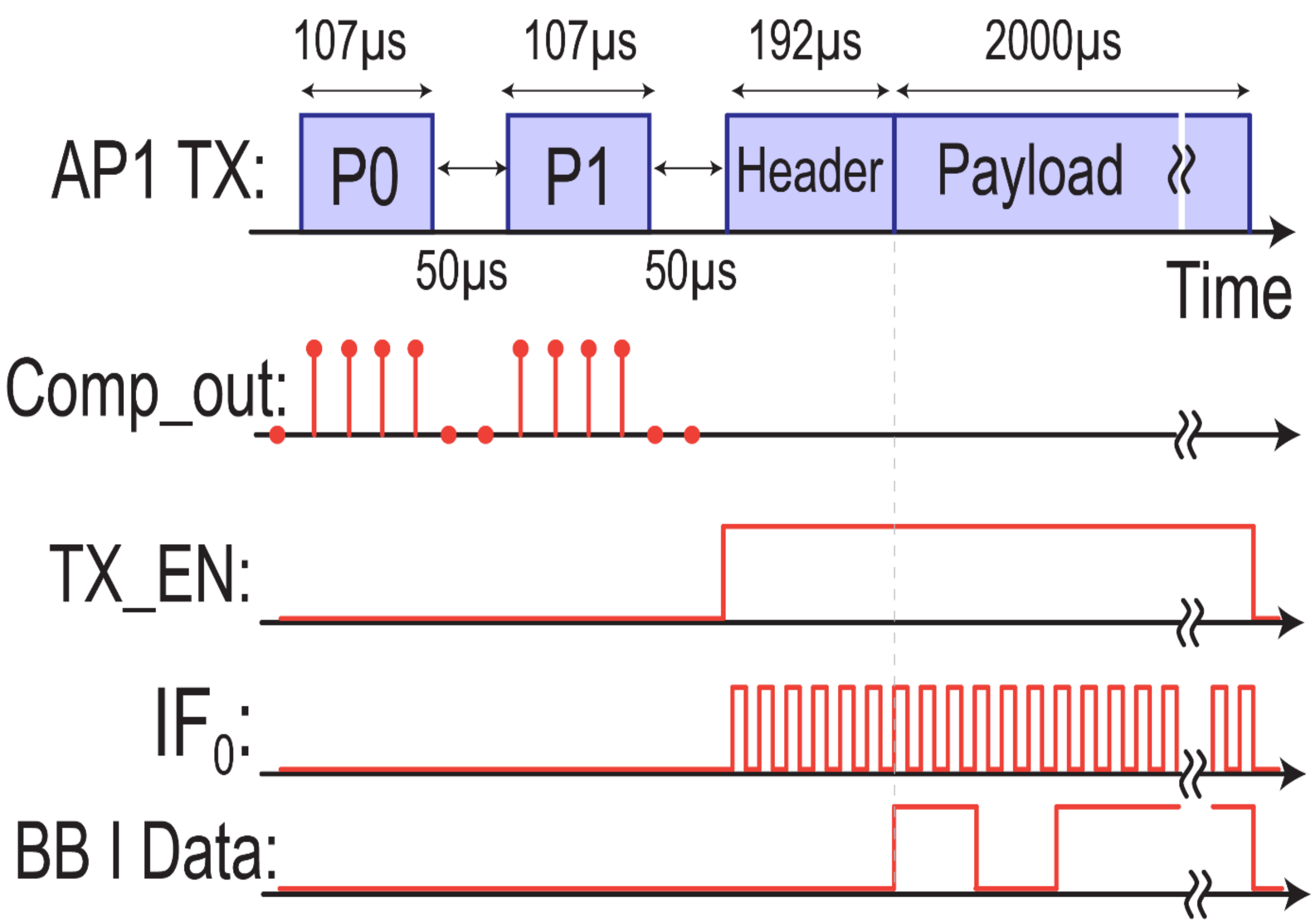
- Direct envelope detection architecture for low standby power
- 8dB passive voltage gain from input matching network
- WiFi packet is oversampled and compared by 11-bit correlator

Block diagram of Uplink

- 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



- Wake-up signal consists of P0 and P1
- Header is backscattered first without alteration to ensure correct reception by AP2
- After header, payload is modulated by tag data and then backscattered to AP2

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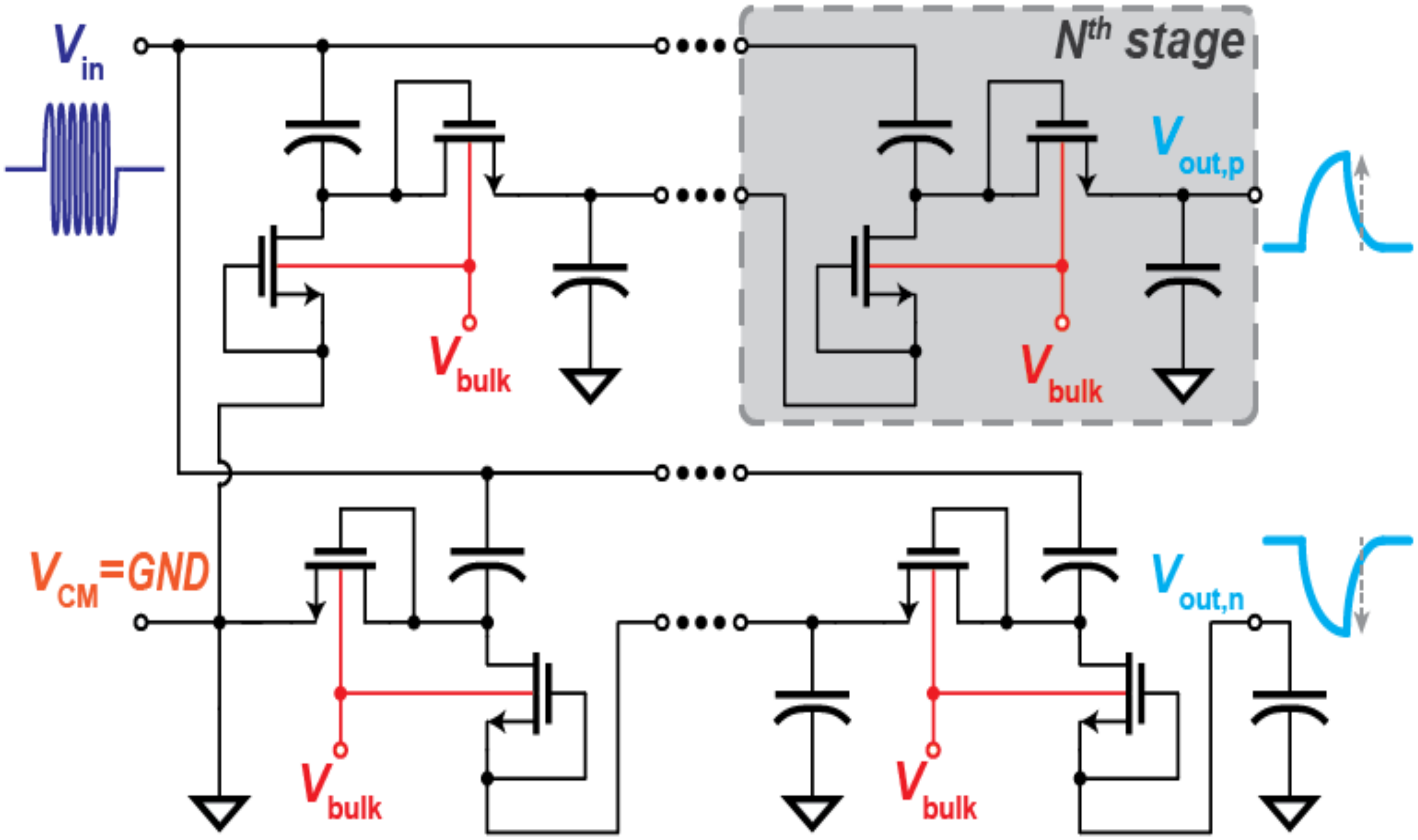
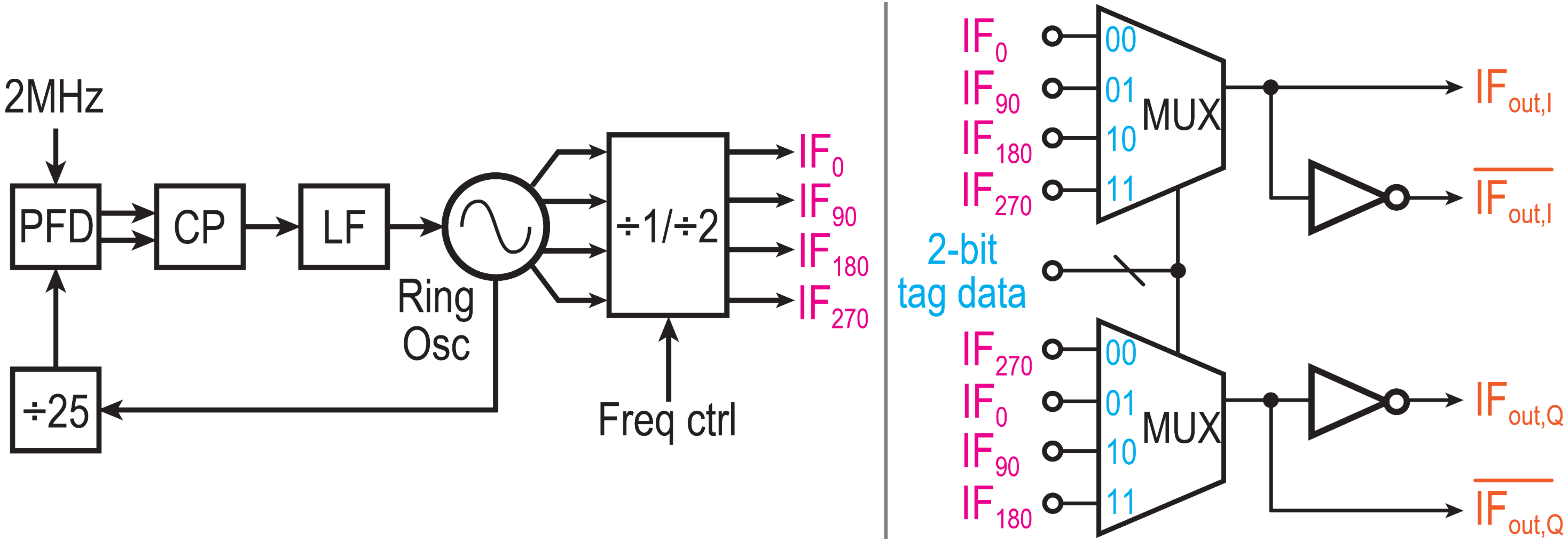
Passive pseudo-balun envelope detector



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



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

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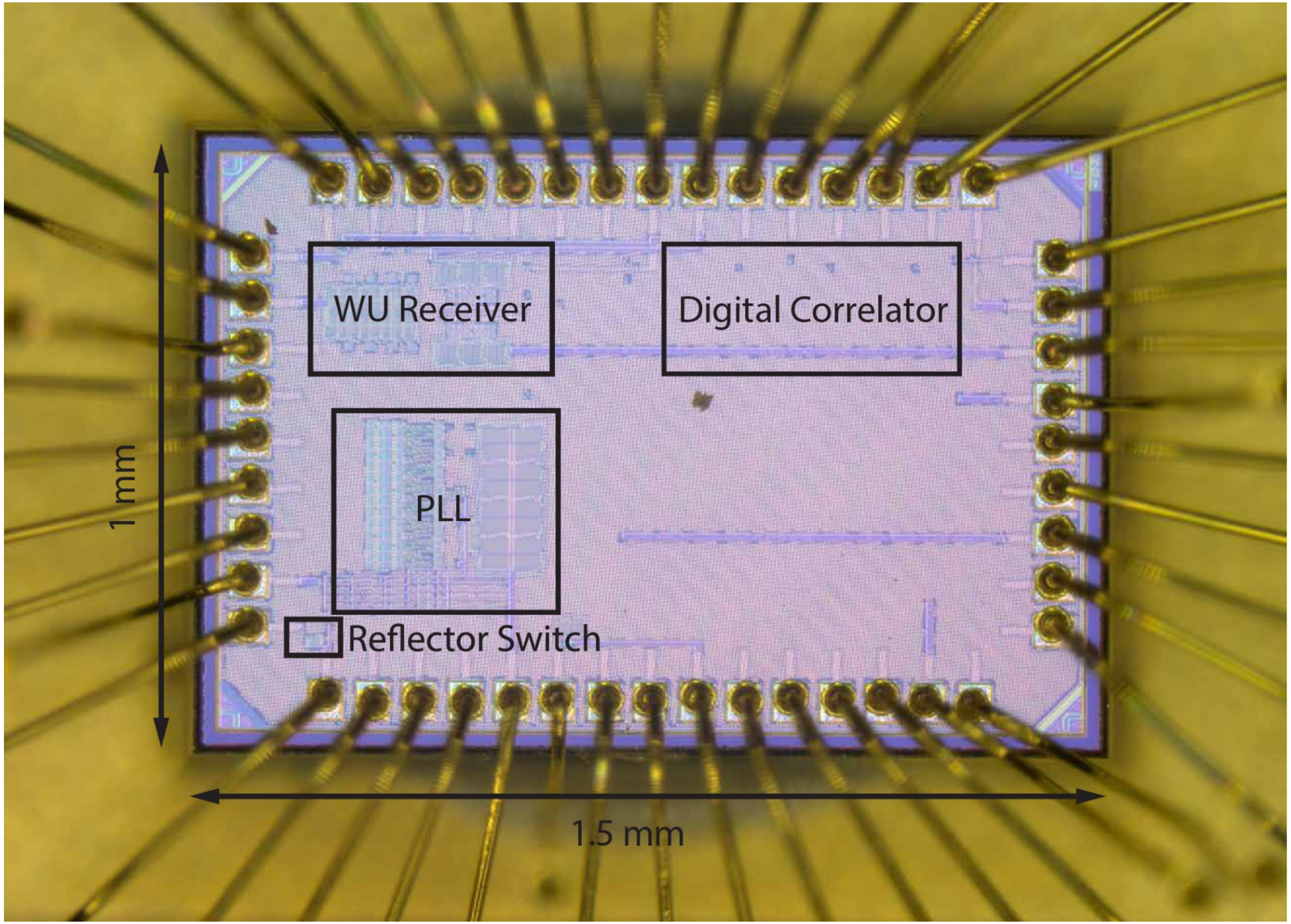
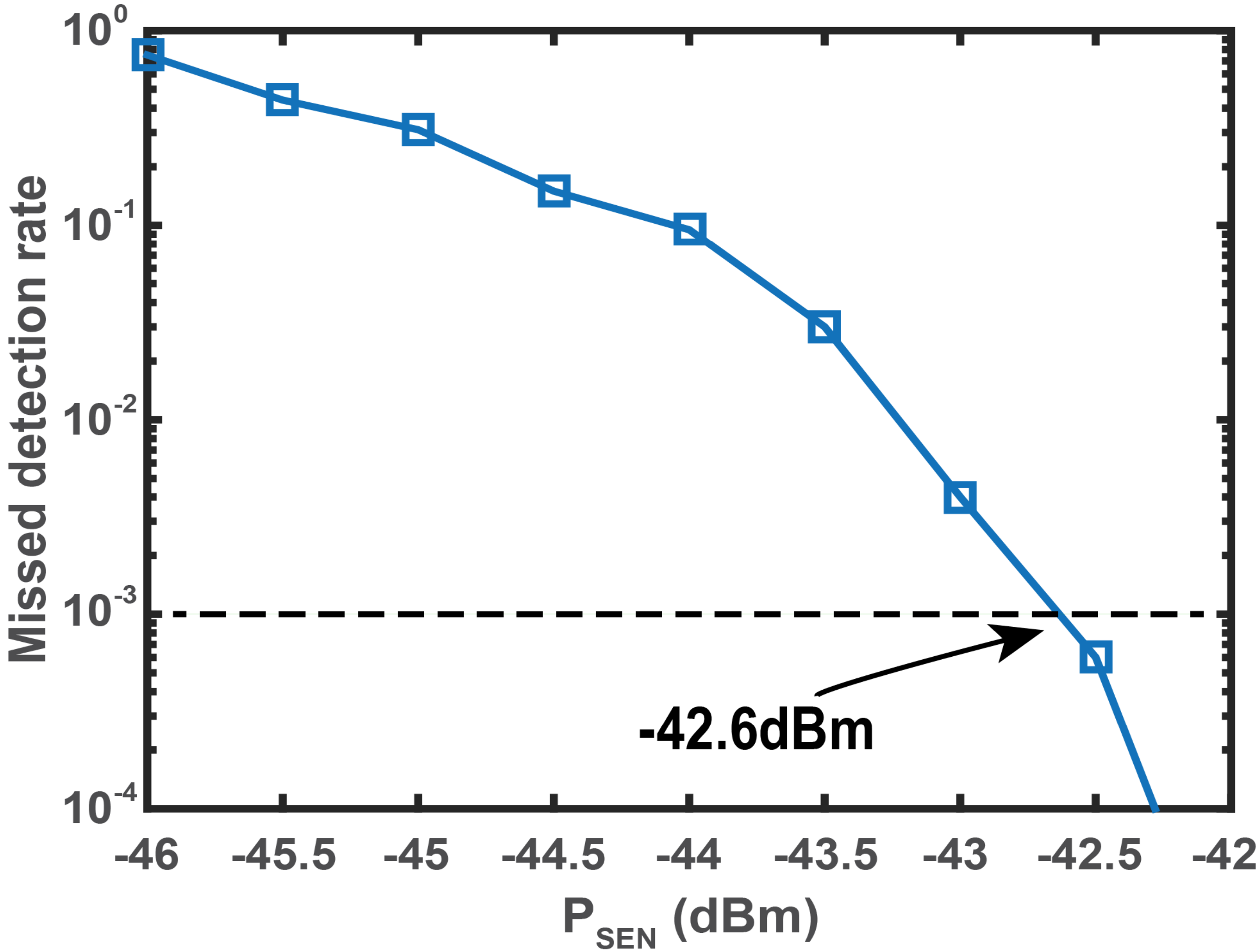
Die micrograph



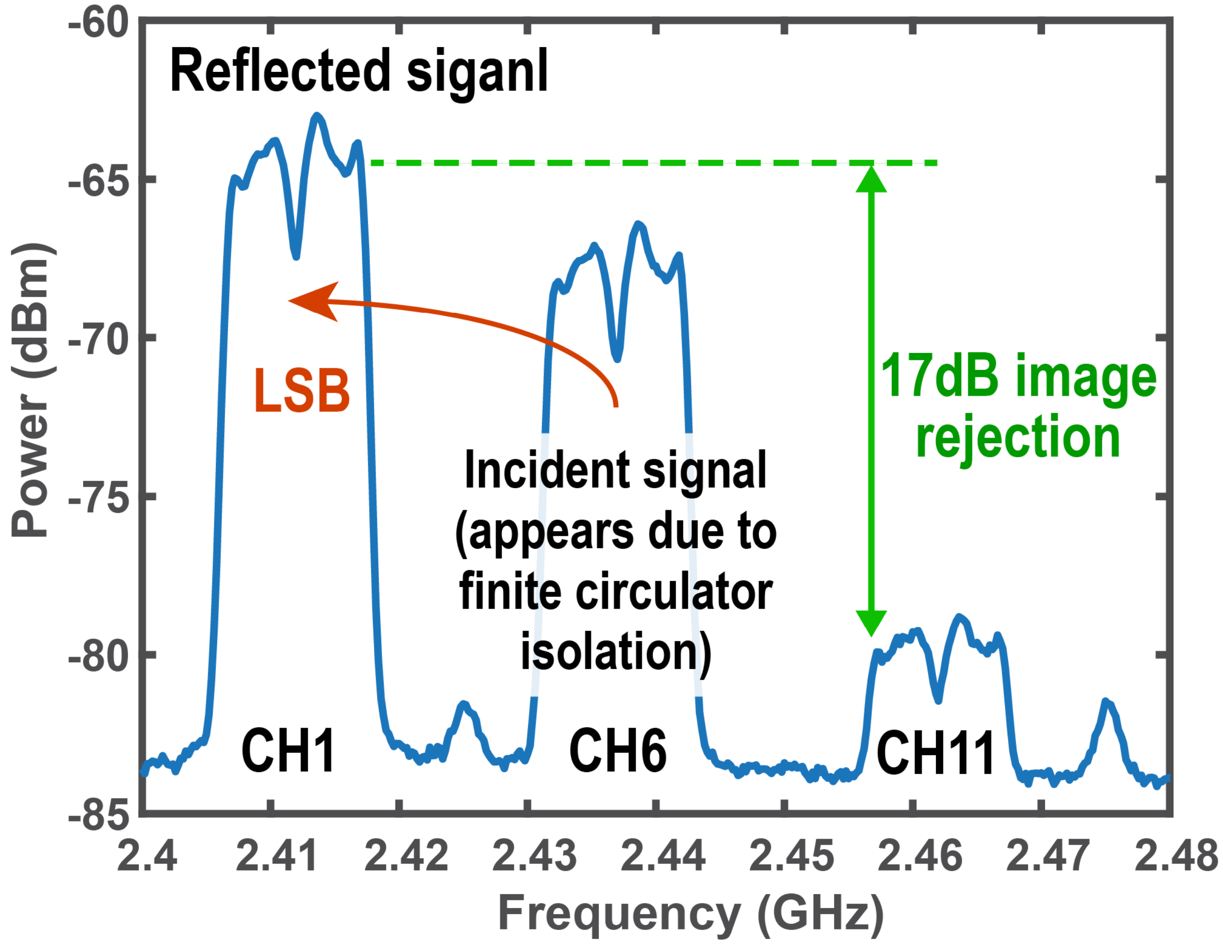
- 65nm CMOS
- Active area~0.5mm^2
- DL: 0.2mm^2; 2.8μW
  UL: 0.3mm^2; 28μW

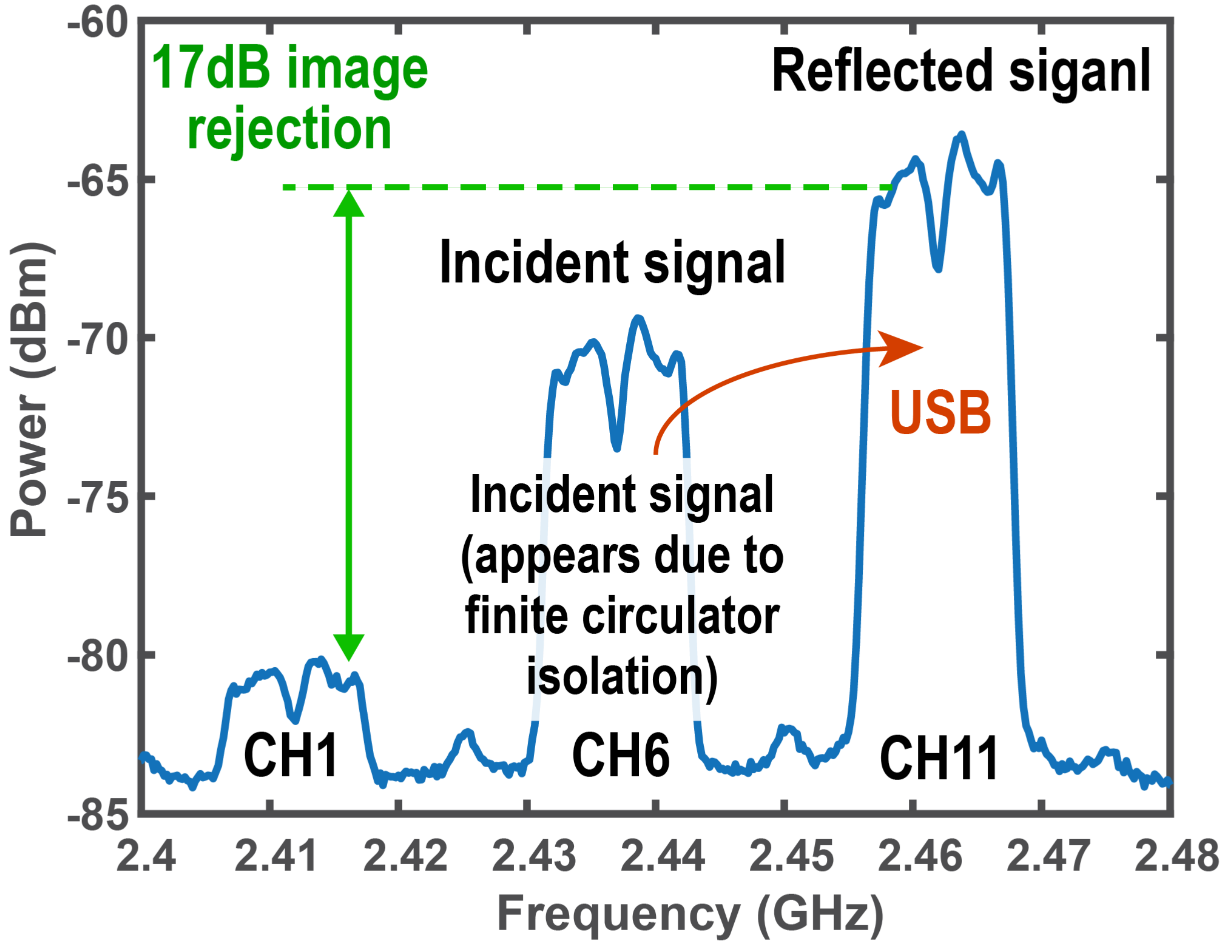
Downlink Sensitivity



- -42.6dBm downlink sensitivity for 1e-3 wake-up event missed detection rate

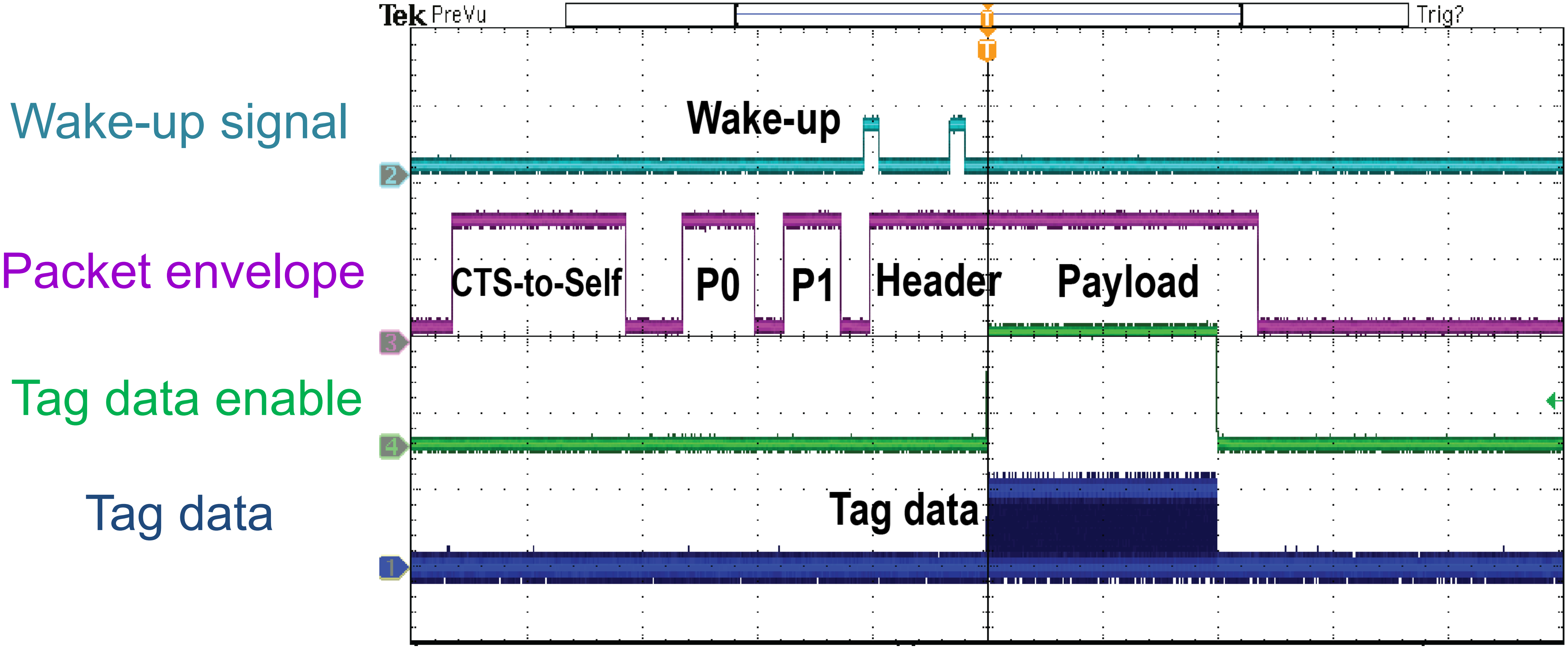
SSB backscatter-based frequency translation





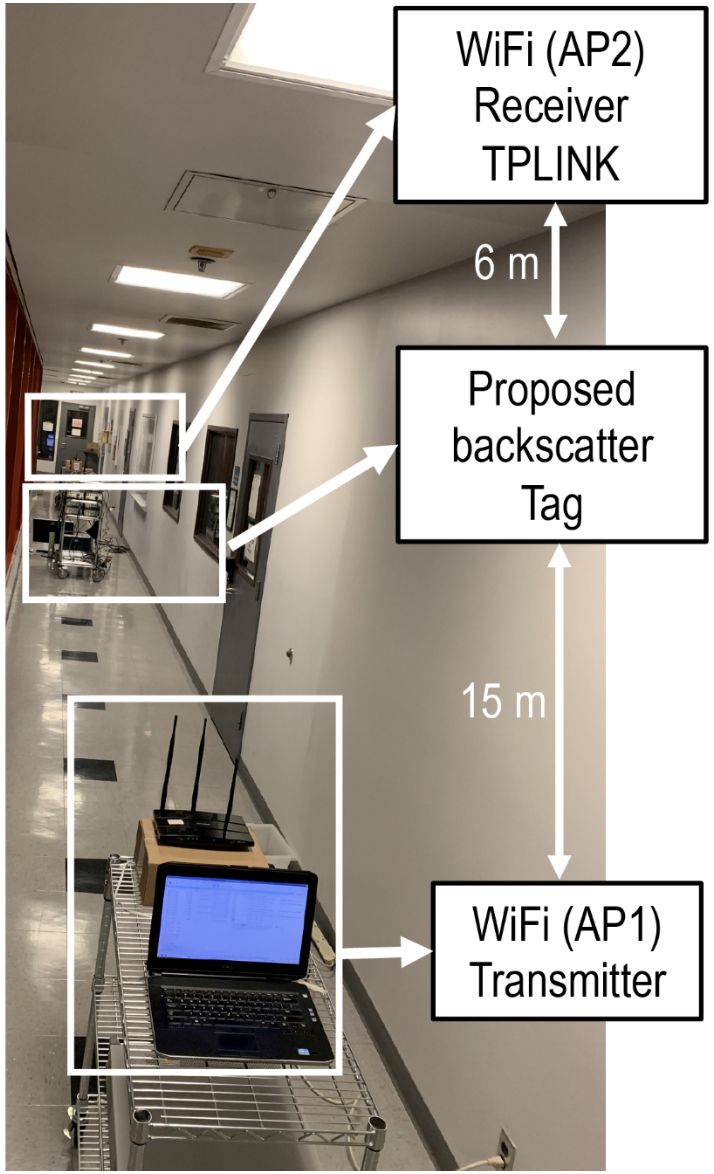
- Incident signal at CH6 reflected to either CH1 or CH11 based on logic setting with 17dB image rejection

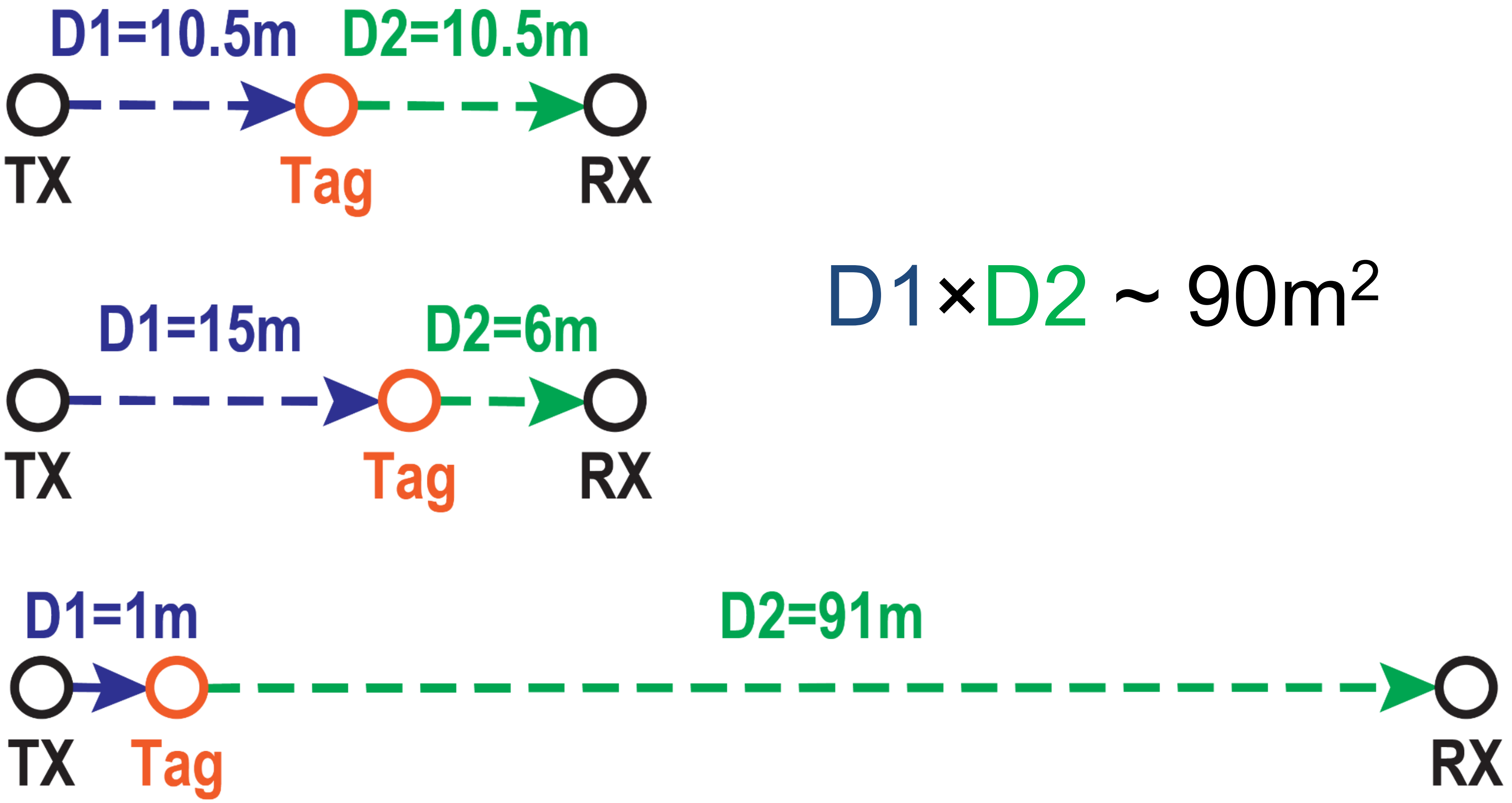
Wake-up and backscatter sequence



- Tag data enabled after correct wake-up and header packet

Wireless measurement





$$D1 \times D2 \sim 90m^2$$

- For received tag data BER=1e-4

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Conclusion

- The first IC demonstrating WiFi-compatible backscatter-based communication that can enable new classes of IoT applications
- This design improves range and spectral efficiency under low power compared to prior backscatter solutions by using:
  - A codeword translation technique that enables low-power radio solution
  - A WuRX triggered by WiFi-compliant packet for downlink
  - A single-side-band QPSK backscatter modulator for uplink
- Result: A 2.8μW standby power, 28μW transmitting power, WiFi-compatible backscatter radio with >20m communication range
- Acknowledgement: This work was supported in part by the National Science Foundation (NSF) under Grant No. 1923902.