An LTE-harvesting BLE-to-WiFi Backscattering Chip for Single-Device RFID-like Interrogation

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IoT Devices with RFID-like Communication

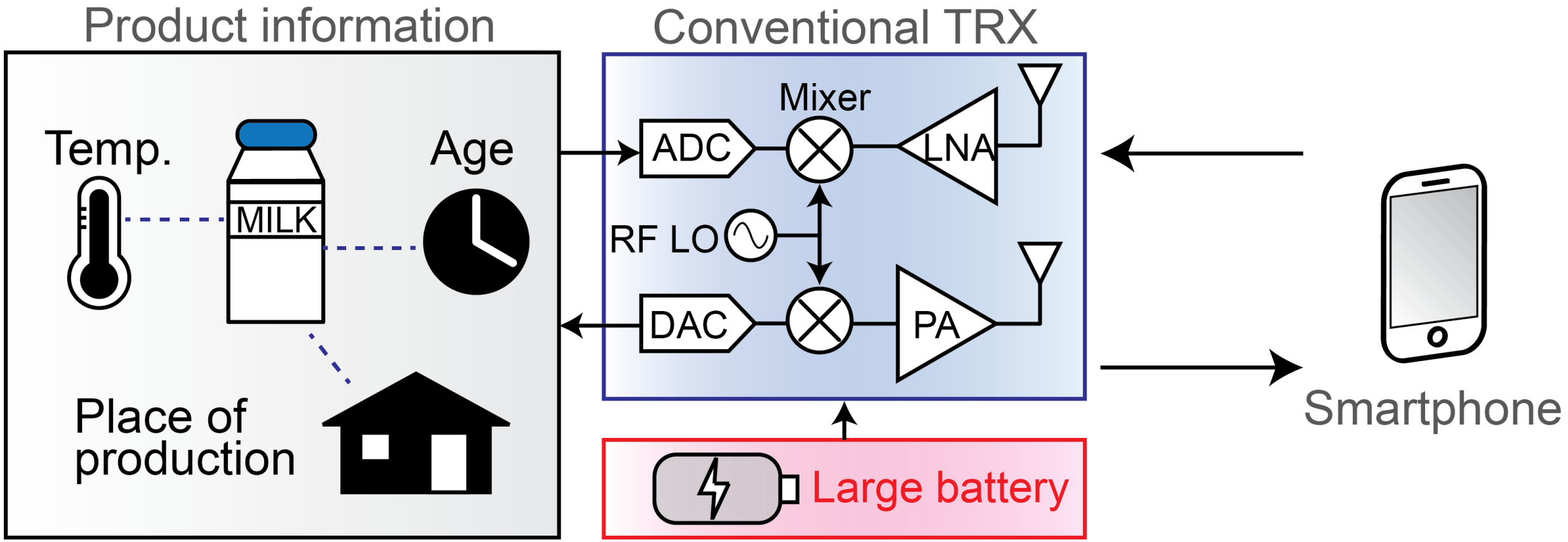
Warehouse inventory management

Cashier-less grocery store

Dedicated far-field RFID readers are required

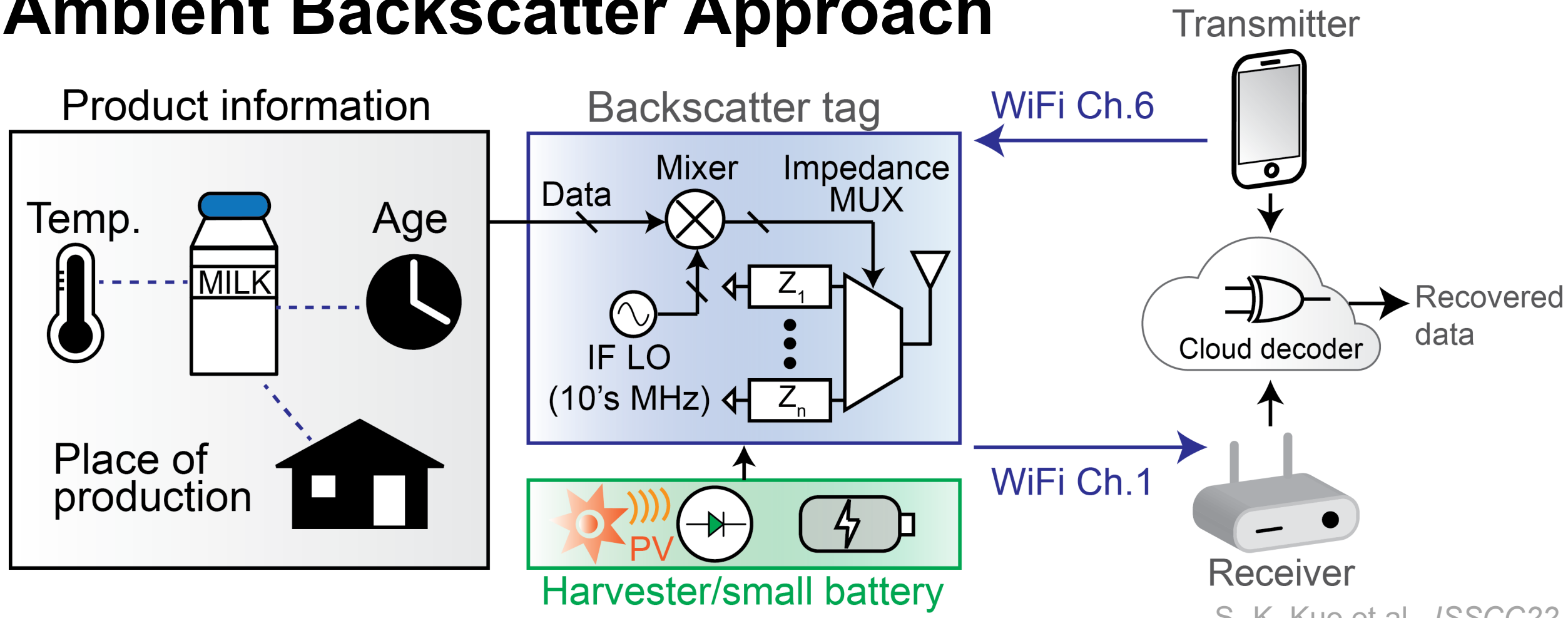
Can we replace the far-field RFID reader with a phone?

Conventional TRX Approach



Conventional TRXs require 10s~100s mW active peak power
→ Large size and/or cost

Ambient Backscatter Approach

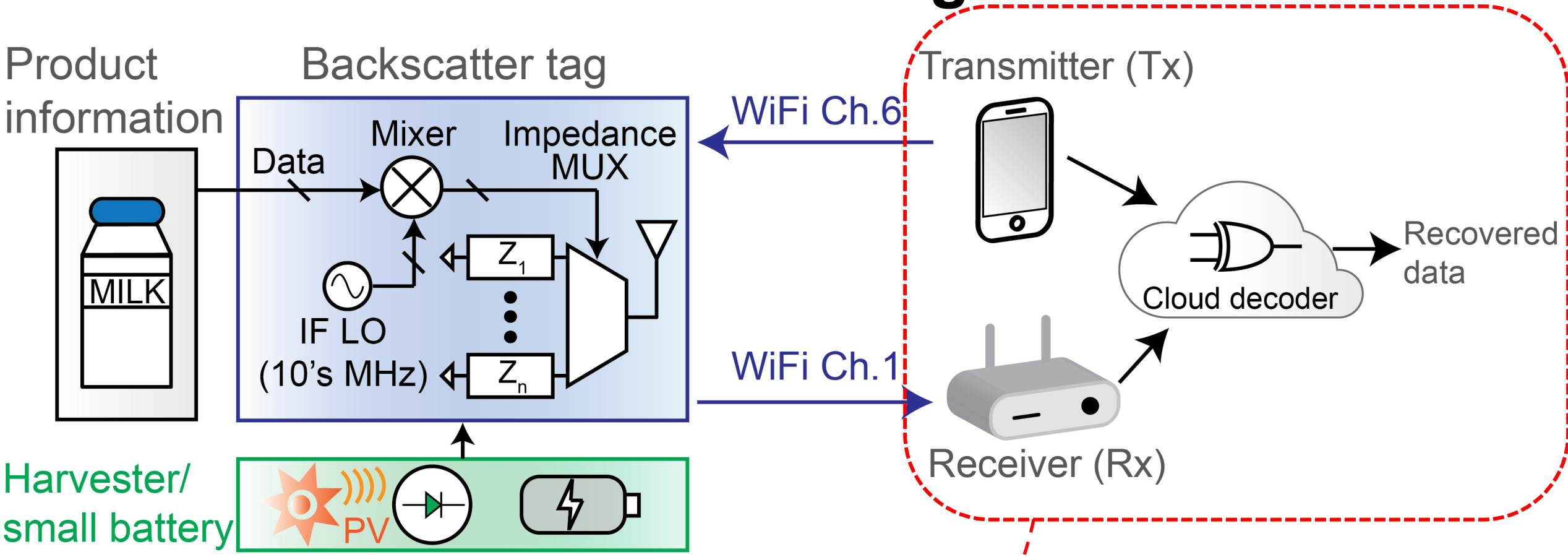


S.-K. Kuo et al., *ISSCC22*

Codeword translation on the tag enables WiFi-to-WiFi and BLE-to-BLE backscatter

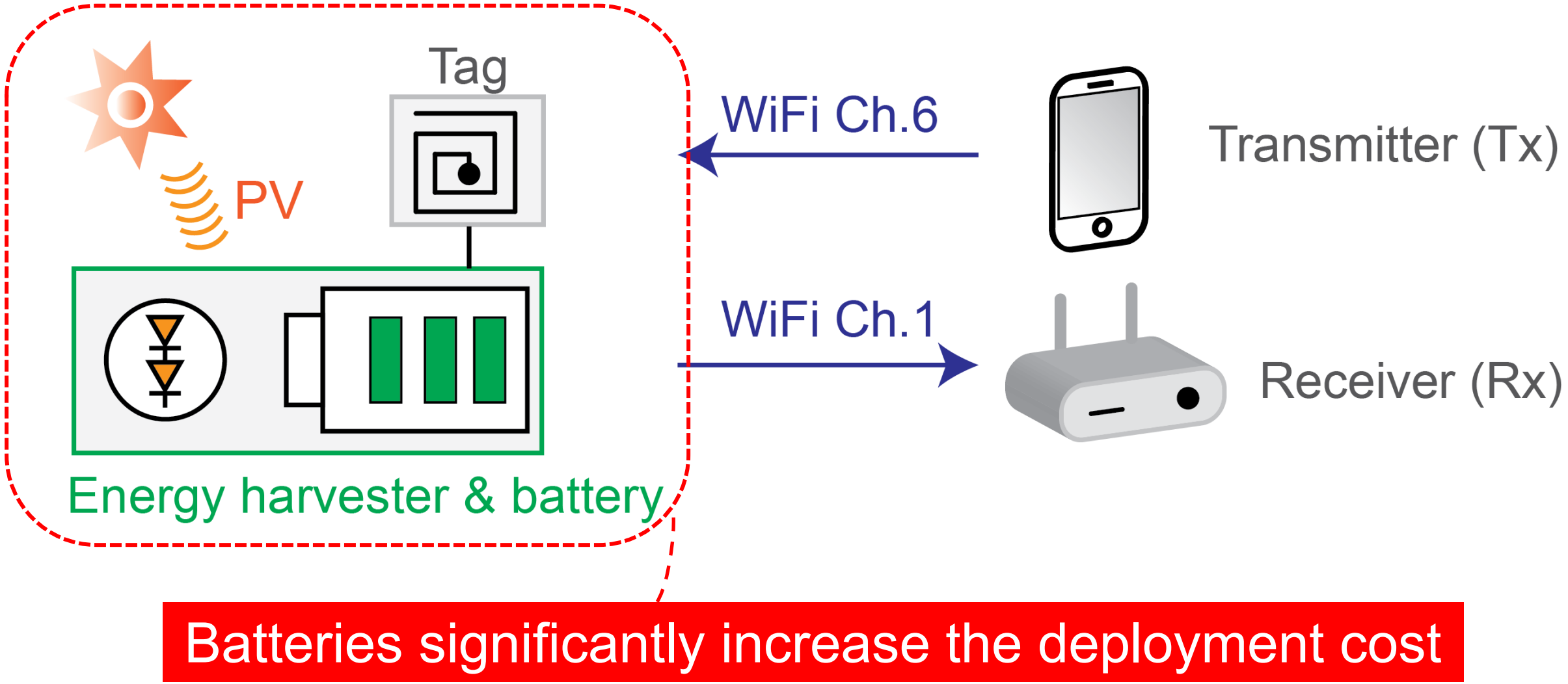
Elimination of RF circuits enables 1000x lower power consumption

Ambient Backscatter Challenges I



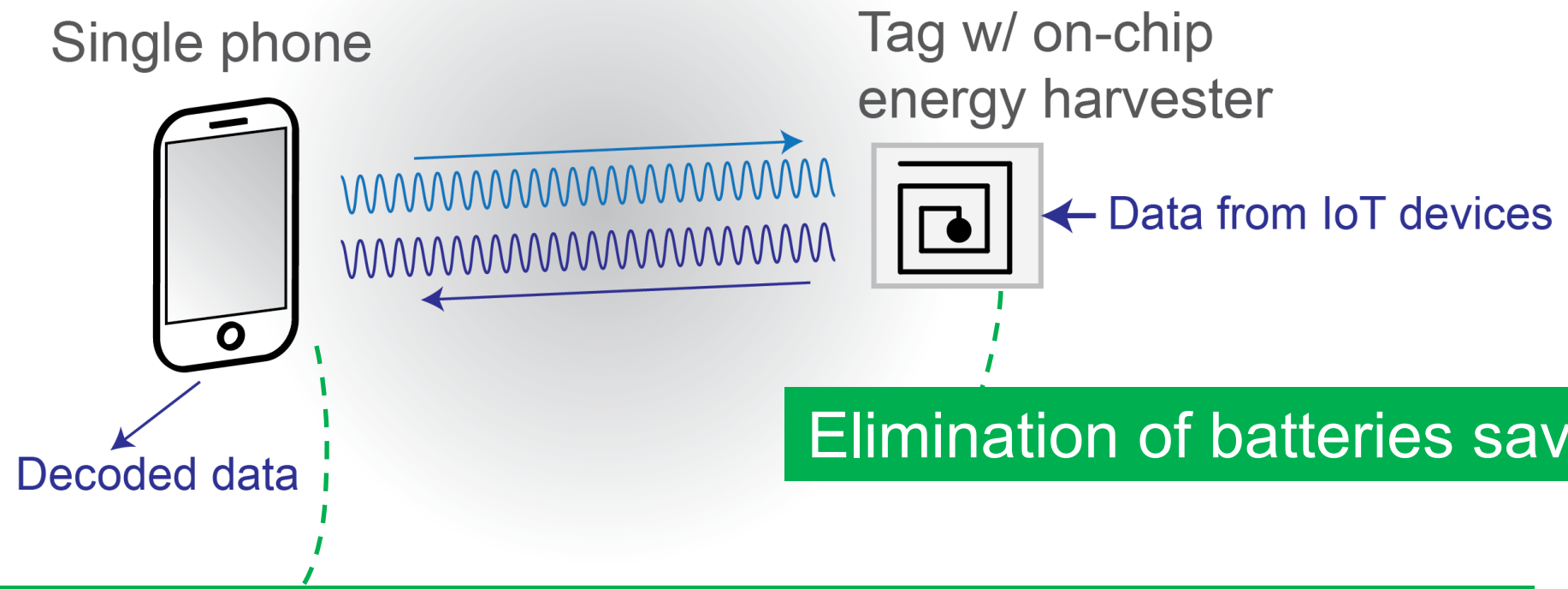
Two access points are required because there are no commercial full-duplex WiFi TRXs, even though Tx and Rx channels are different

Ambient Backscatter Challenges II



Batteries significantly increase the deployment cost

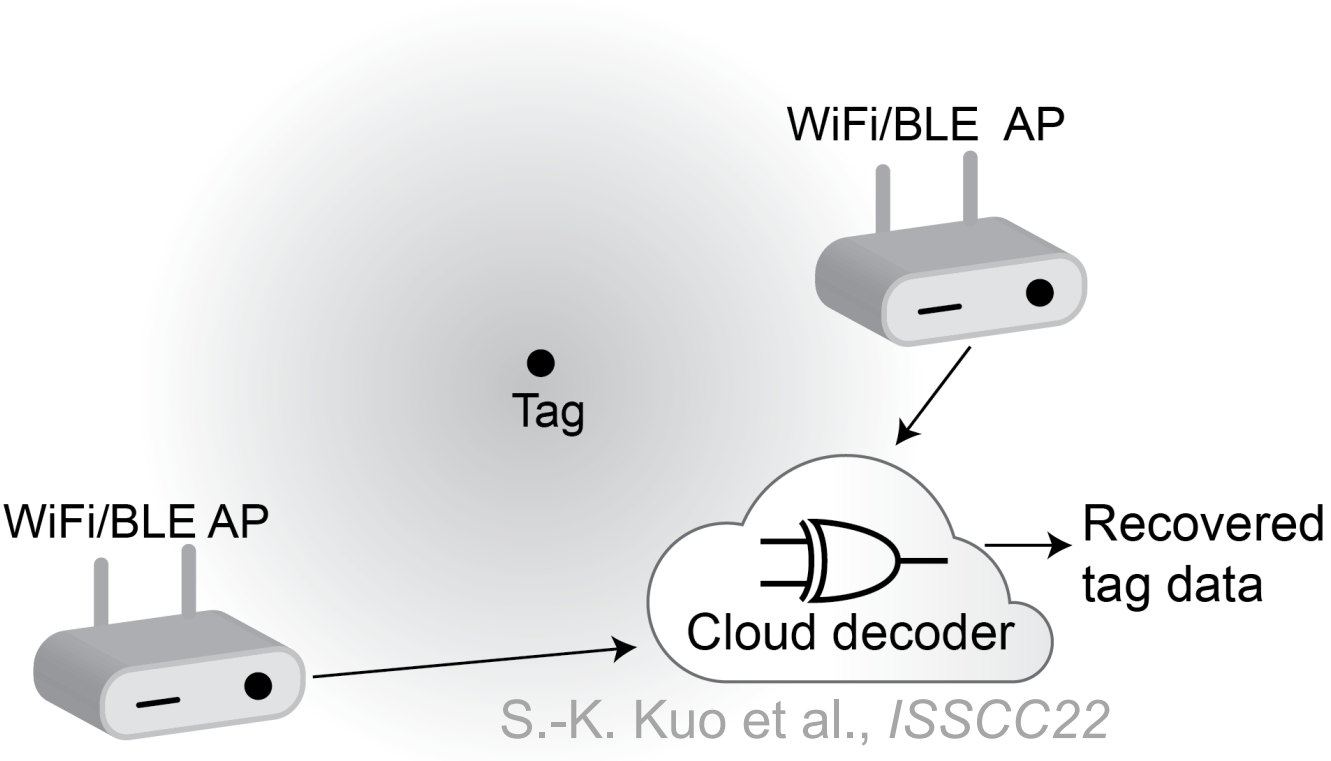
Proposed Solution



Outline

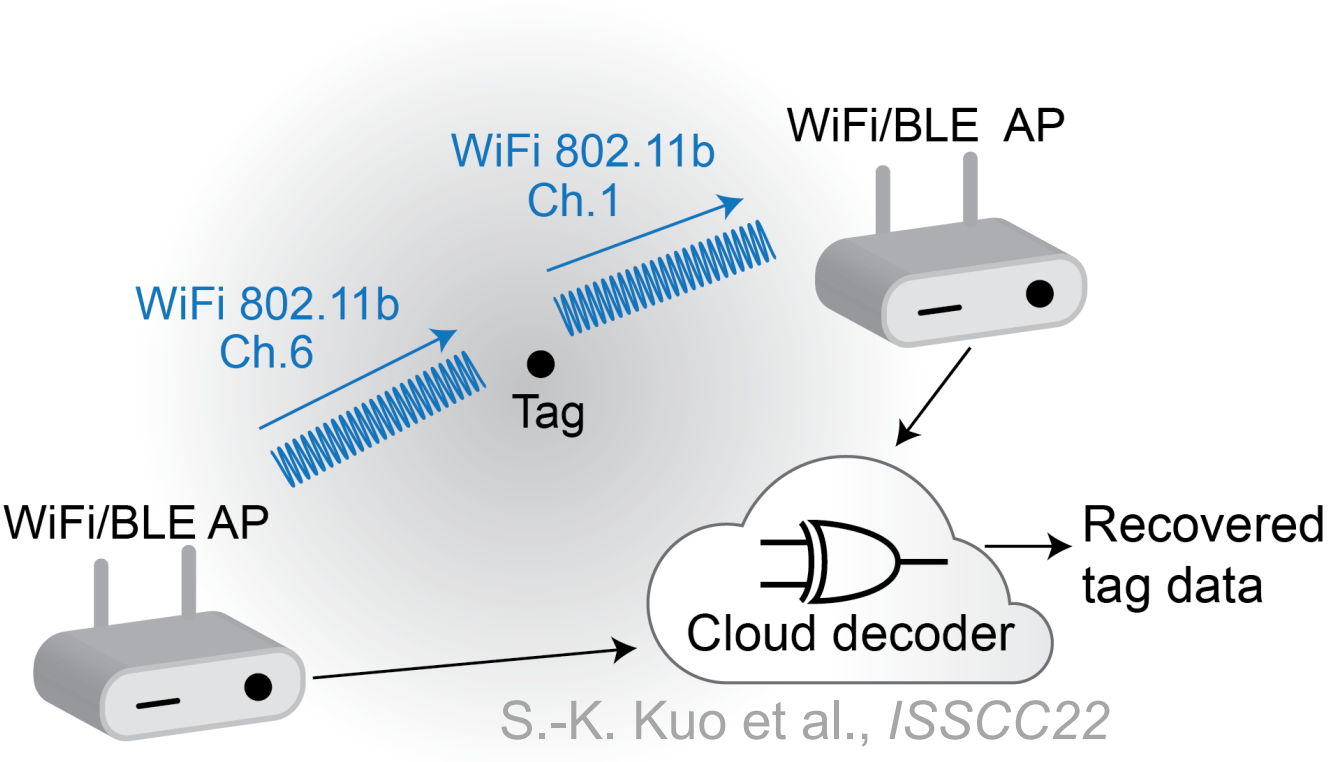
- Motivation
- Prior-art and proposed BLE-to-WiFi backscatter scheme
- Proposed single-device-interrogated backscatter chip
- Measurement results
- Conclusion

Previous Backscatter Approach



Hitchhike

Previous Backscatter Approach



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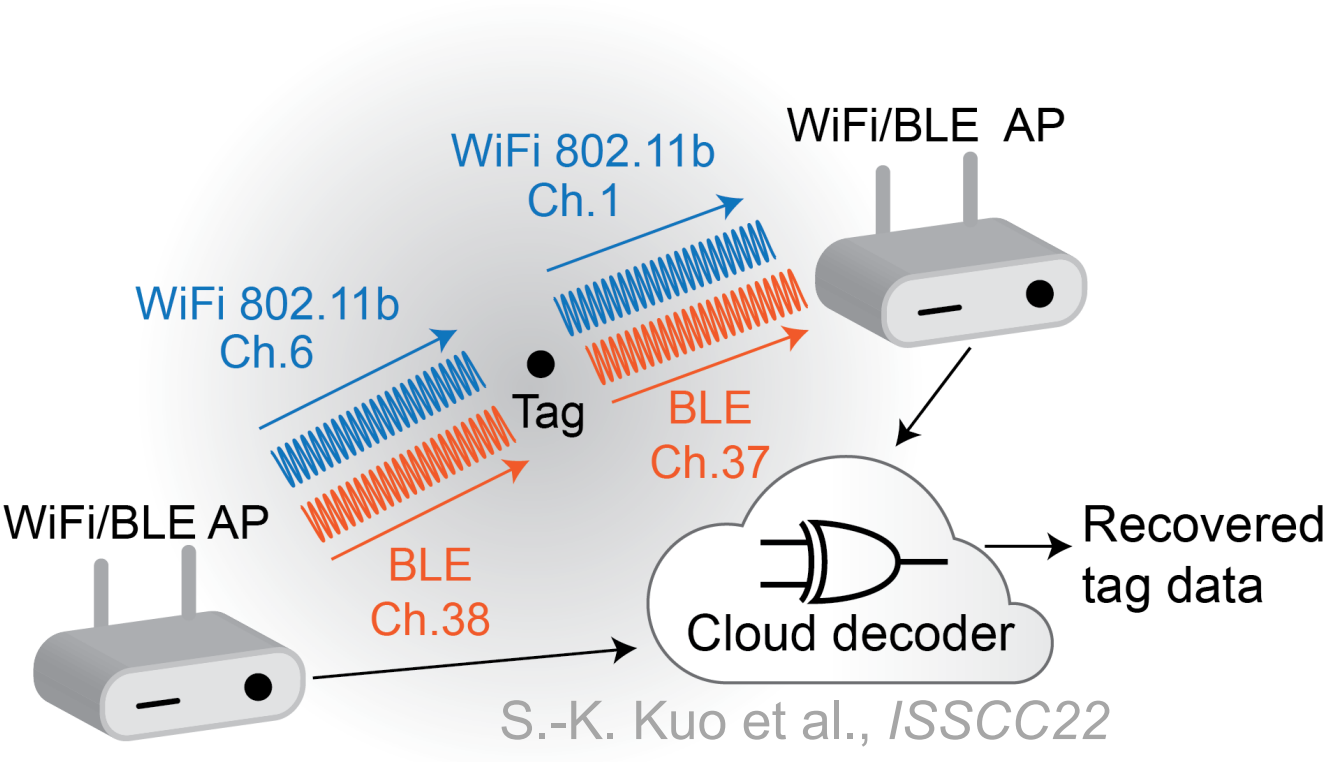

Hitchhike

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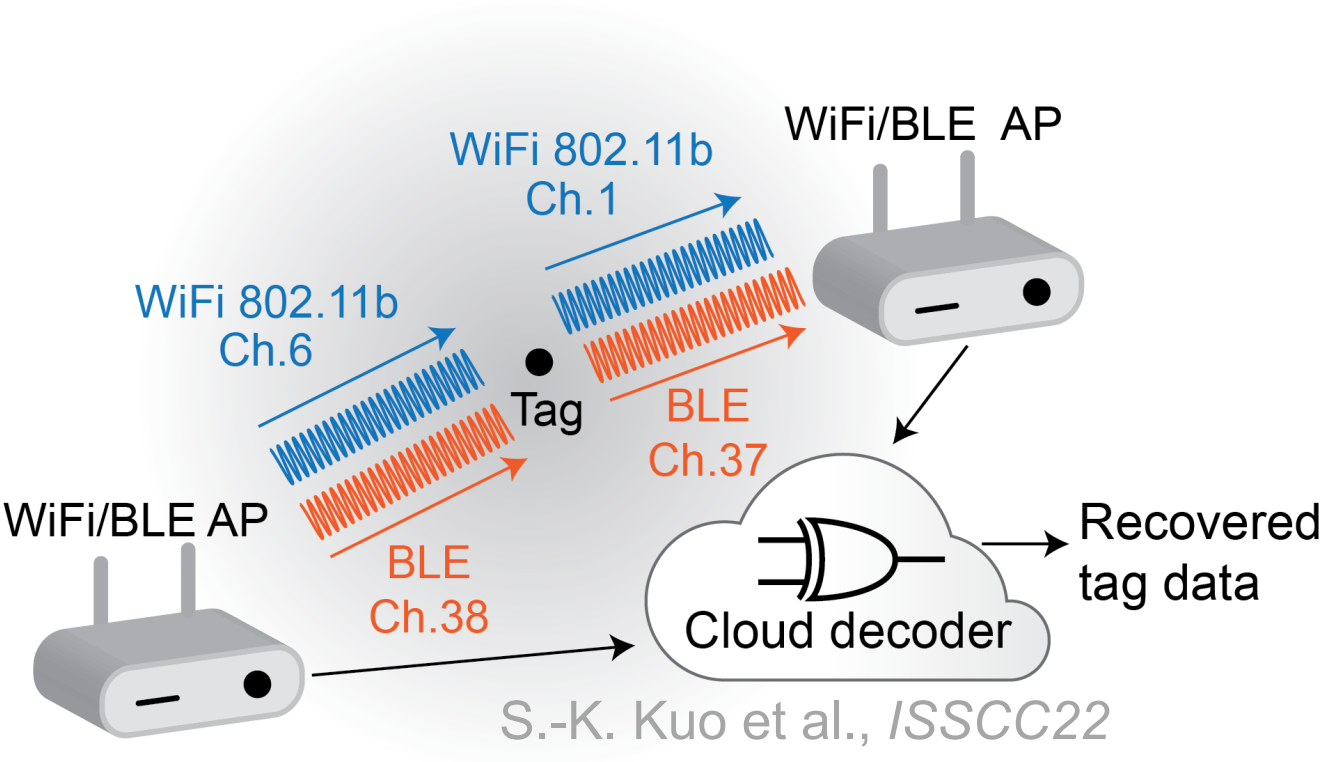
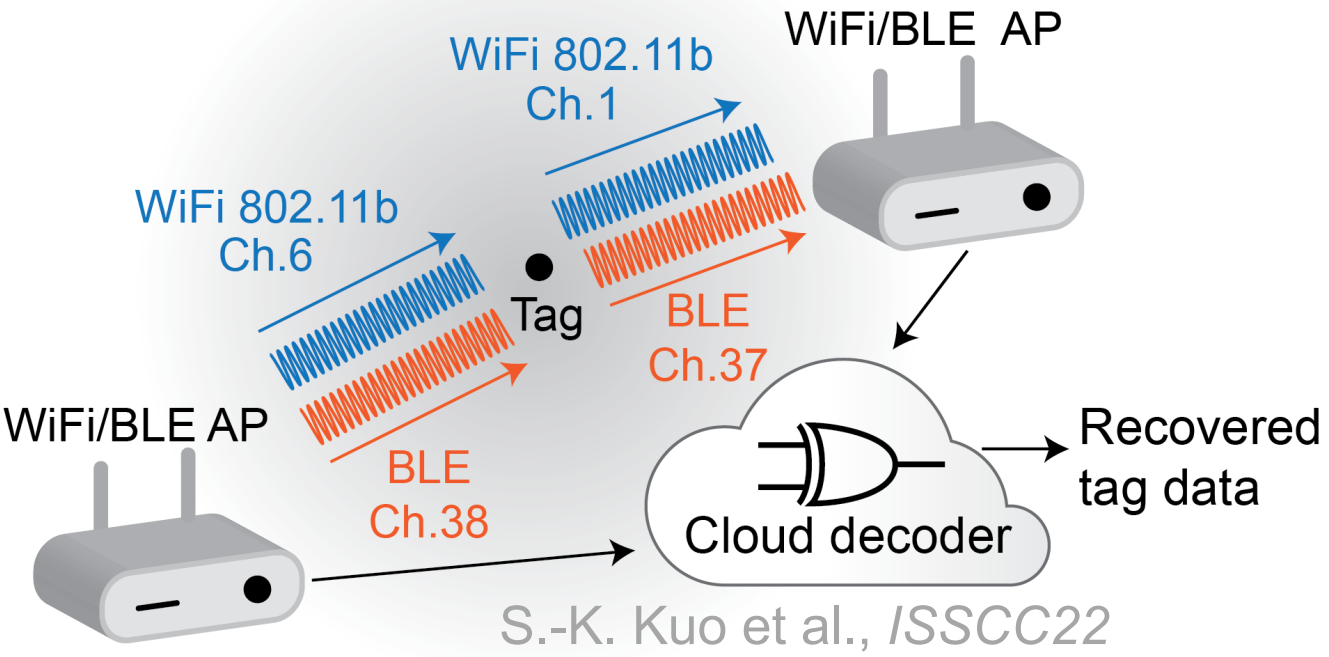


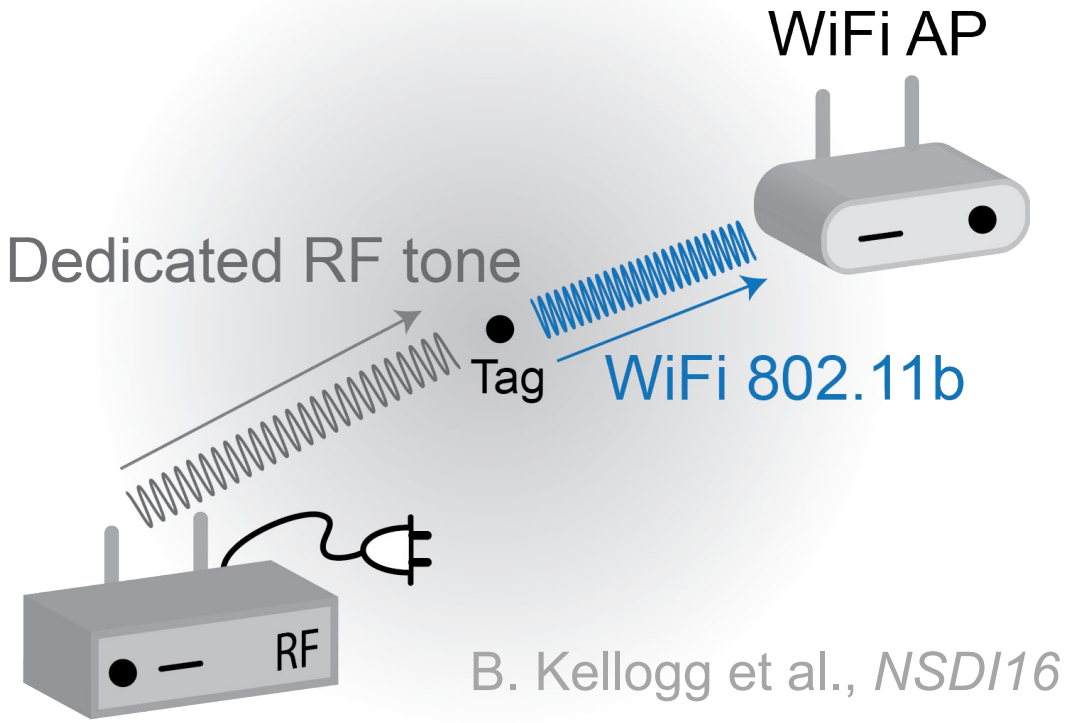
Hitchhike

Requires 2 access points

Previous Backscatter Approach



S.-K. Kuo et al., *ISSCC22*



B. Kellogg et al., *NSDI16*

Hitchhike

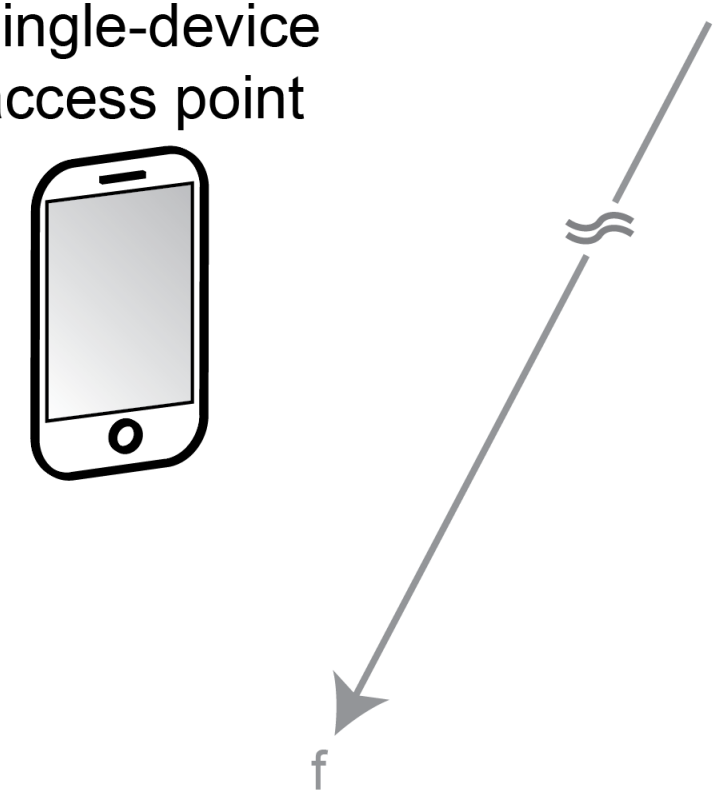
Requires 2 access points

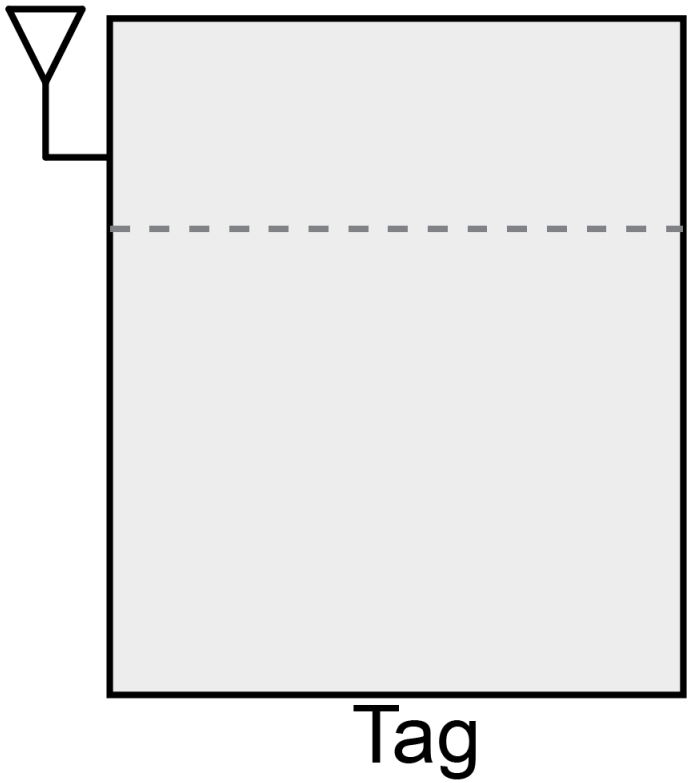
Passive WiFi

Dedicated tone generator is required

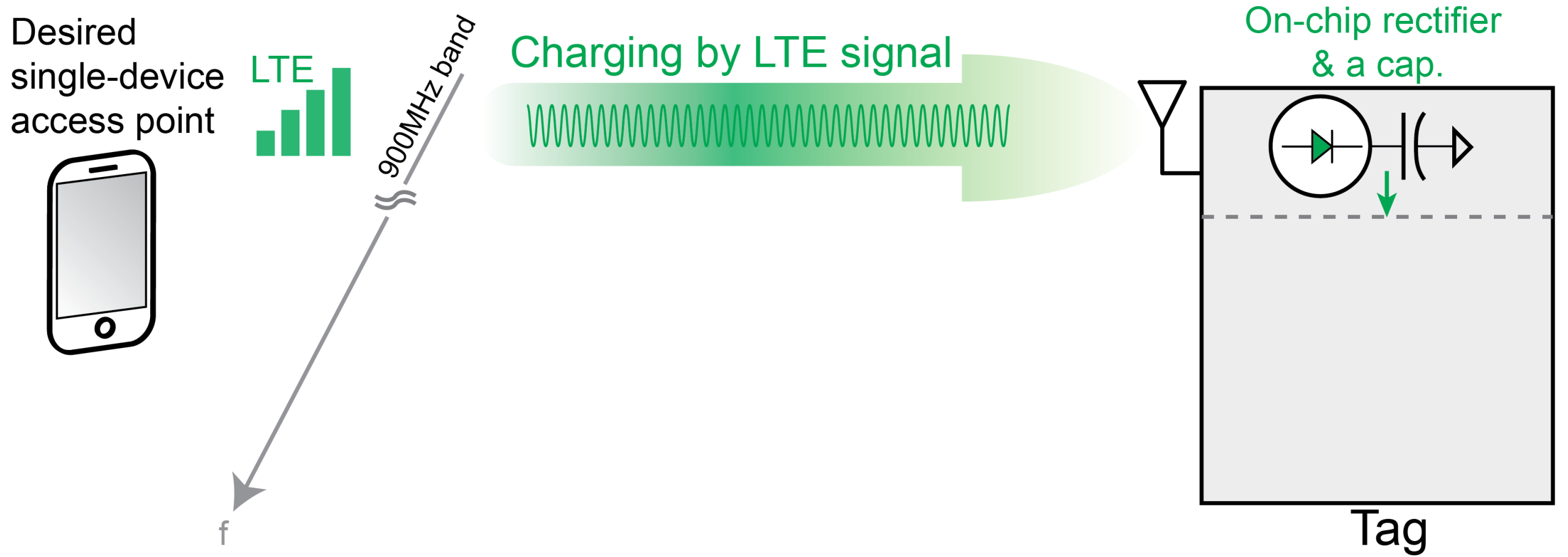
Proposed Architecture

Desired
single-device
access point





Proposed Architecture



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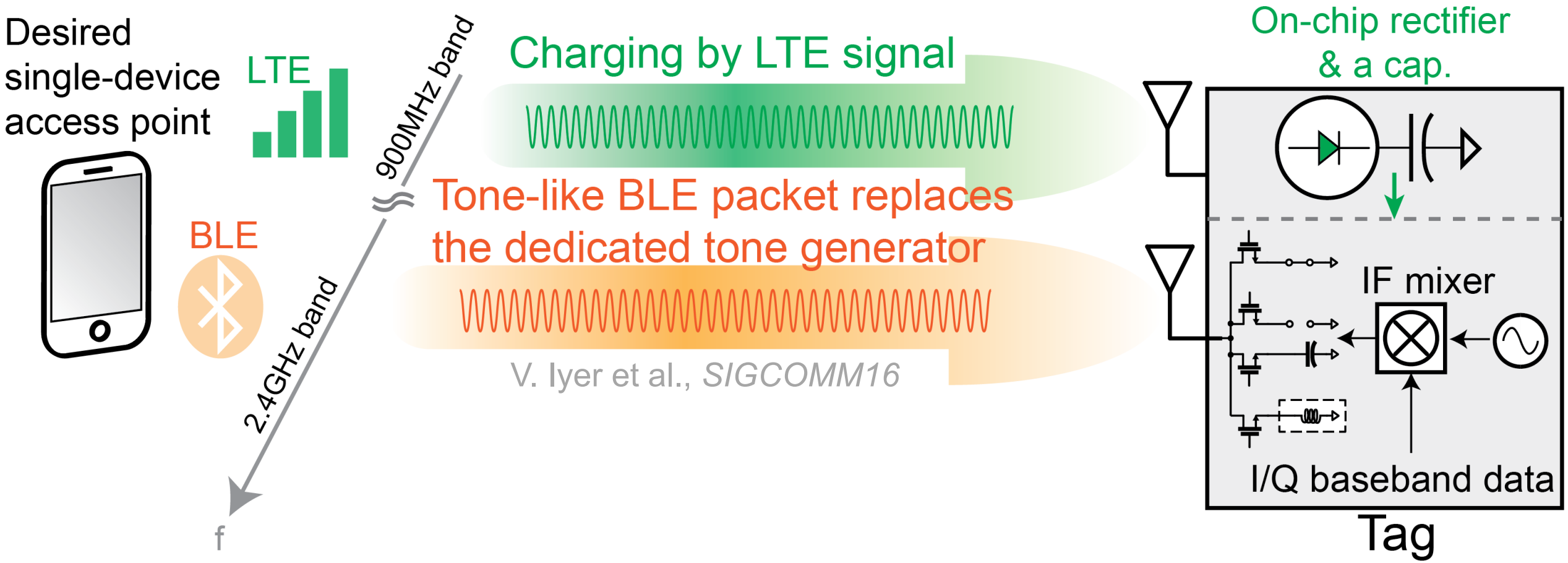
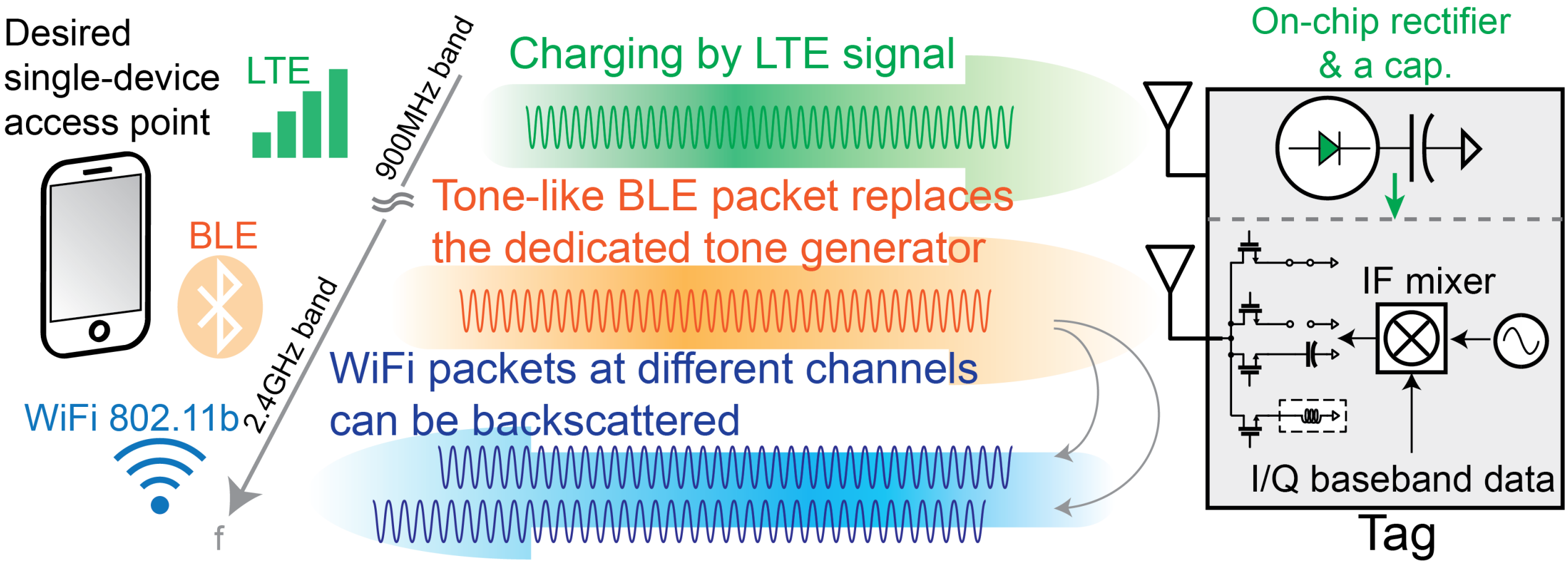


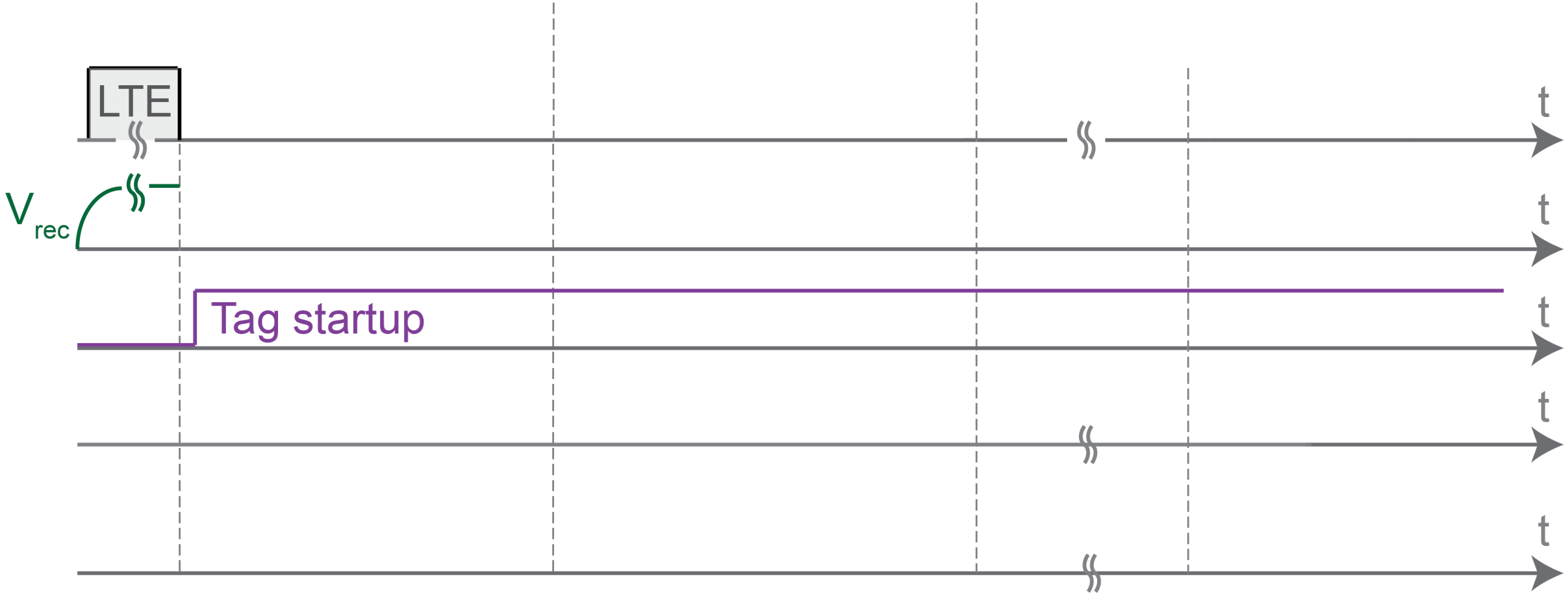
Proposed Architecture



Battery-less operation with single-device interrogation

Proposed Timing

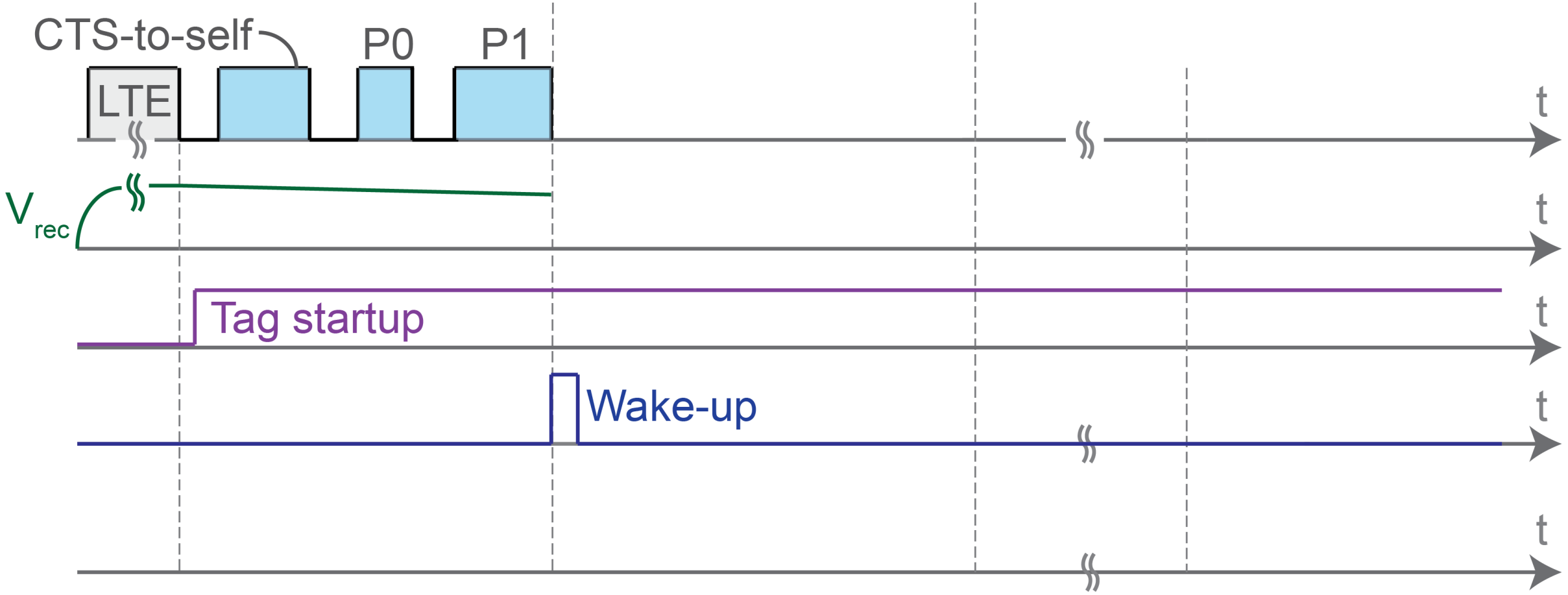
Step 1: LTE signal charges the tag



Proposed Timing

Step 1: LTE signal charges the tag

Step 2: Tag wakes up after detecting WiFi packets P0 & P1 with specific length (CTS-to-self packet is used to clear WiFi ch.)



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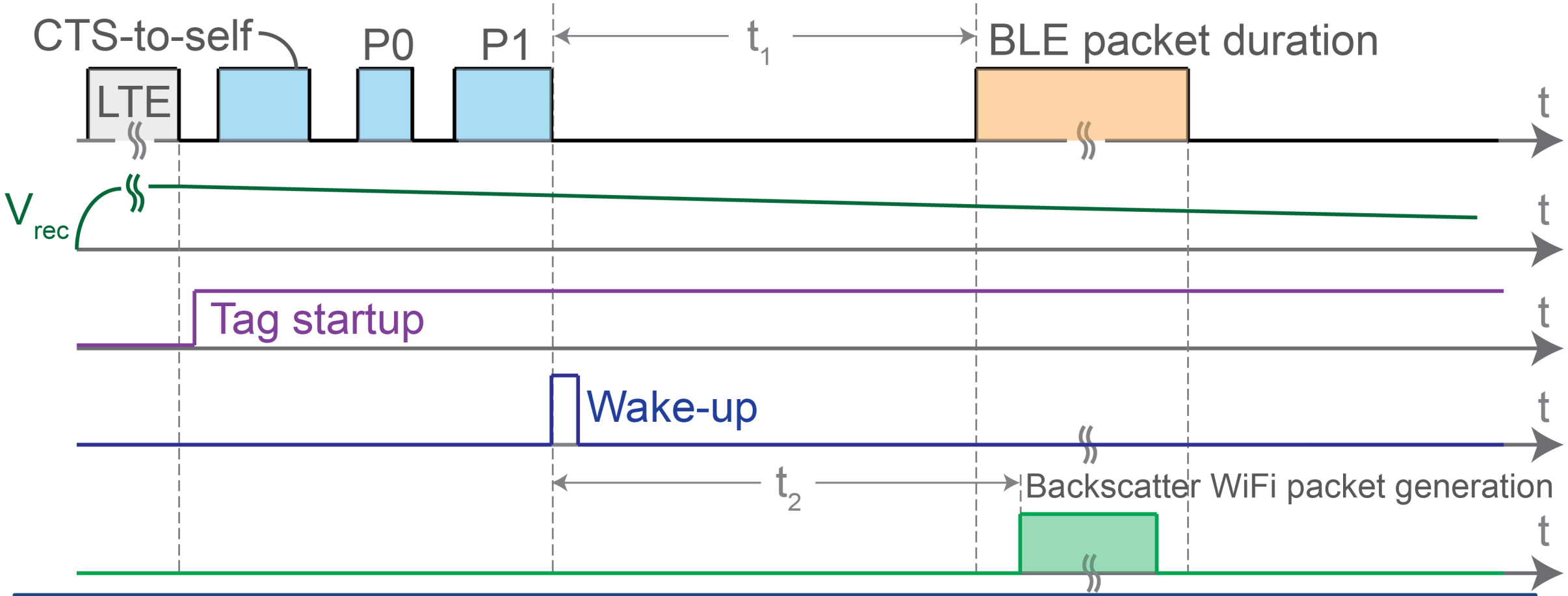


Step 3: Perform backscatter within BLE packet duration (t_2>t_1)

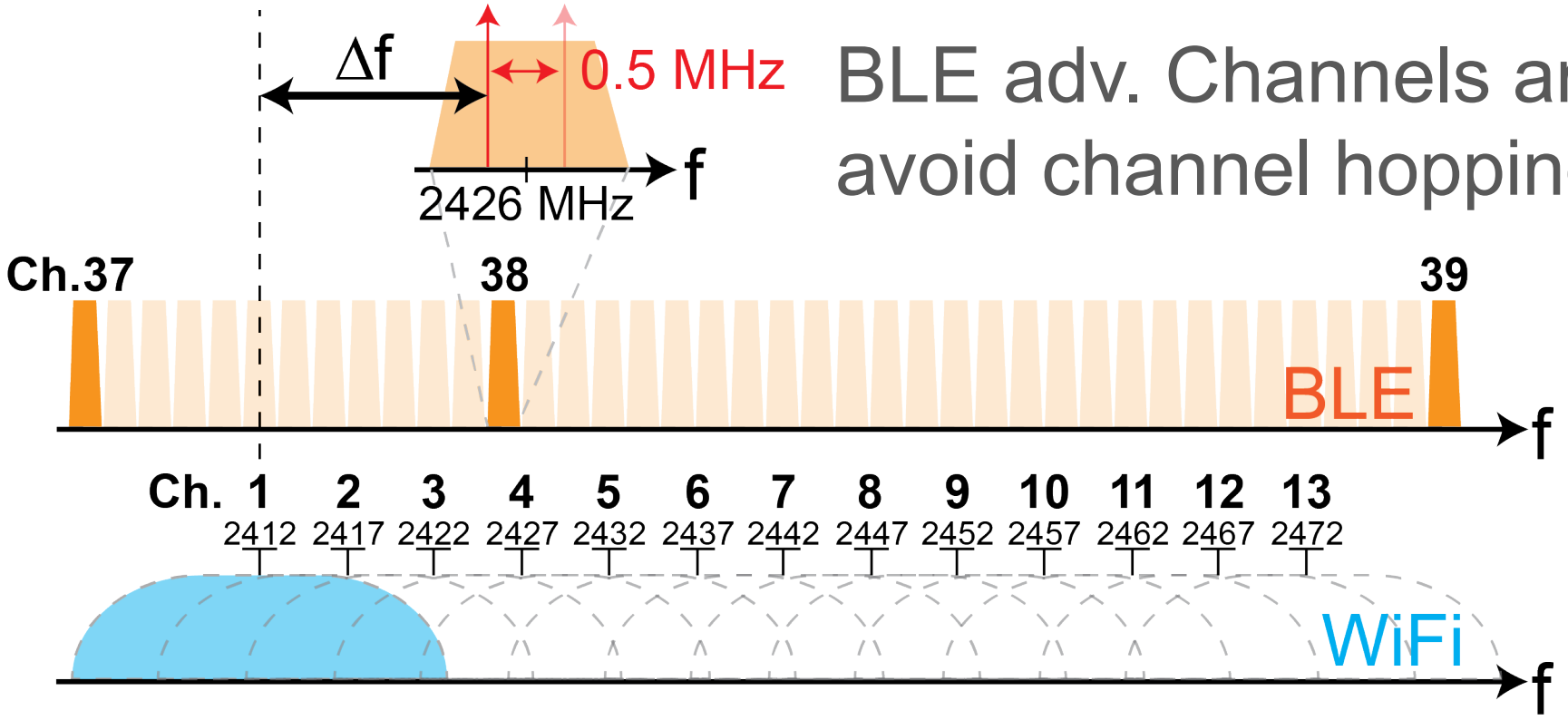
Backscatter Frequency Requirements

Frequency requirement I:

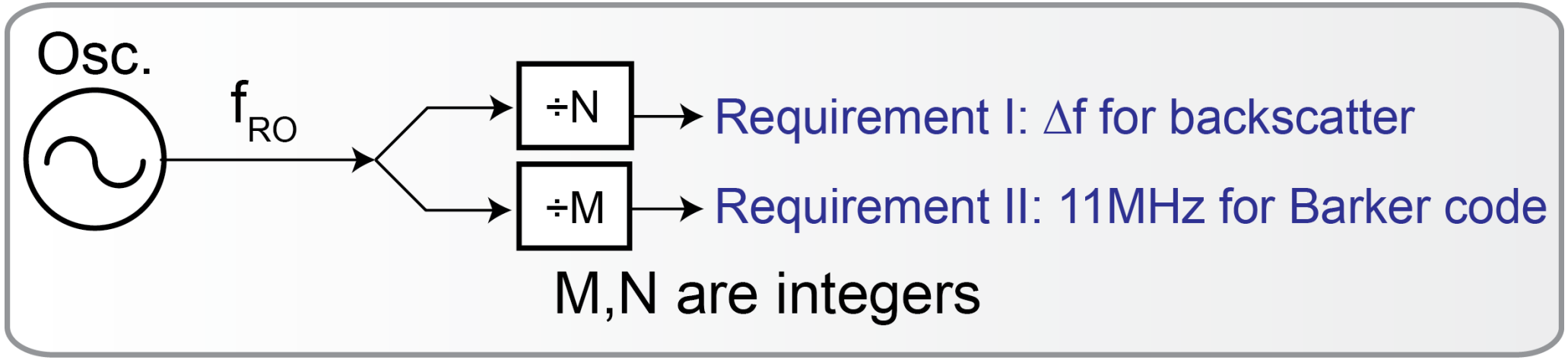
From BLE tone to WiFi channel, Δf is needed. For example, Δf=13.75MHz from BLE ch.38 (left) to WiFi ch.1

Frequency requirement II:

In 802.11b, an 11MHz clock is needed to generate an 11-bit Barker code



Backscatter Frequency Generation

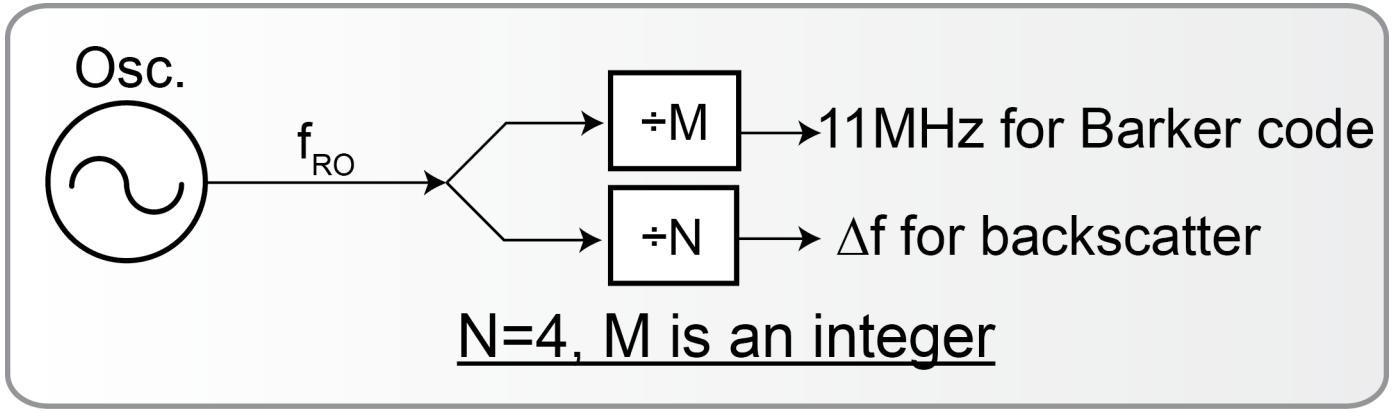


- f_{RO} is an integer multiple of 11MHz.
- Therefore, $f_{RO} \in \mathbb{N}$
- Recall that **Δ**f is (x ± 0.25) MHz for BLE-to-WiFi, where $x \in \mathbb{N}$

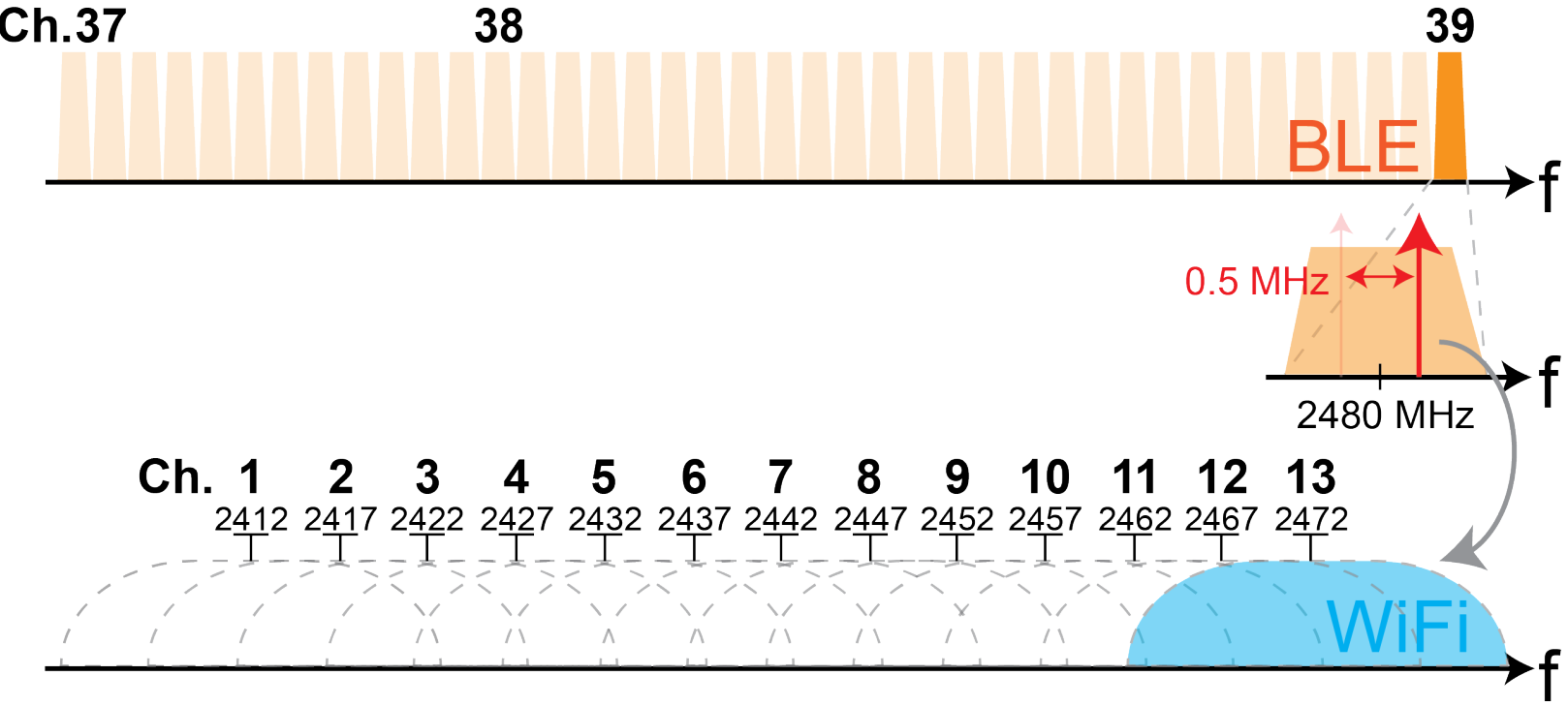
⇒ Min. N=4 to satisfy the constraints

Next step:
Look for M that enables **Δ**f which fits in BLE adv. ch. tone to WiFi ch.

Backscatter Frequency Plan

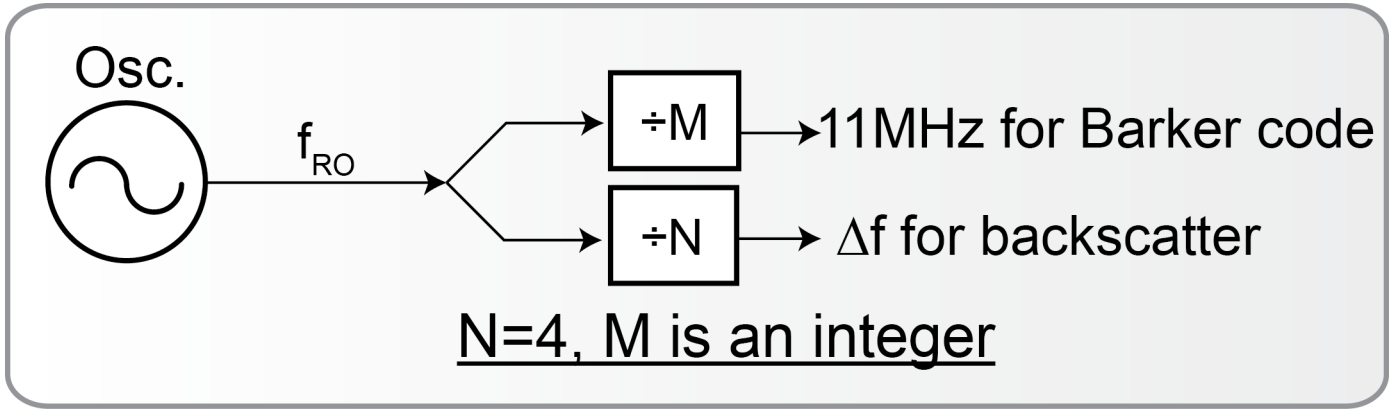


Case 1

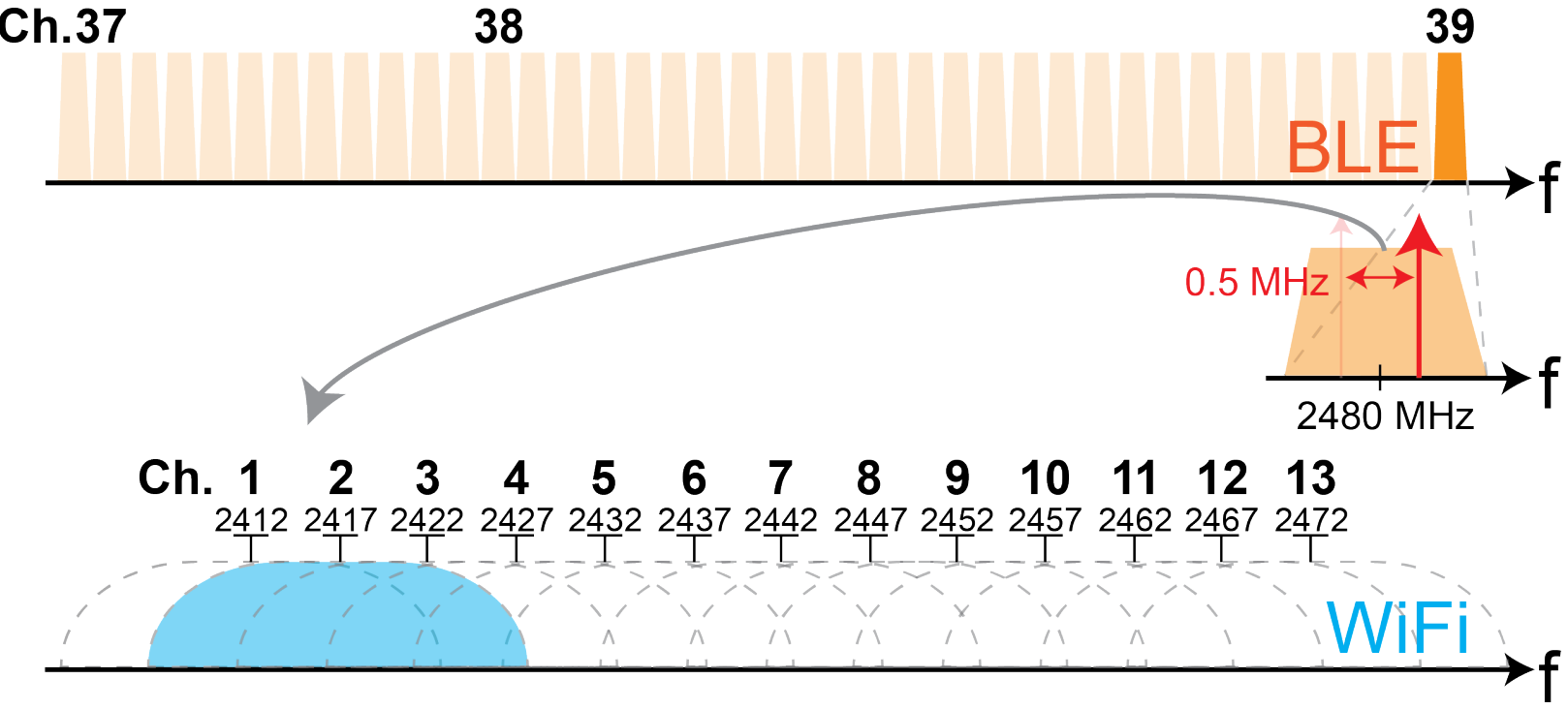


M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13

Backscatter Frequency Plan

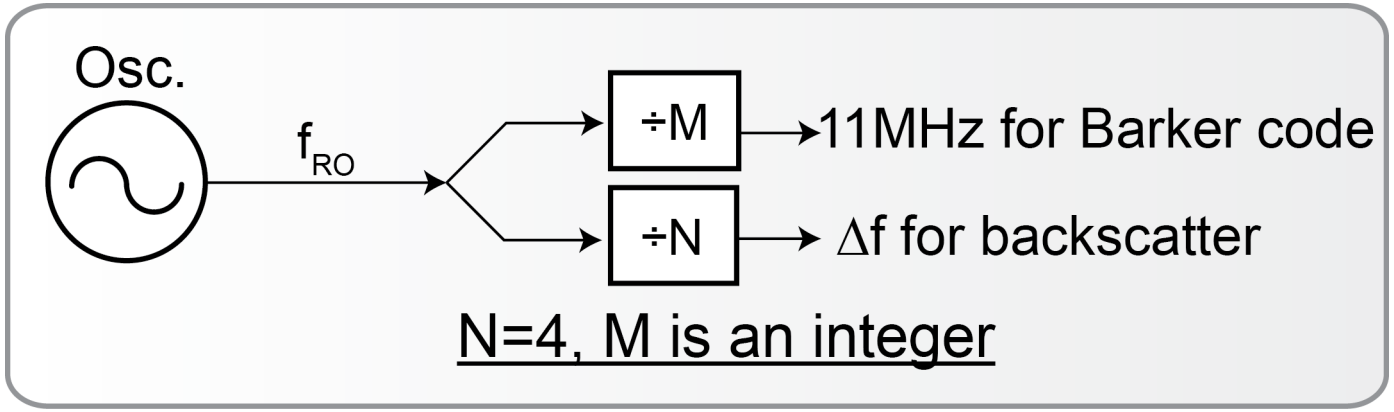


Case 2

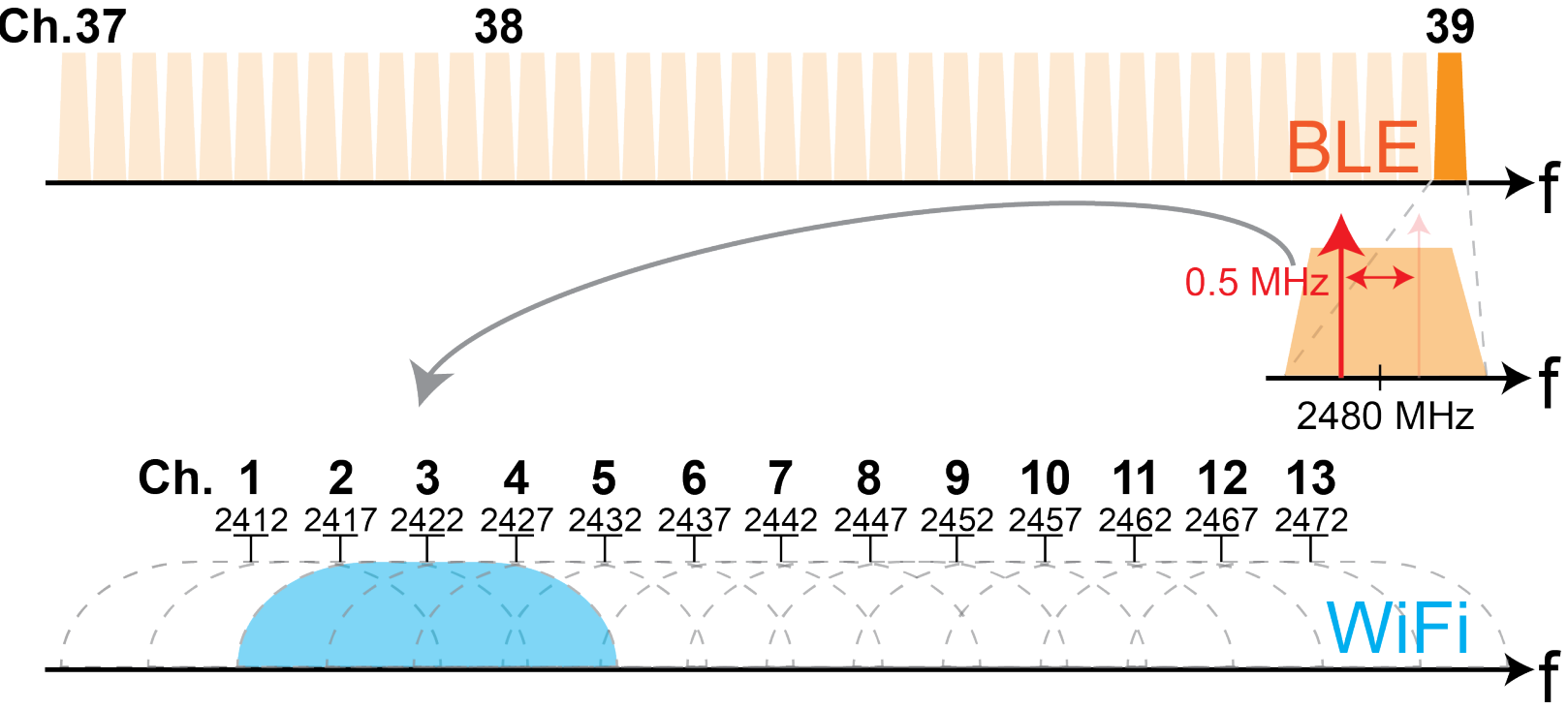


M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13
23	63.25	253	39 to 2

Backscatter Frequency Plan

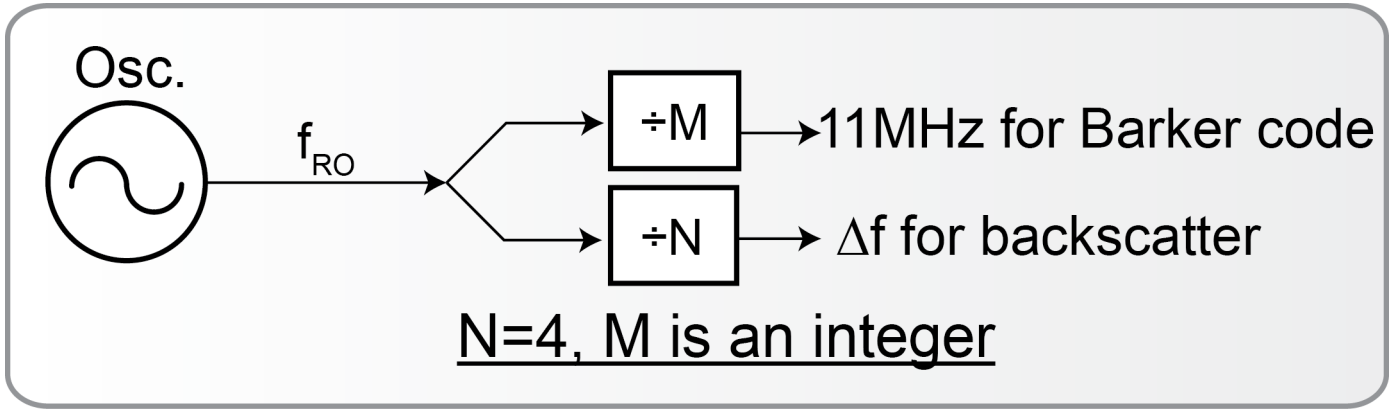


Case 3

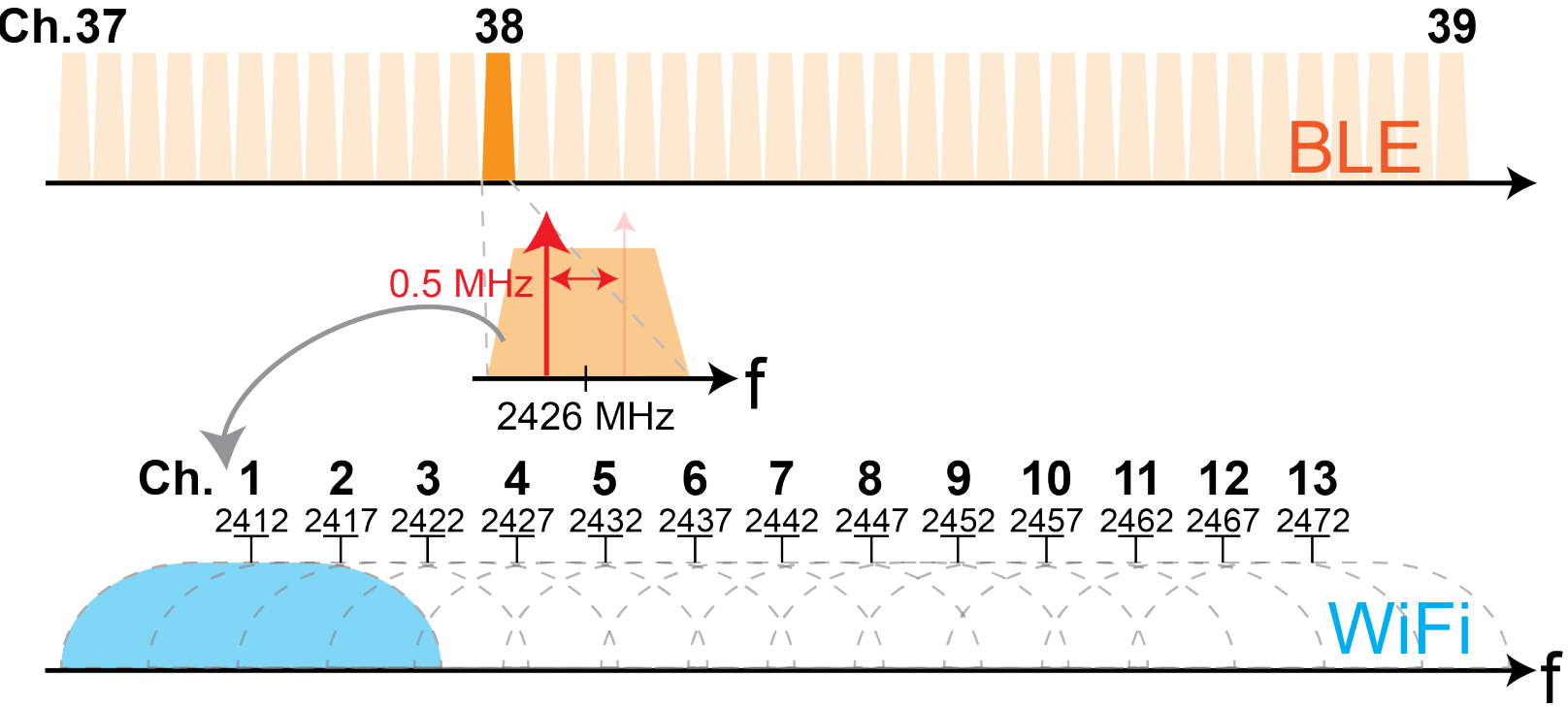


M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13
21	47.75	231	39 to 3
23	63.25	253	39 to 2

Backscatter Frequency Plan

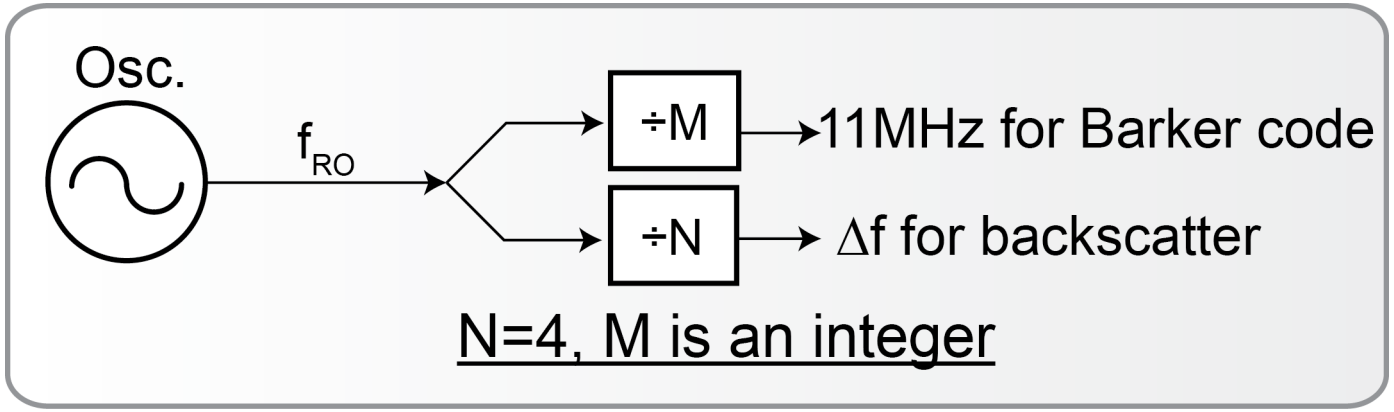


Case 4

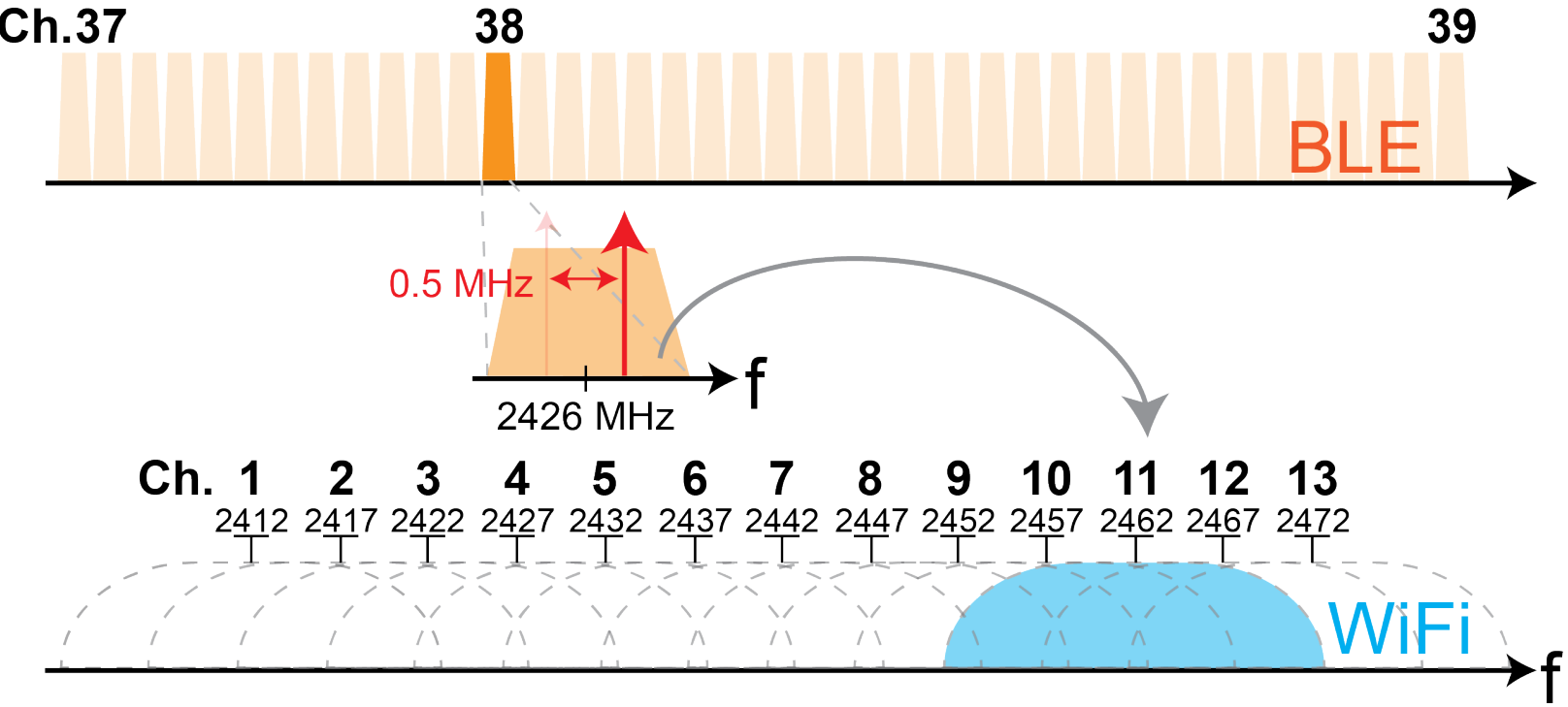


M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13
5	13.75	55	38 to 1
21	47.75	231	39 to 3
23	63.25	253	39 to 2

Backscatter Frequency Plan

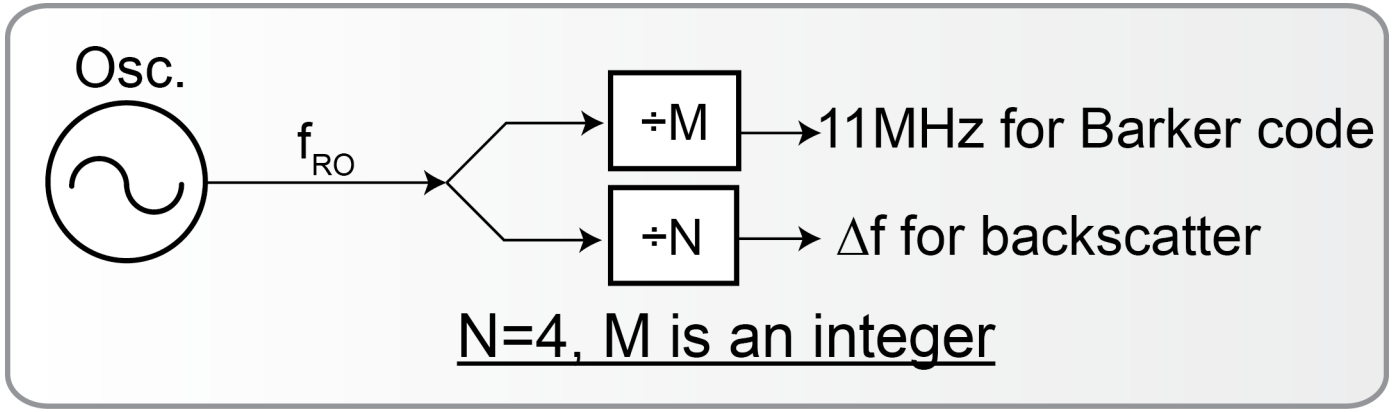


Case 5

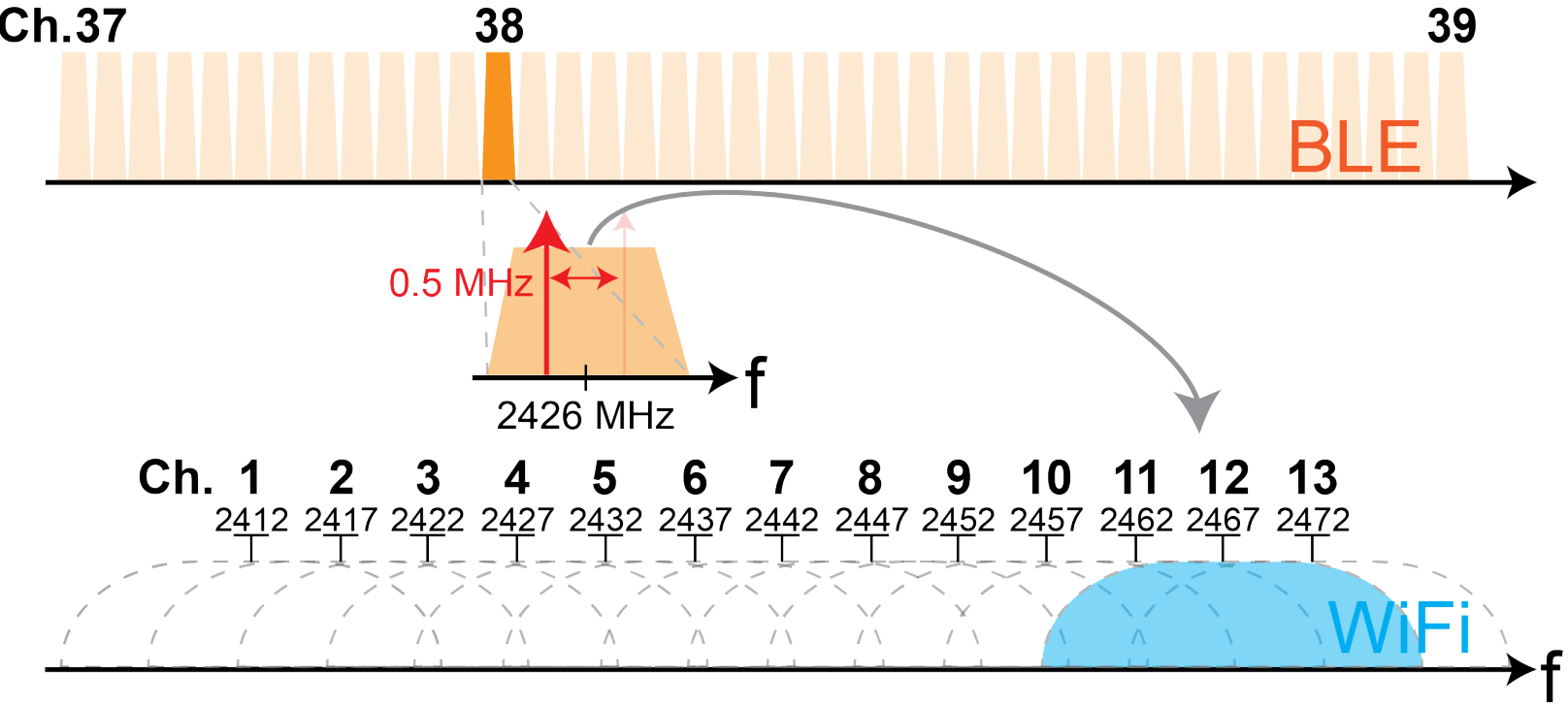


M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13
5	13.75	55	38 to 1
13	35.75	143	38 to 11
21	47.75	231	39 to 3
23	63.25	253	39 to 2

Backscatter Frequency Plan

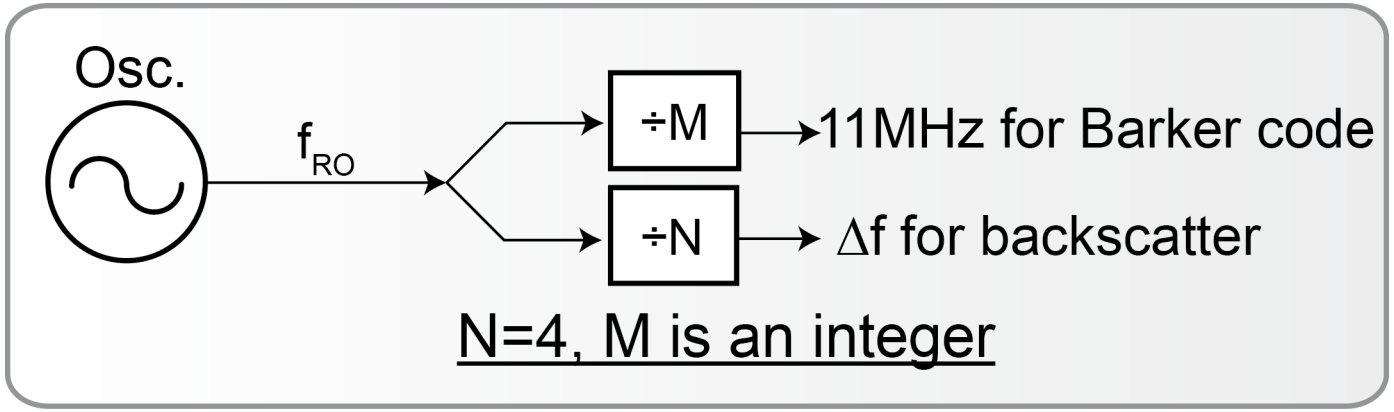


Case 6

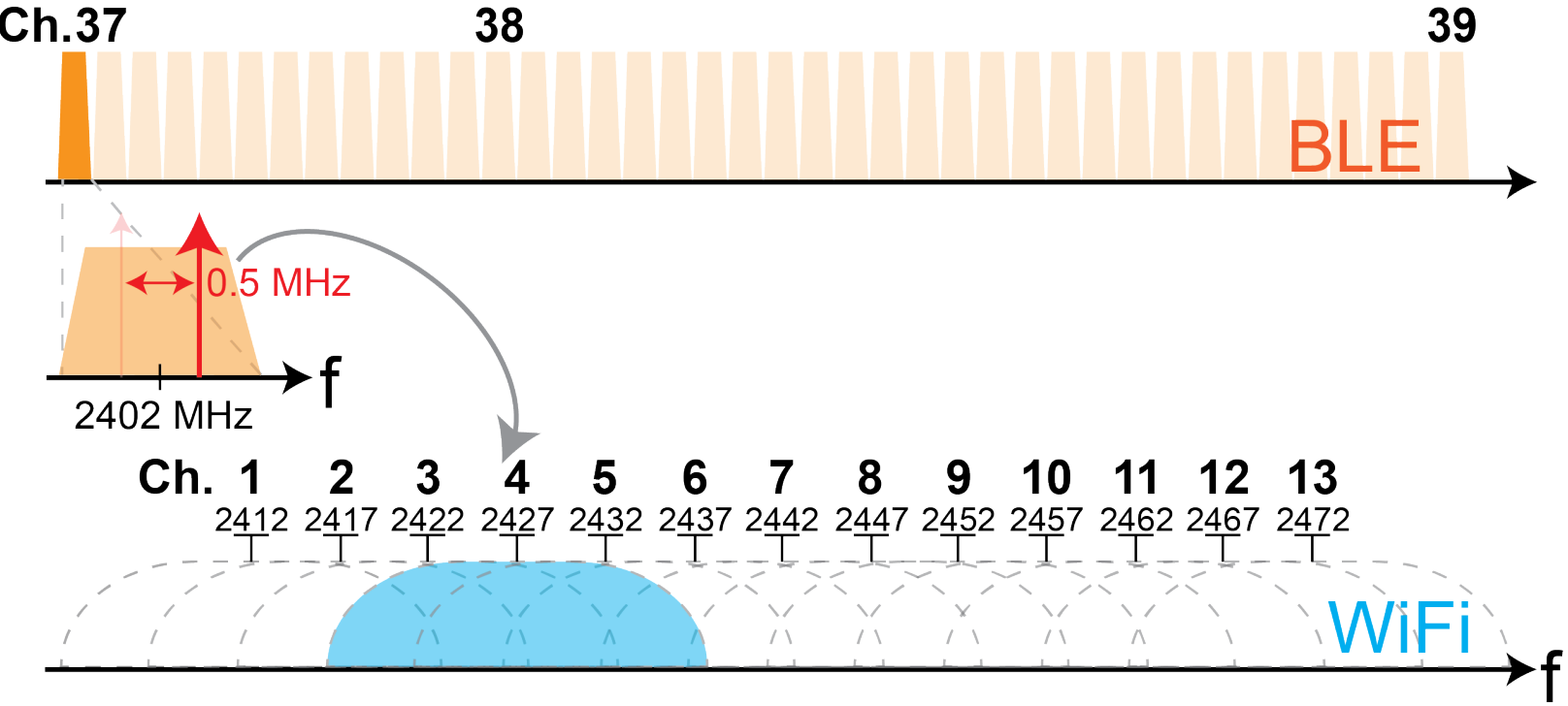


M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13
5	13.75	55	38 to 1
13	35.75	143	38 to 11
15	41.25	165	38 to 12
21	47.75	231	39 to 3
23	63.25	253	39 to 2

Backscatter Frequency Plan



Case 7



M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13
5	13.75	55	38 to 1
9	24.75	99	37 to 4
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15	41.25	165	38 to 12
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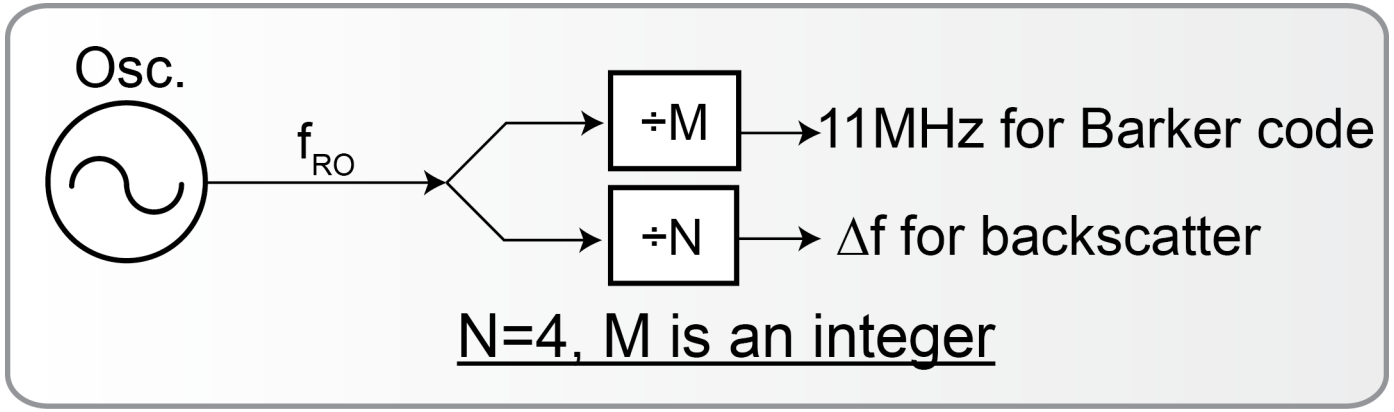
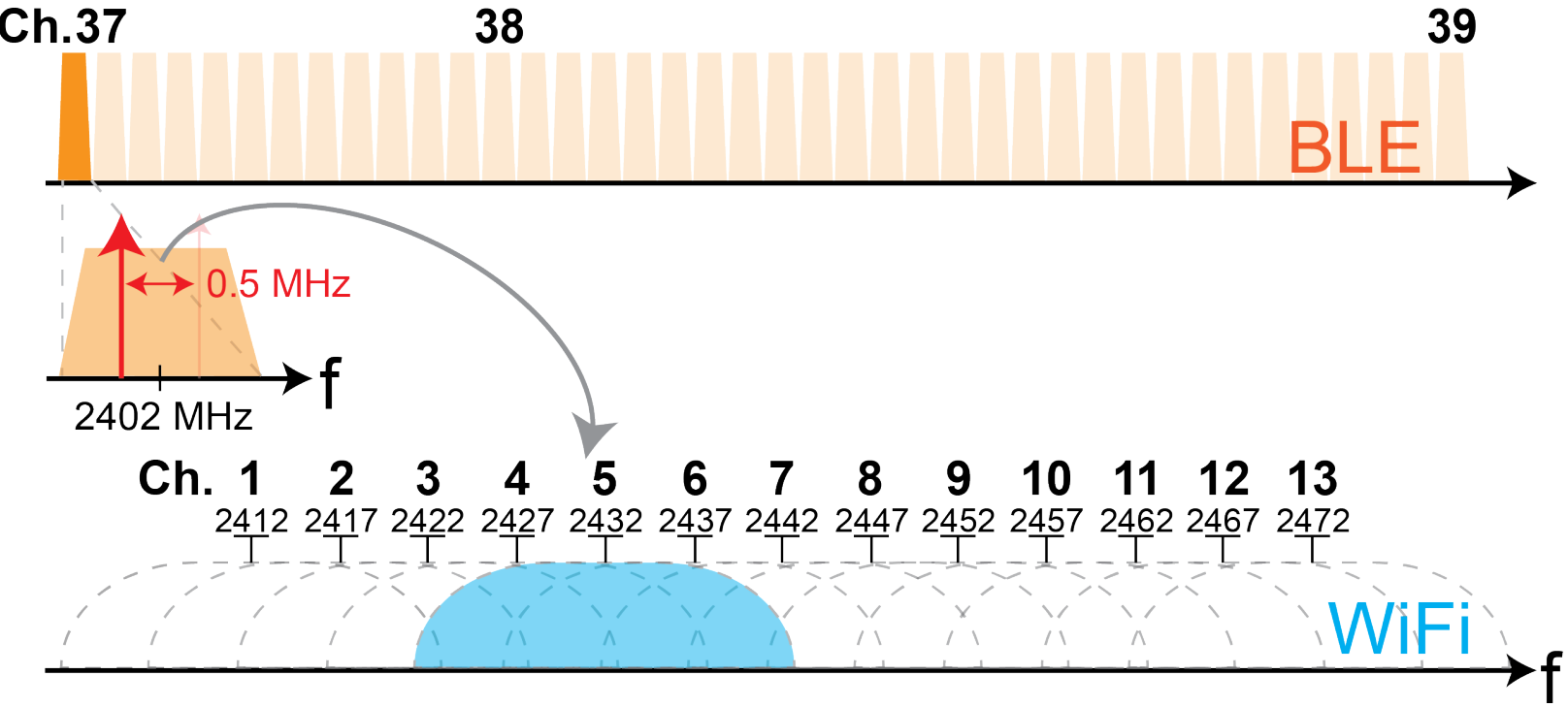
Backscatter Frequency Plan

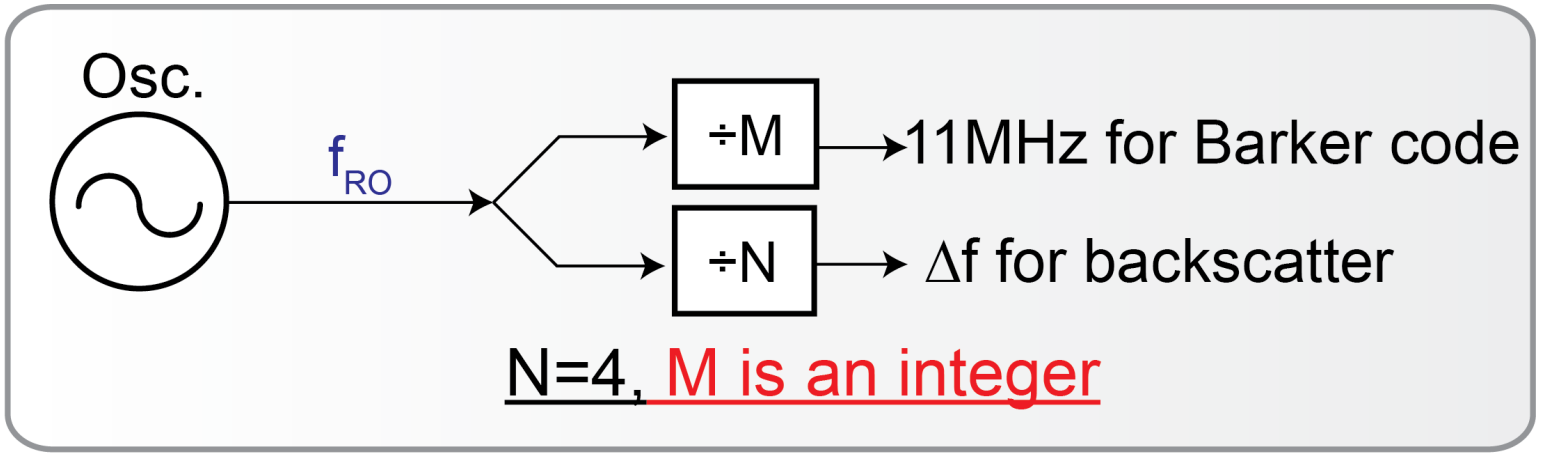


Case 8



M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13
5	13.75	55	38 to 1
9	24.75	99	37 to 4
11	30.25	121	37 to 5
13	35.75	143	38 to 11
15	41.25	165	38 to 12
21	47.75	231	39 to 3
23	63.25	253	39 to 2

Backscatter Frequency Plan Summary



M	Δf (MHz)	f_{RO} (MHz)	Channel
3	8.25	33	39 to 13
5	13.75	55	38 to 1
9	24.75	99	37 to 4
11	30.25	121	37 to 5
13	35.75	143	38 to 11
15	41.25	165	38 to 12
21	47.75	231	39 to 3
23	63.25	253	39 to 2

- f_{RO} tuning range = 33~253 MHz
- 8 cases are supported

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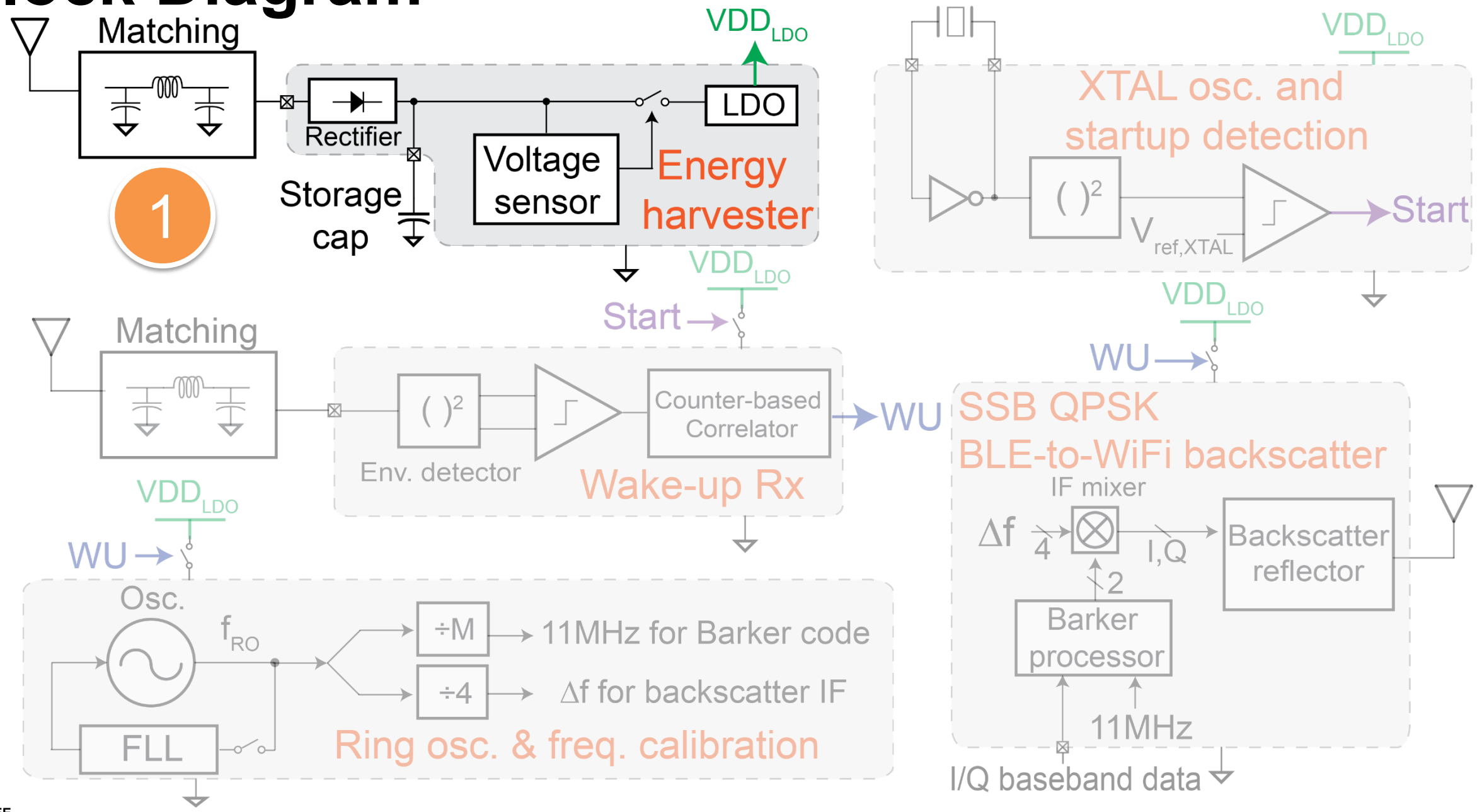
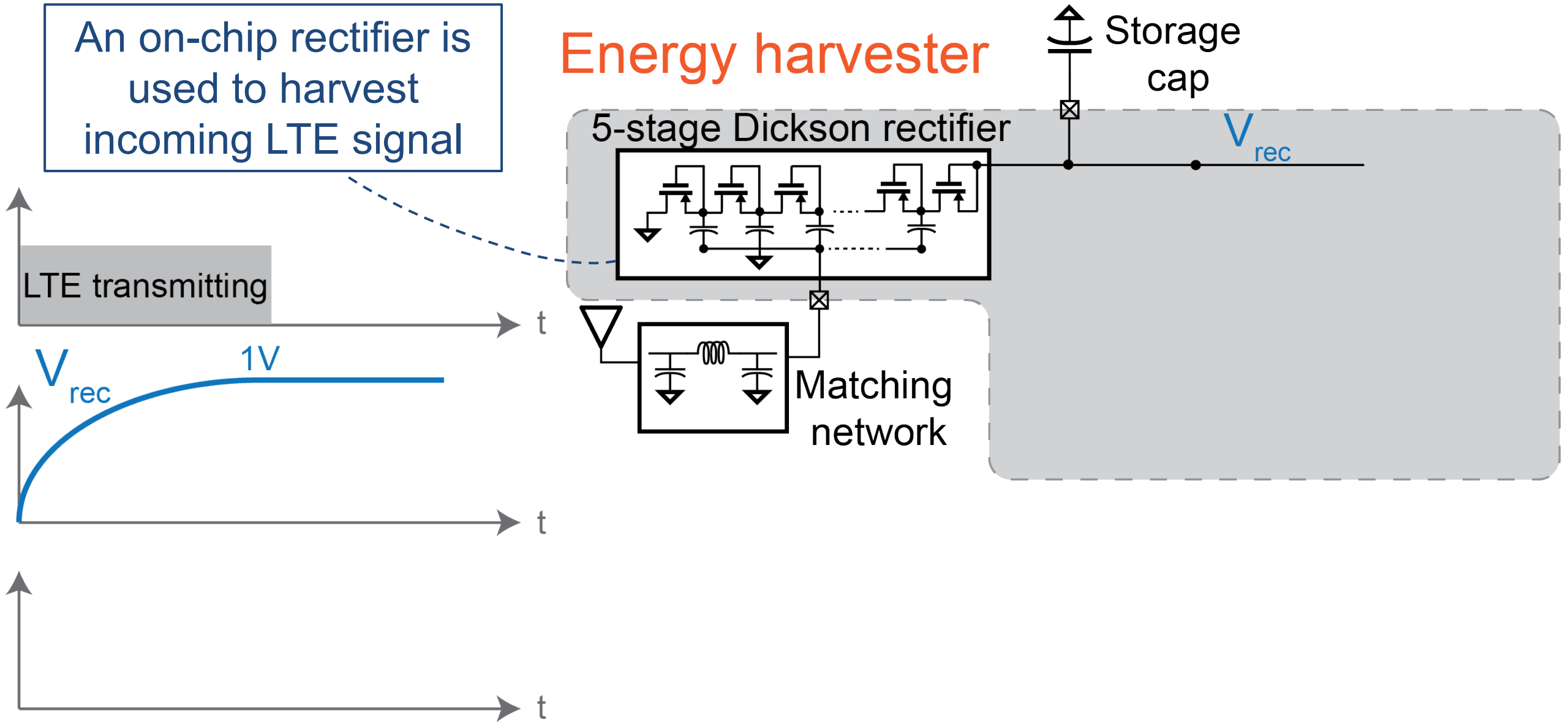
Block Diagram



Energy Harvesting and Voltage Sensing

An on-chip rectifier is used to harvest incoming LTE signal



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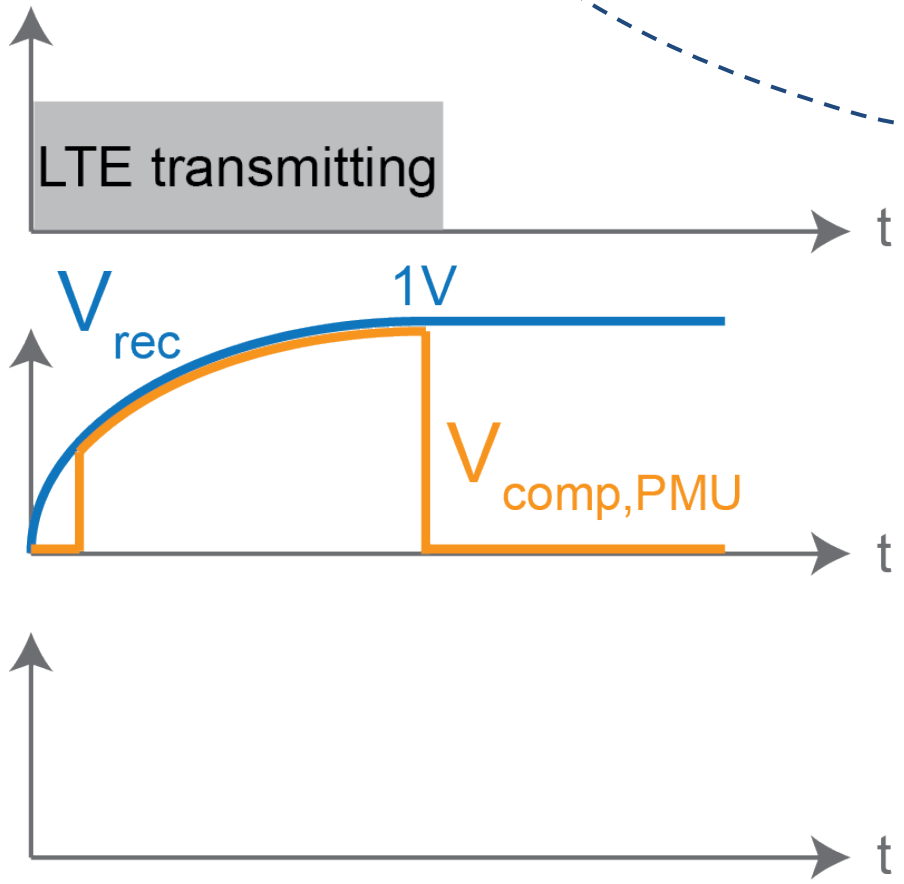

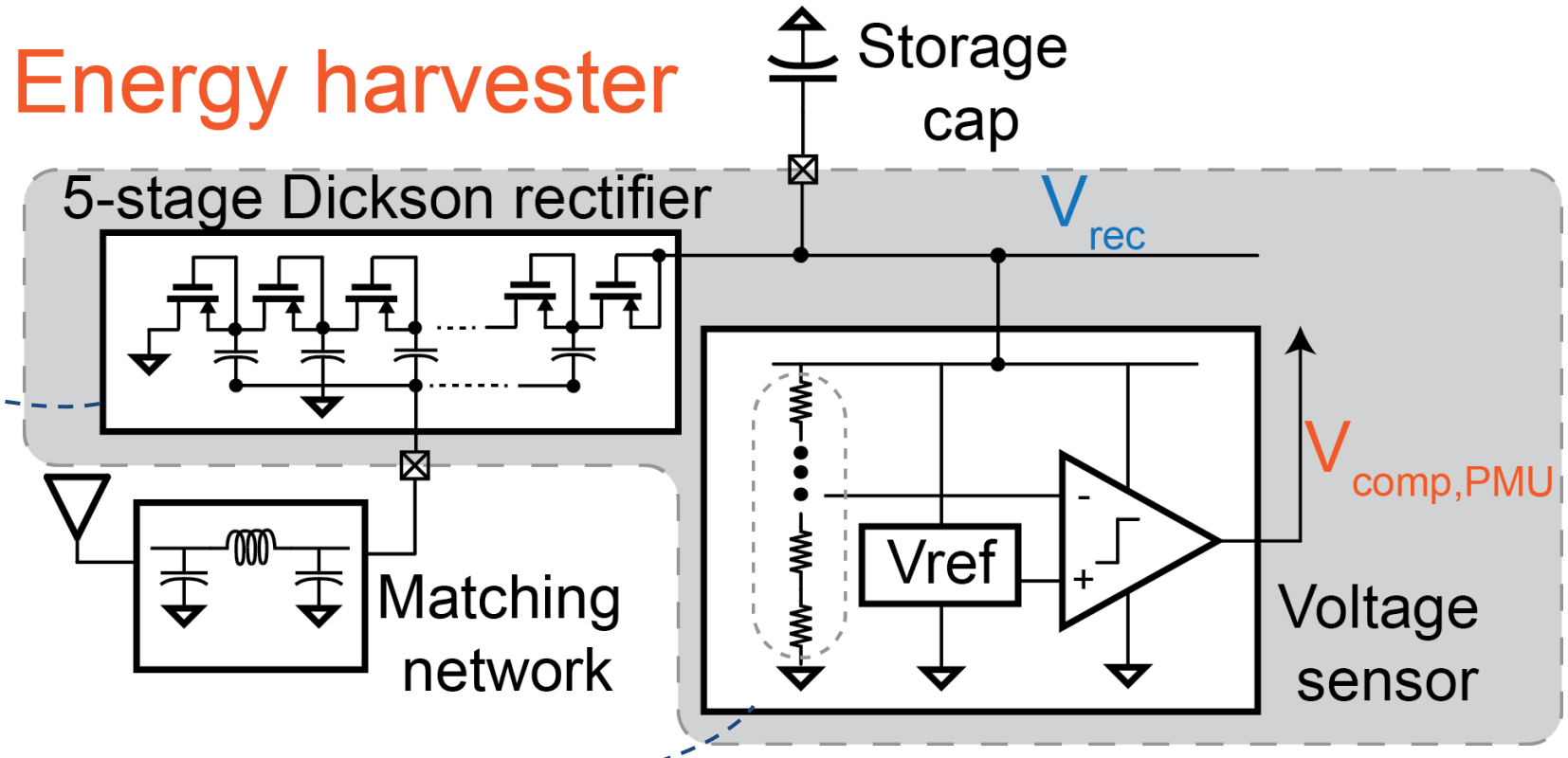

V_{rec} is sensed by a voltage ref. generator, a trip voltage generator and a comparator

Energy Harvesting and Voltage Sensing

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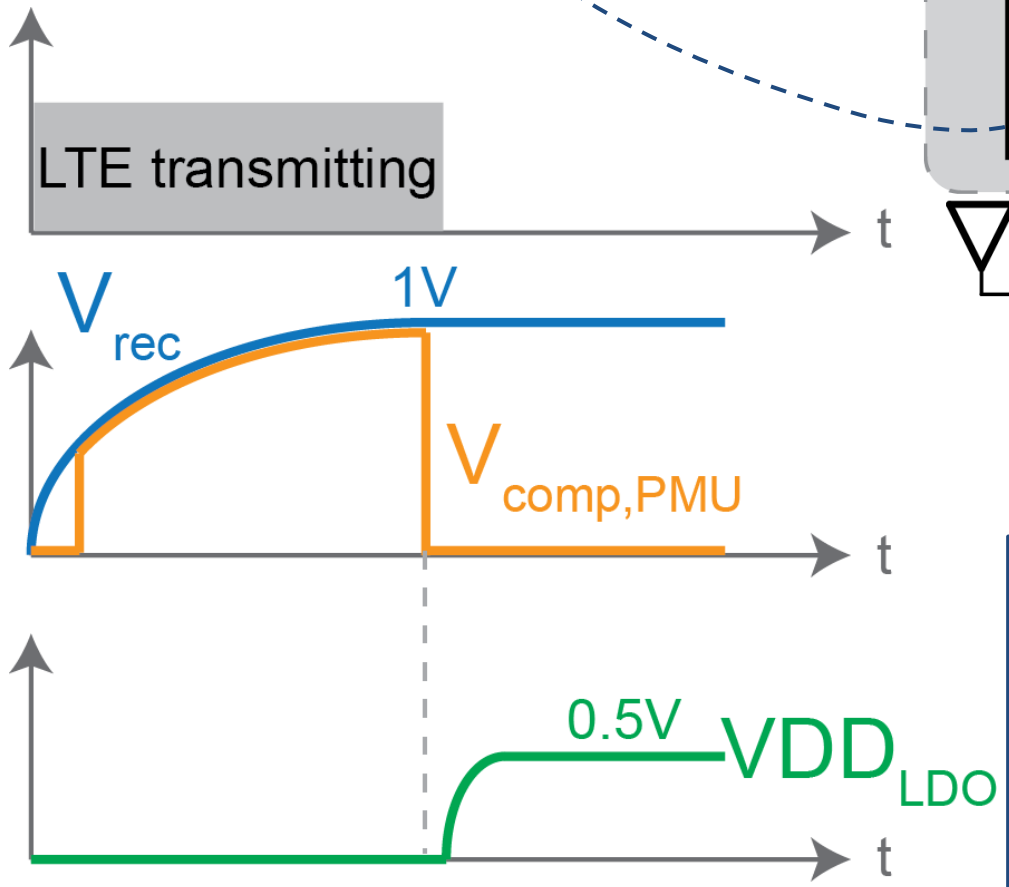
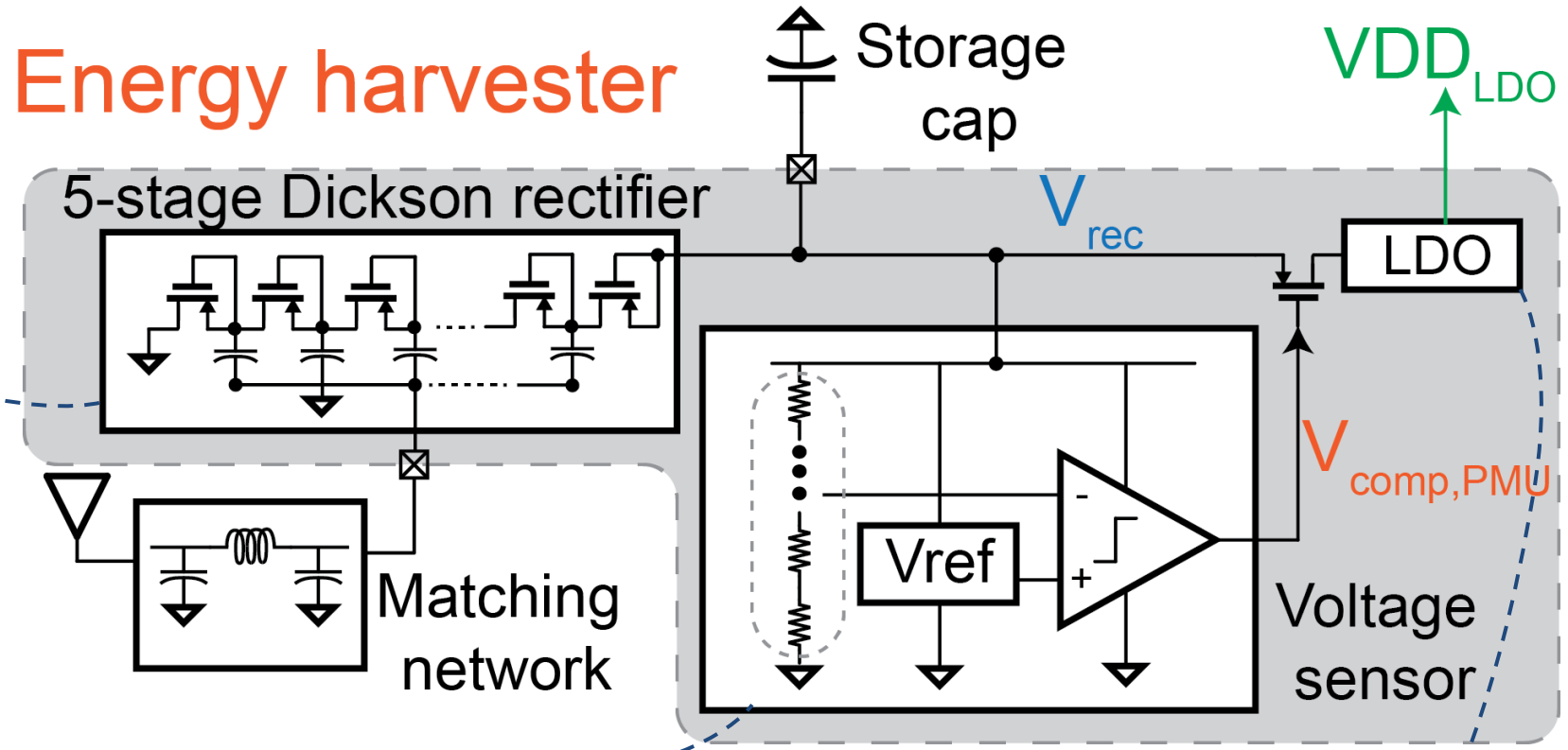
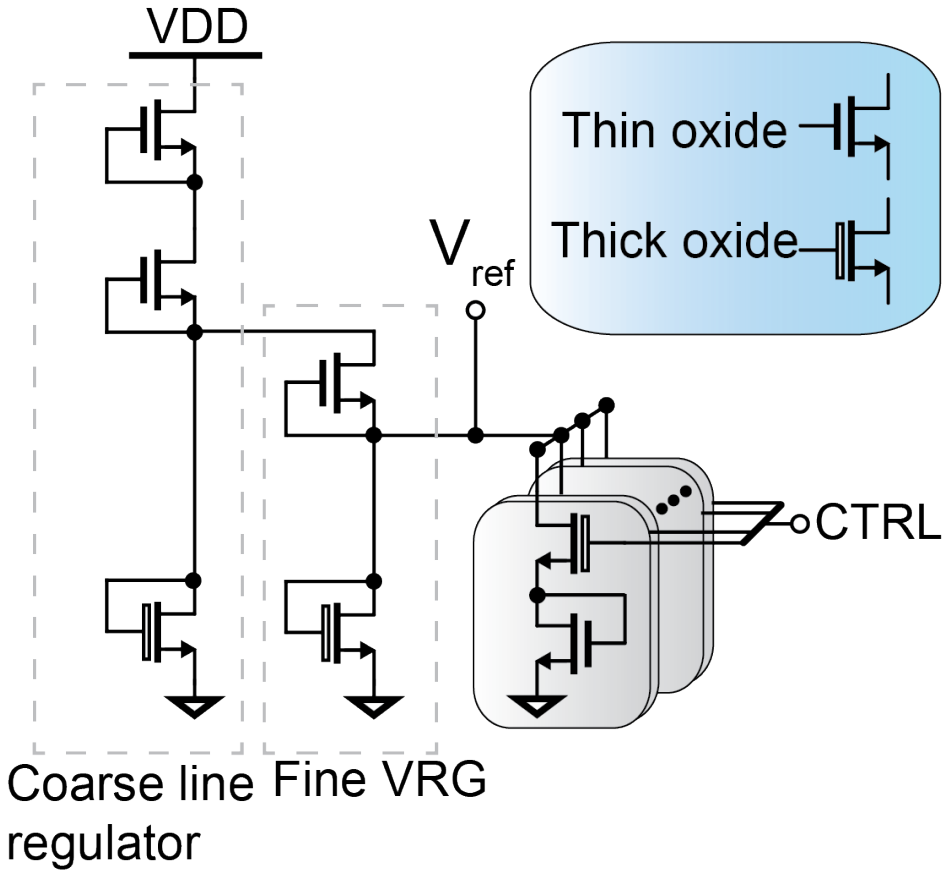


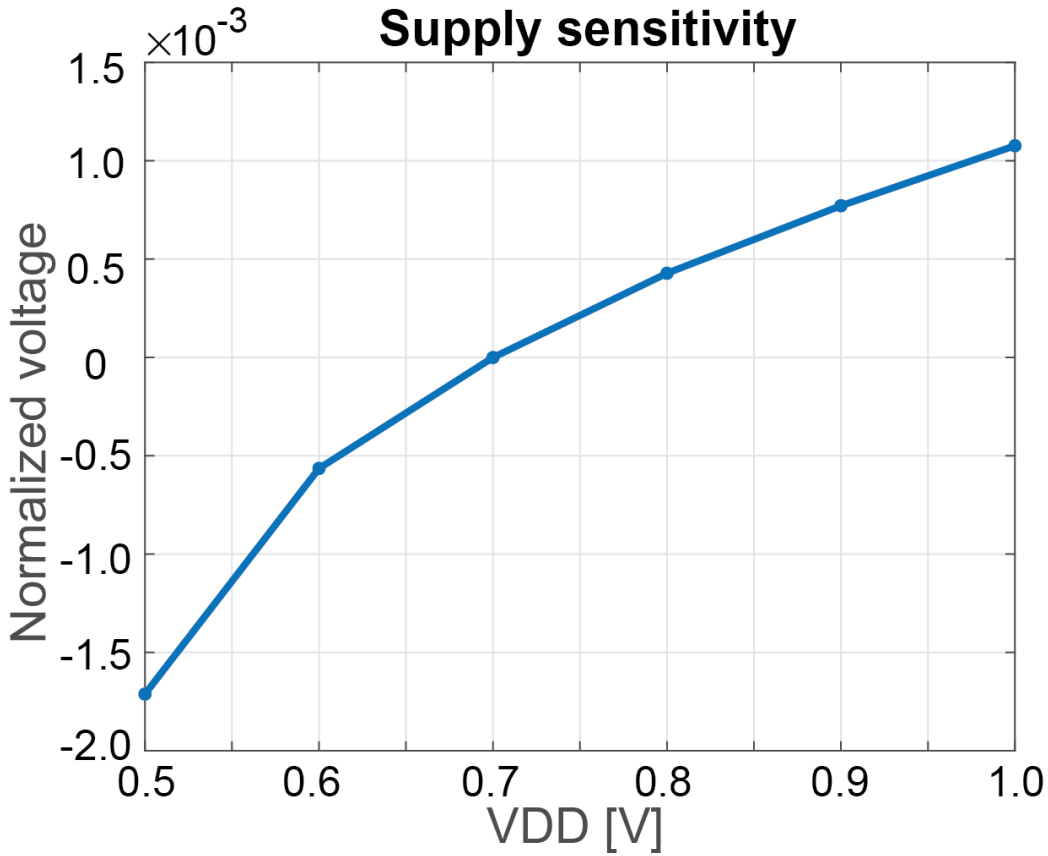


V_{rec} is sensed by a voltage ref. generator, a trip voltage generator and a comparator

LDO turns on after harvesting

Voltage Reference Generator (VRG)

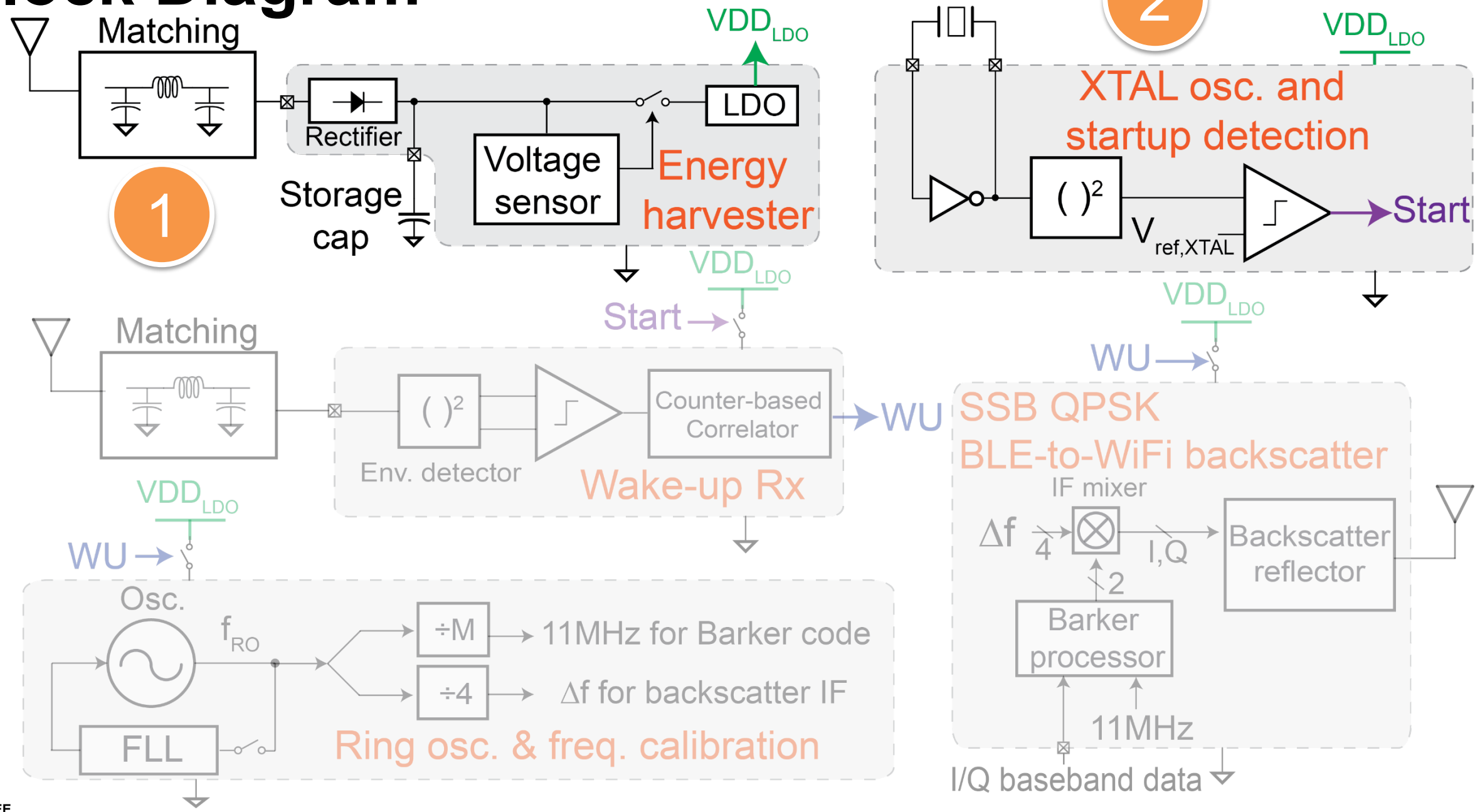




- Two-stage push-pull architecture
- Nominal output voltage 0.25V with line sensitivity 0.54%/V when supply voltage ranges from 0.5V to 1V

H. Wang and P. P. Mercier, *ISCAS16*

Block Diagram



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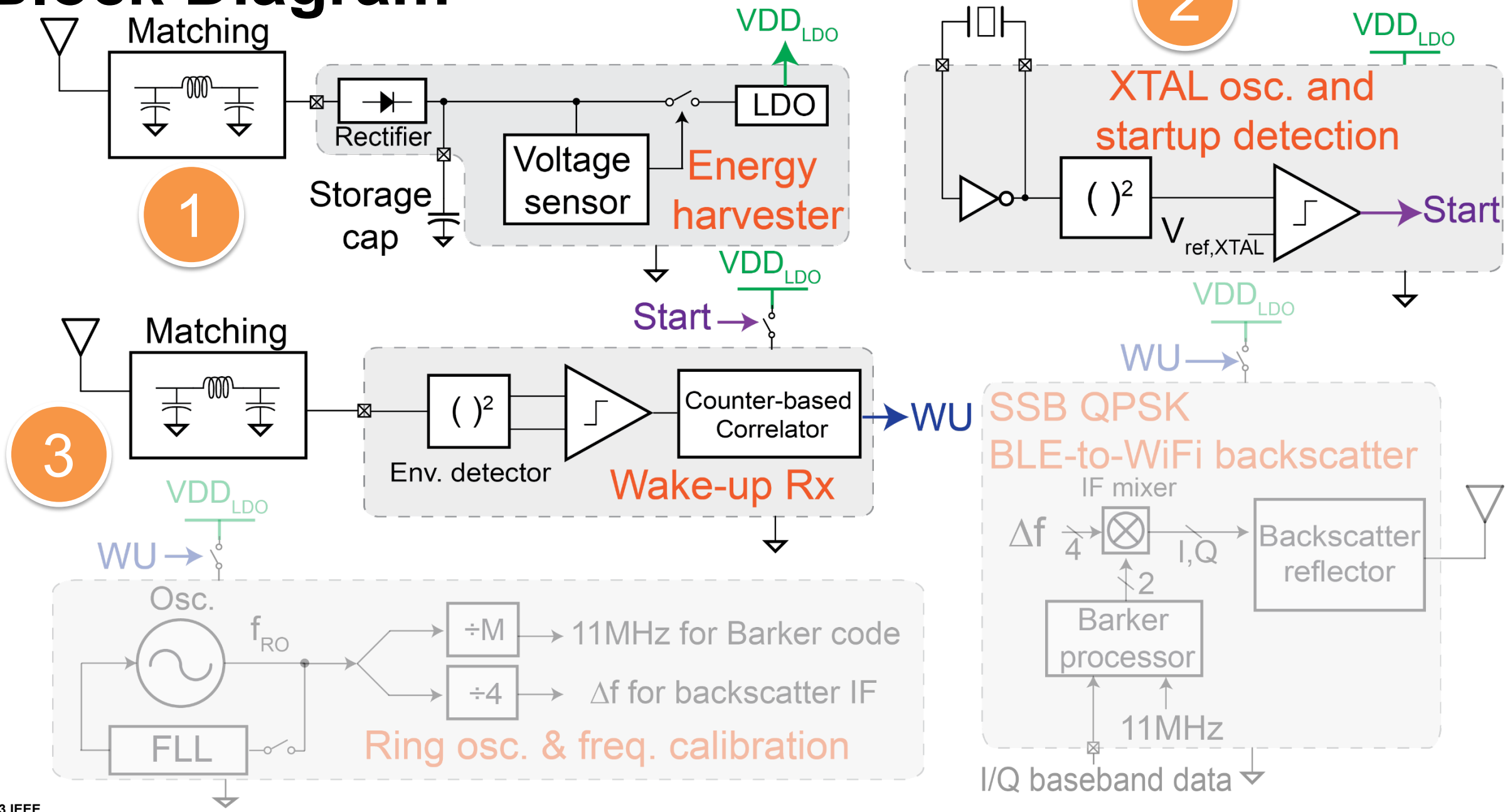
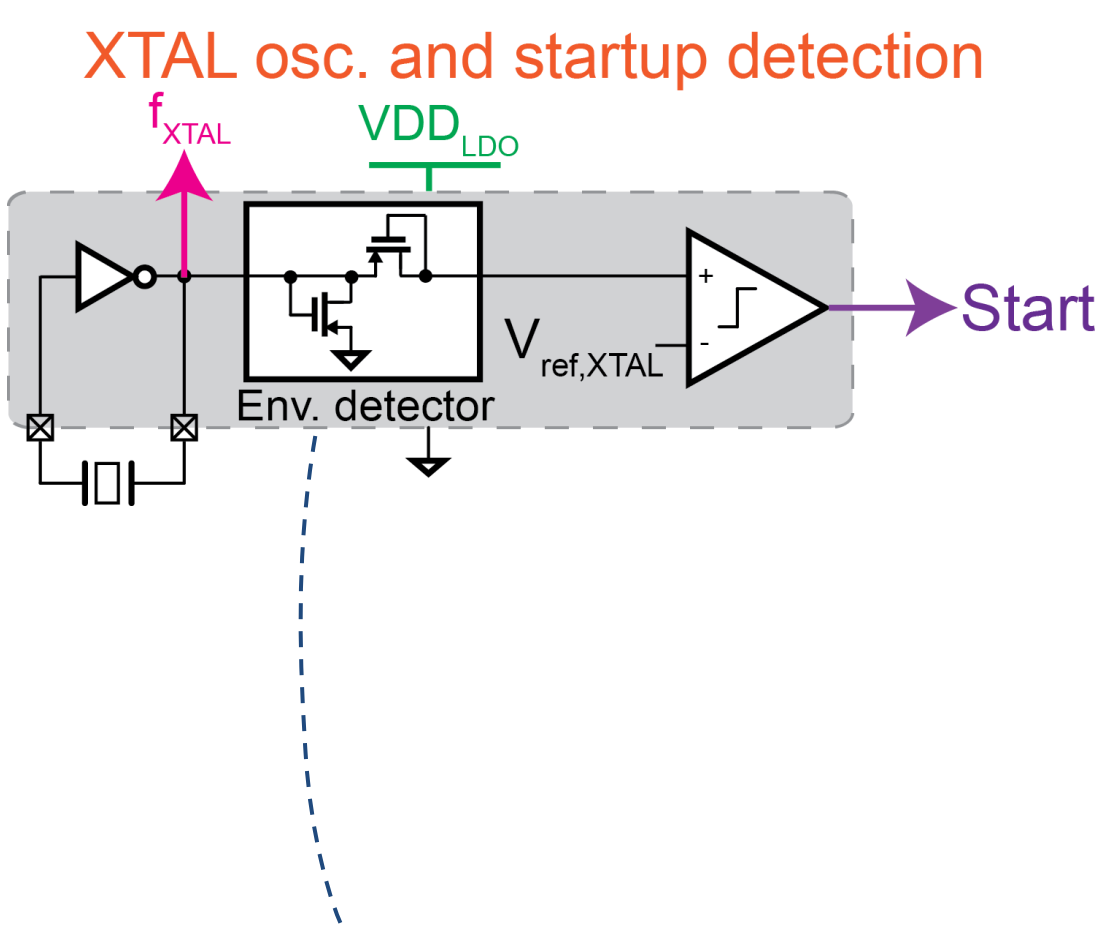
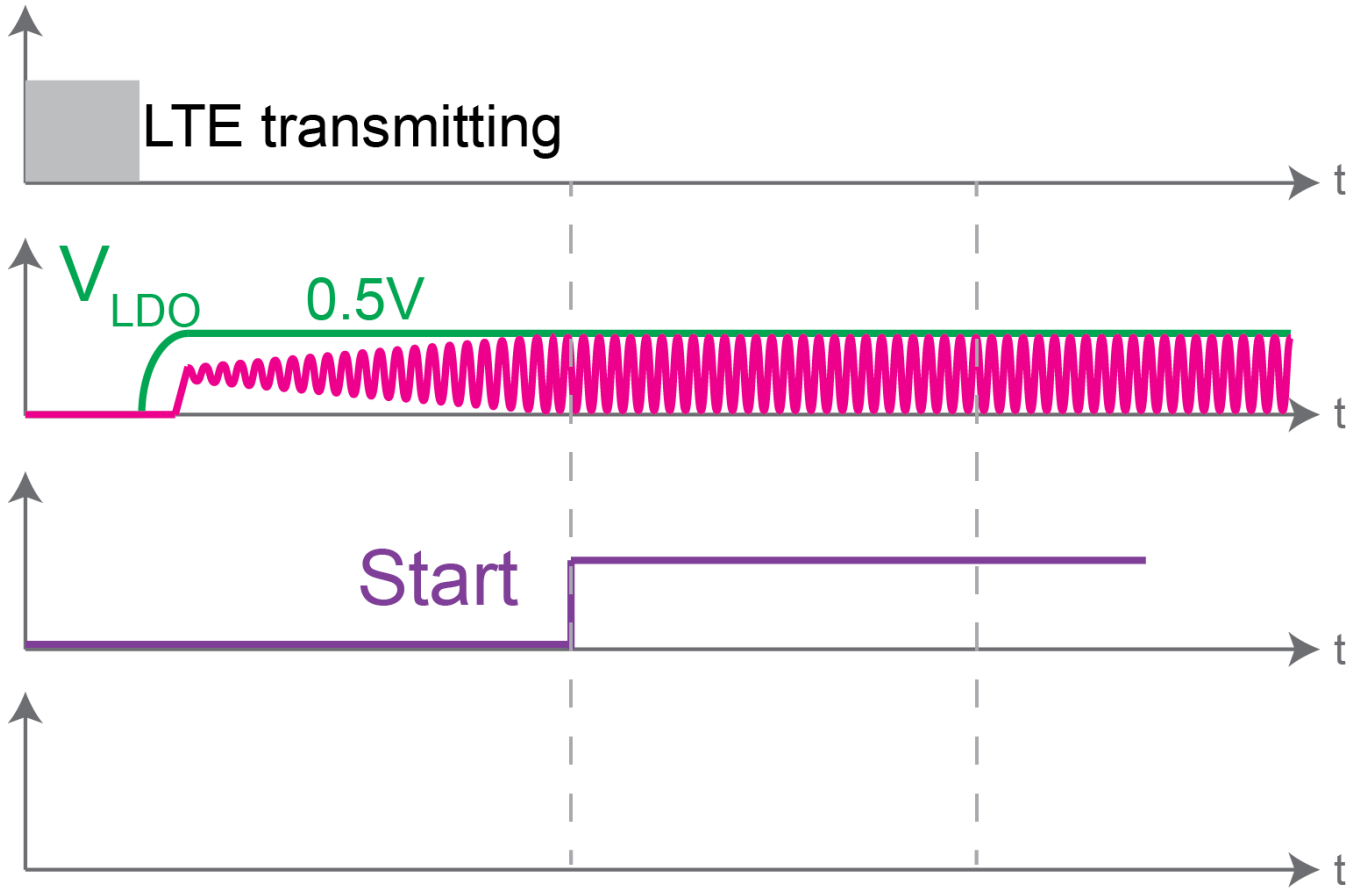


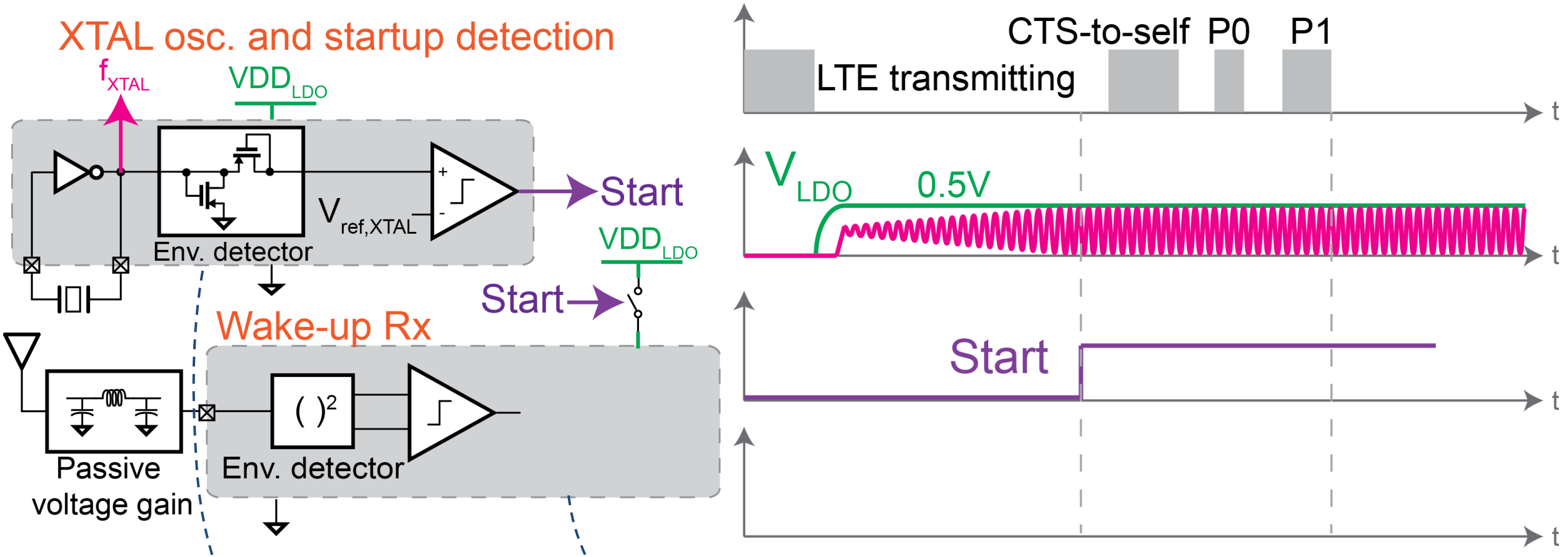
XTAL Startup and Wake-up





An ED and a comparator are used to determine the XTAL startup

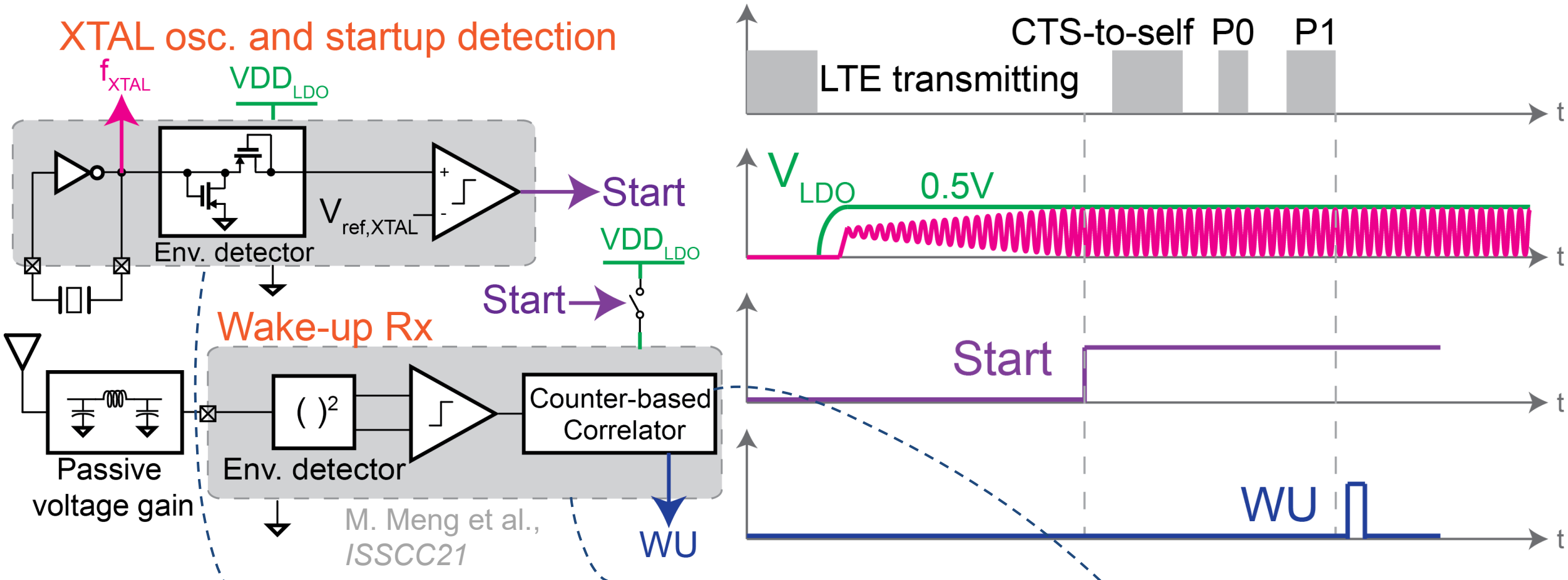
XTAL Startup and Wake-up



An ED and a comparator are used to determine the XTAL startup

An ED-first OOK-based wakeup receiver is used to sense the WiFi pattern

XTAL Startup and Wake-up

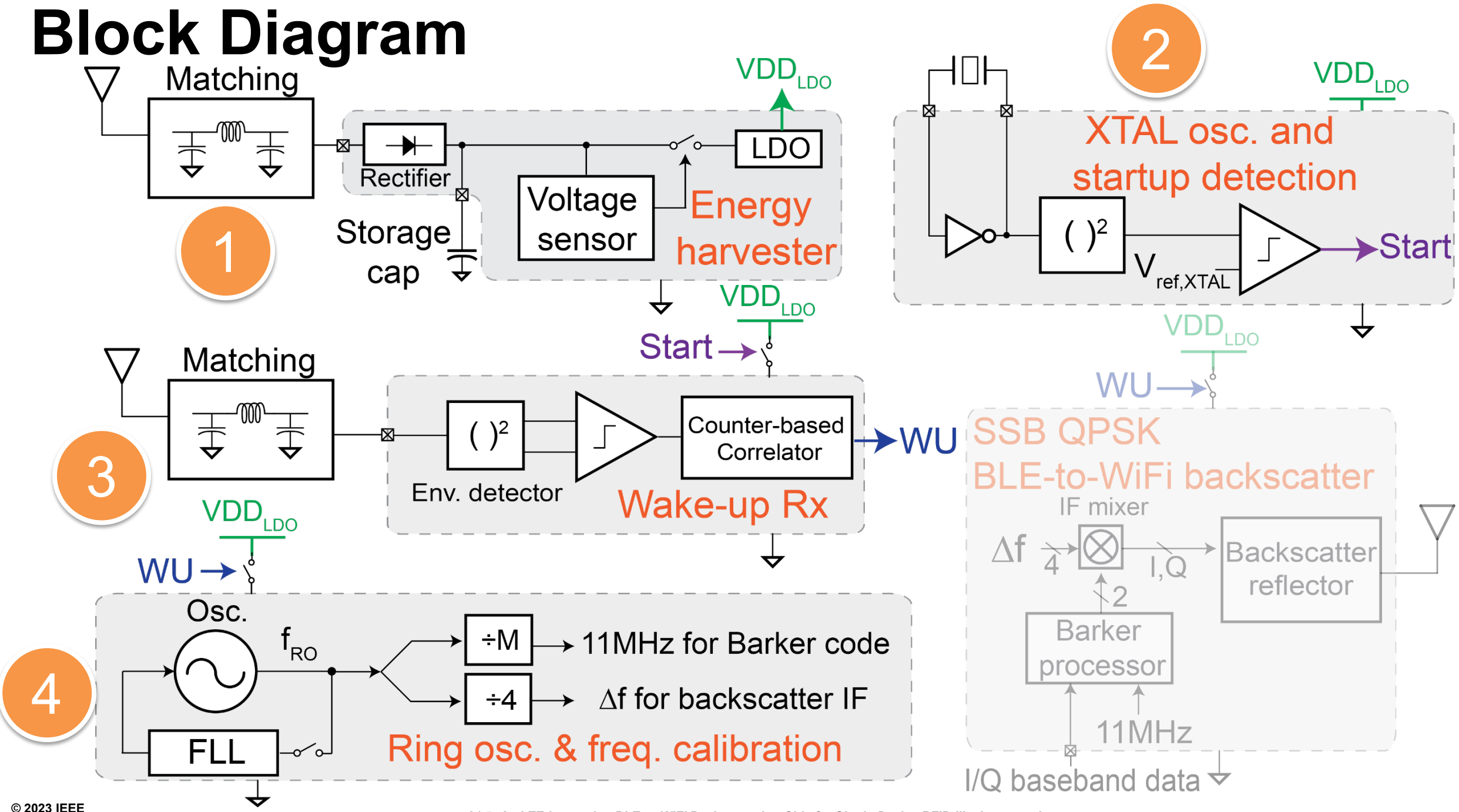


An ED and a comparator are used to determine the XTAL startup

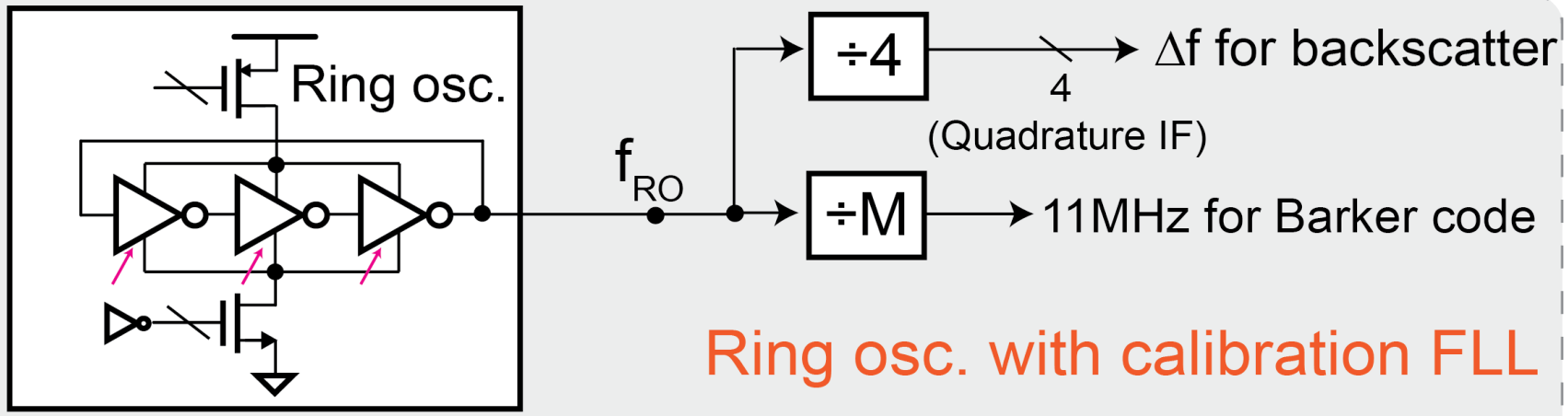
An ED-first OOK-based wakeup receiver is used to sense the WiFi pattern

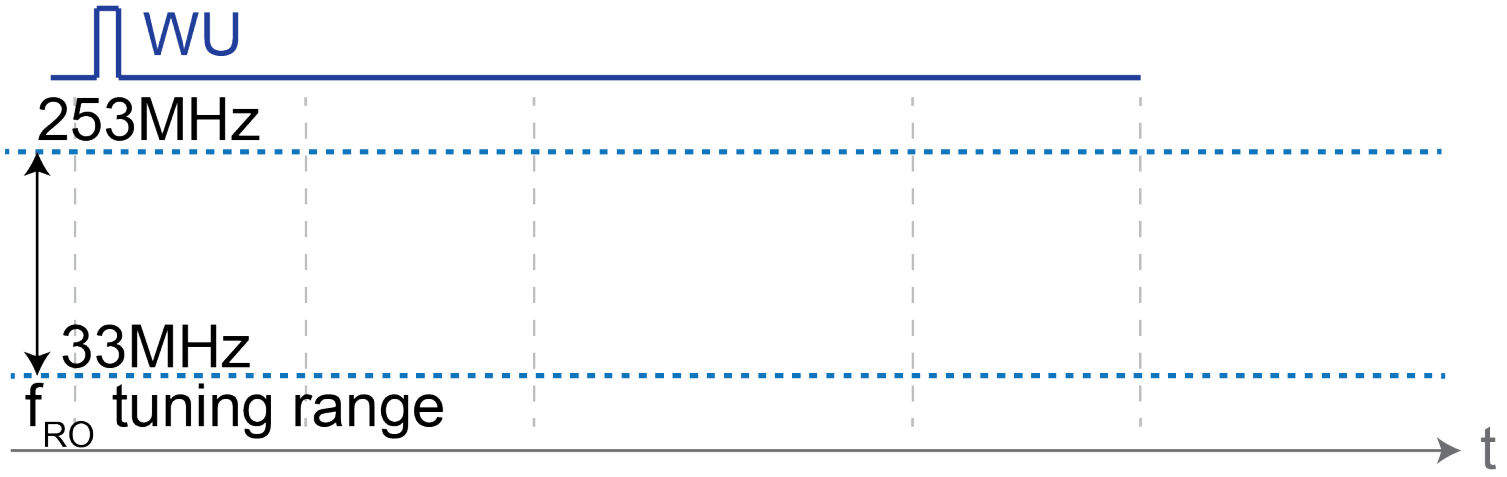
A counter-based correlator determines when the correct WiFi pattern comes

Block Diagram

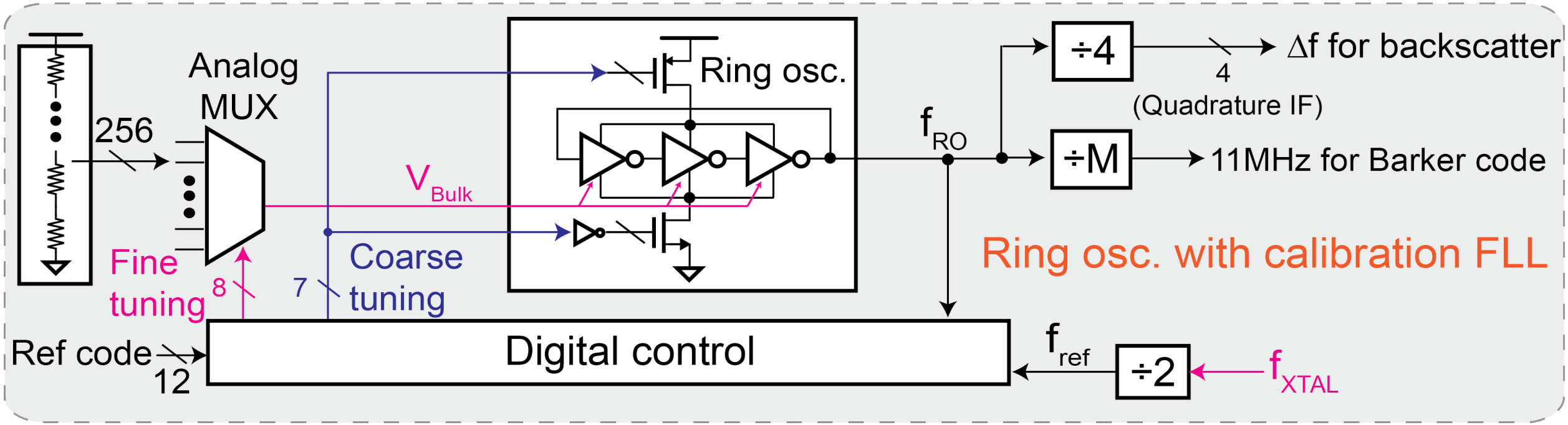


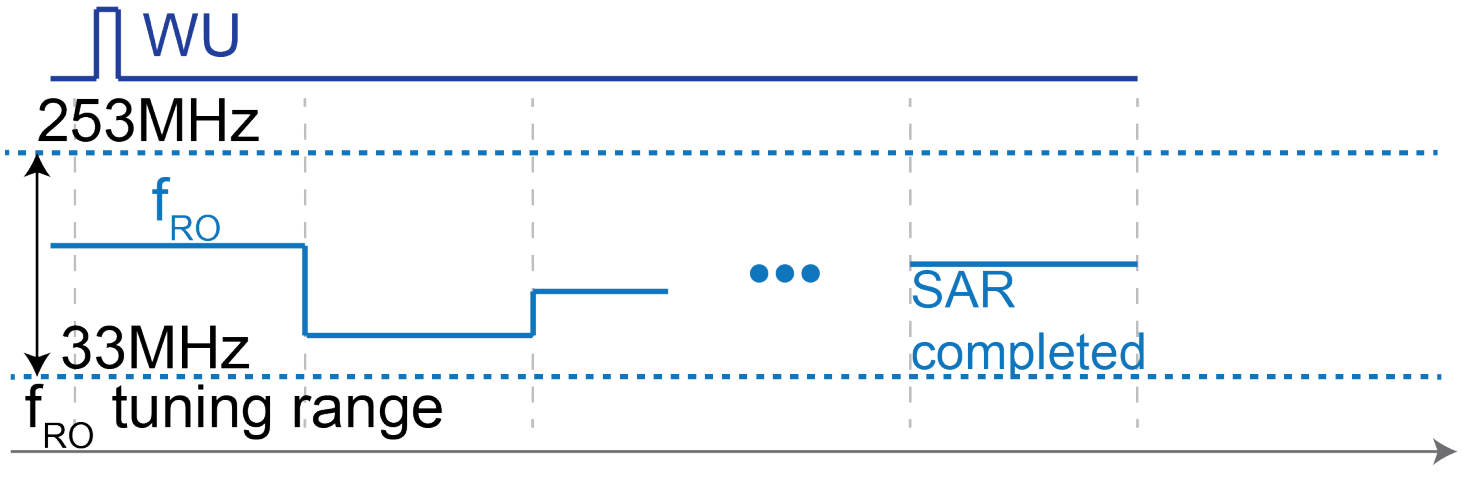
SAR Frequency Calibration





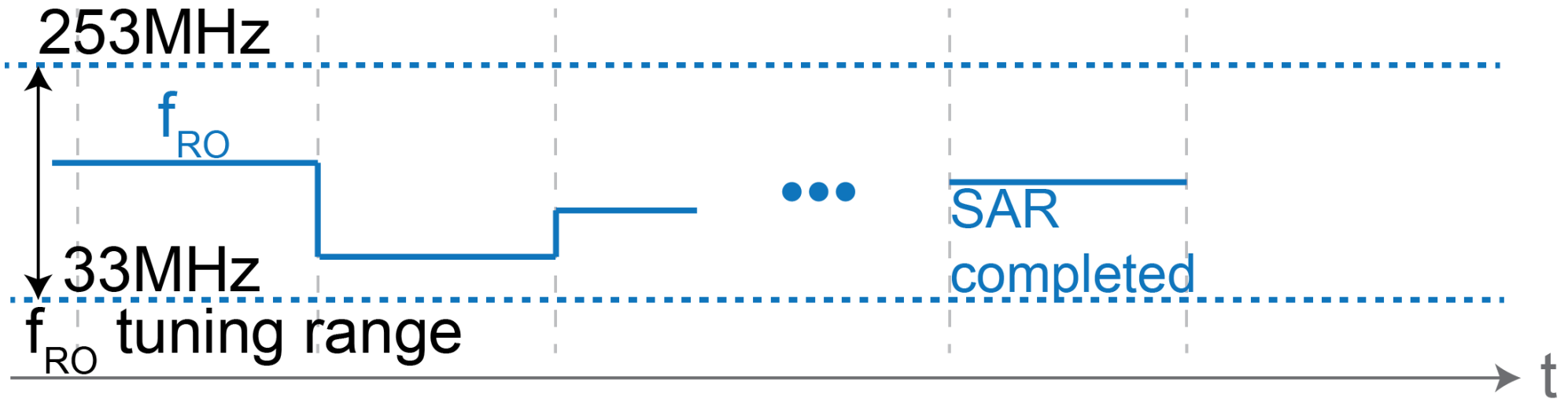
SAR Frequency Calibration





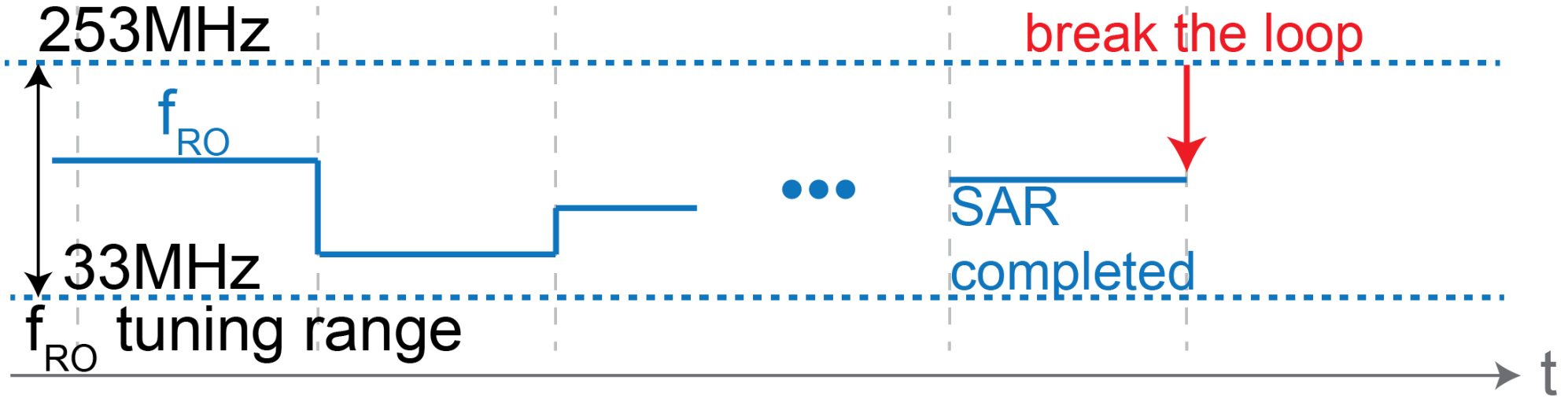
SAR FLL locks the ring osc. output to the desired freq. within 15 cycles (0.915msec)

SAR Frequency Calibration



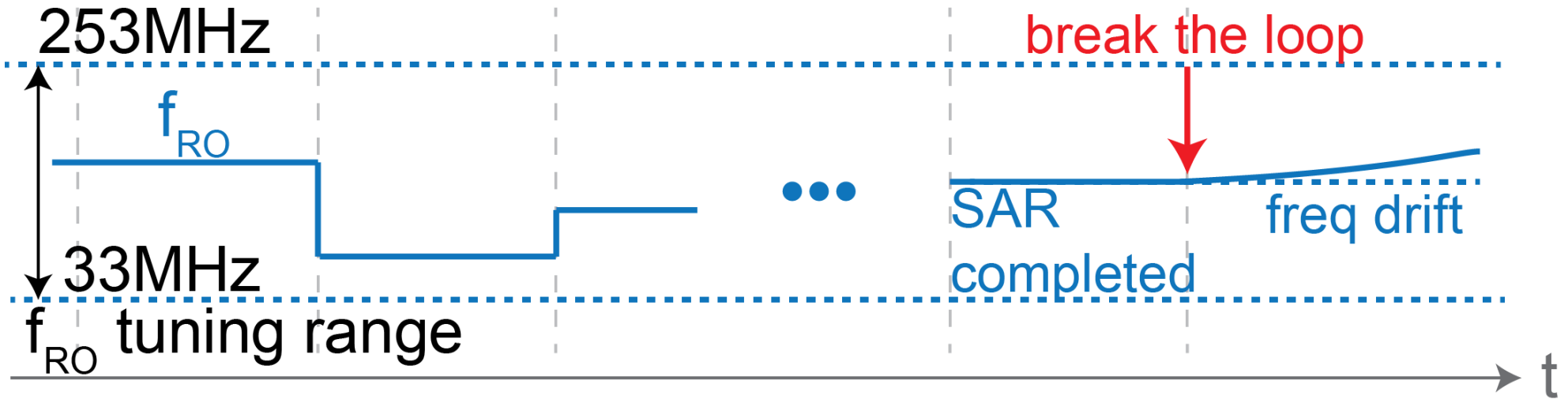
- Max. **Δ**f (backscatter IF clock) freq. offset < 125kHz (L. Lin et al., *VLSI21)*

SAR Frequency Calibration



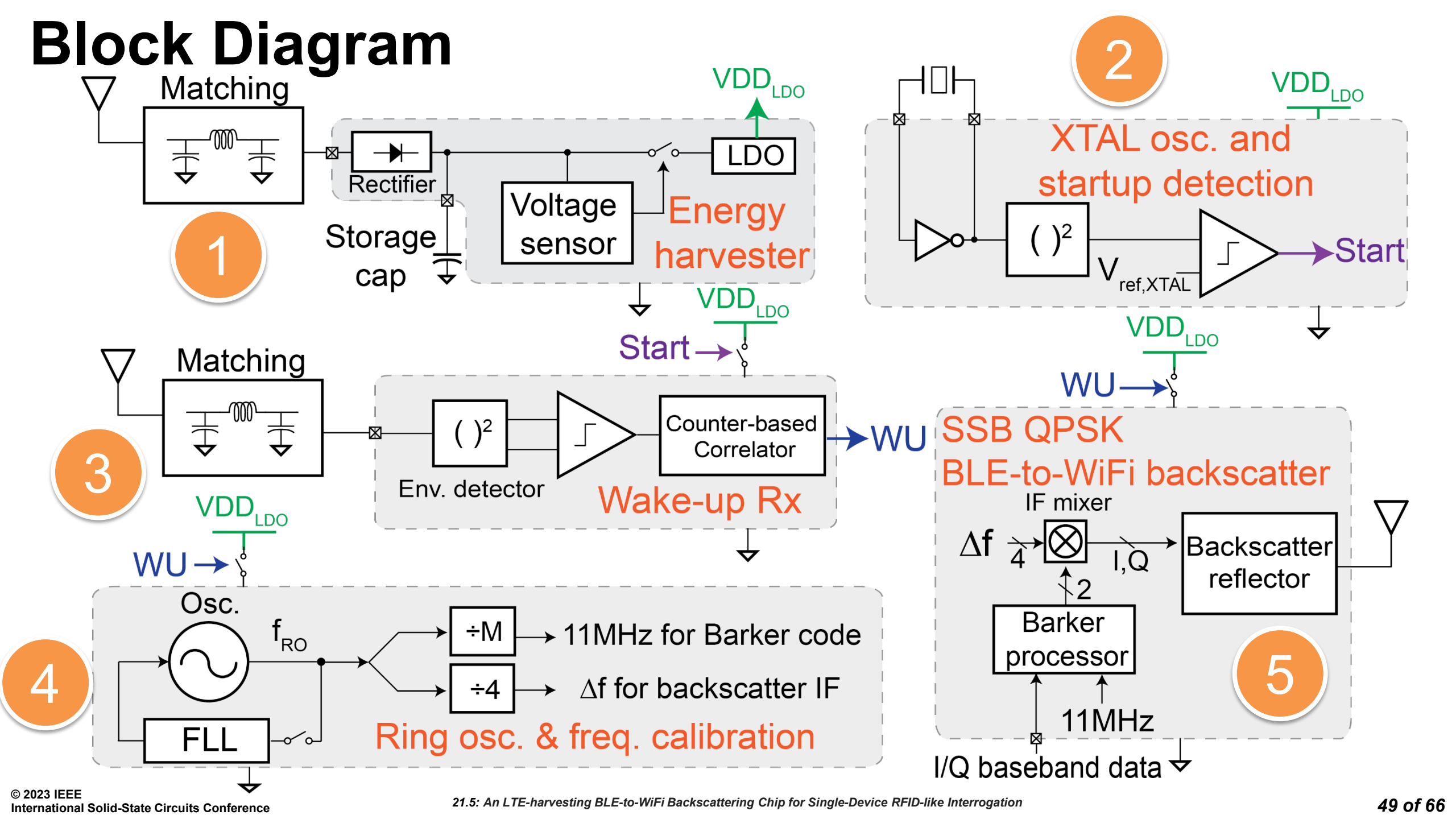
- Max. **Δ**f (backscatter IF clock) freq. offset < 125kHz (L. Lin et al., *VLSI21)*
- Break the loop after SAR process is completed

SAR Frequency Calibration

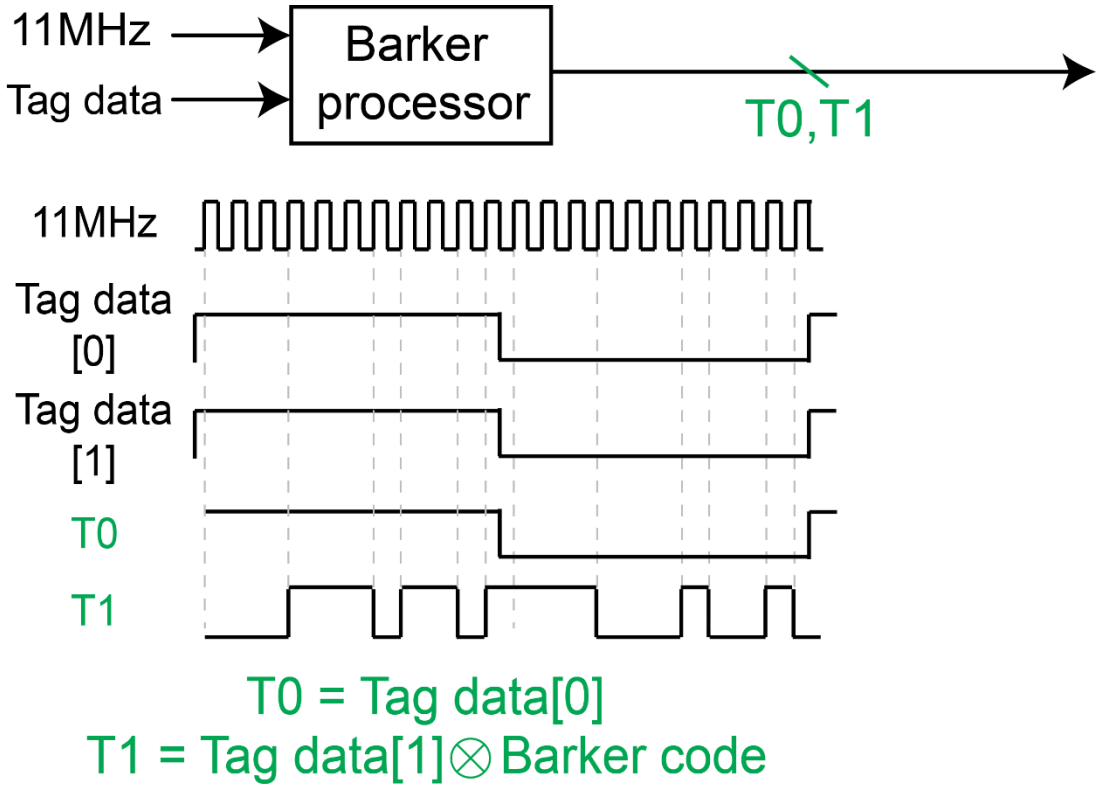


- Max. **Δ**f (backscatter IF clock) freq. offset < 125kHz (L. Lin et al., *VLSI21)*
- Break the loop after SAR process is completed
- The ring osc. becomes free-running
  → backscatter process is done right after breaking the SAR loop
  → phase noise requirement:
  -100dBc/Hz @ 1MHz & -35 dBc integrated from 0.1MHz to 10MHz
  → freq. drift < 125kHz over 1msec packet

Block Diagram

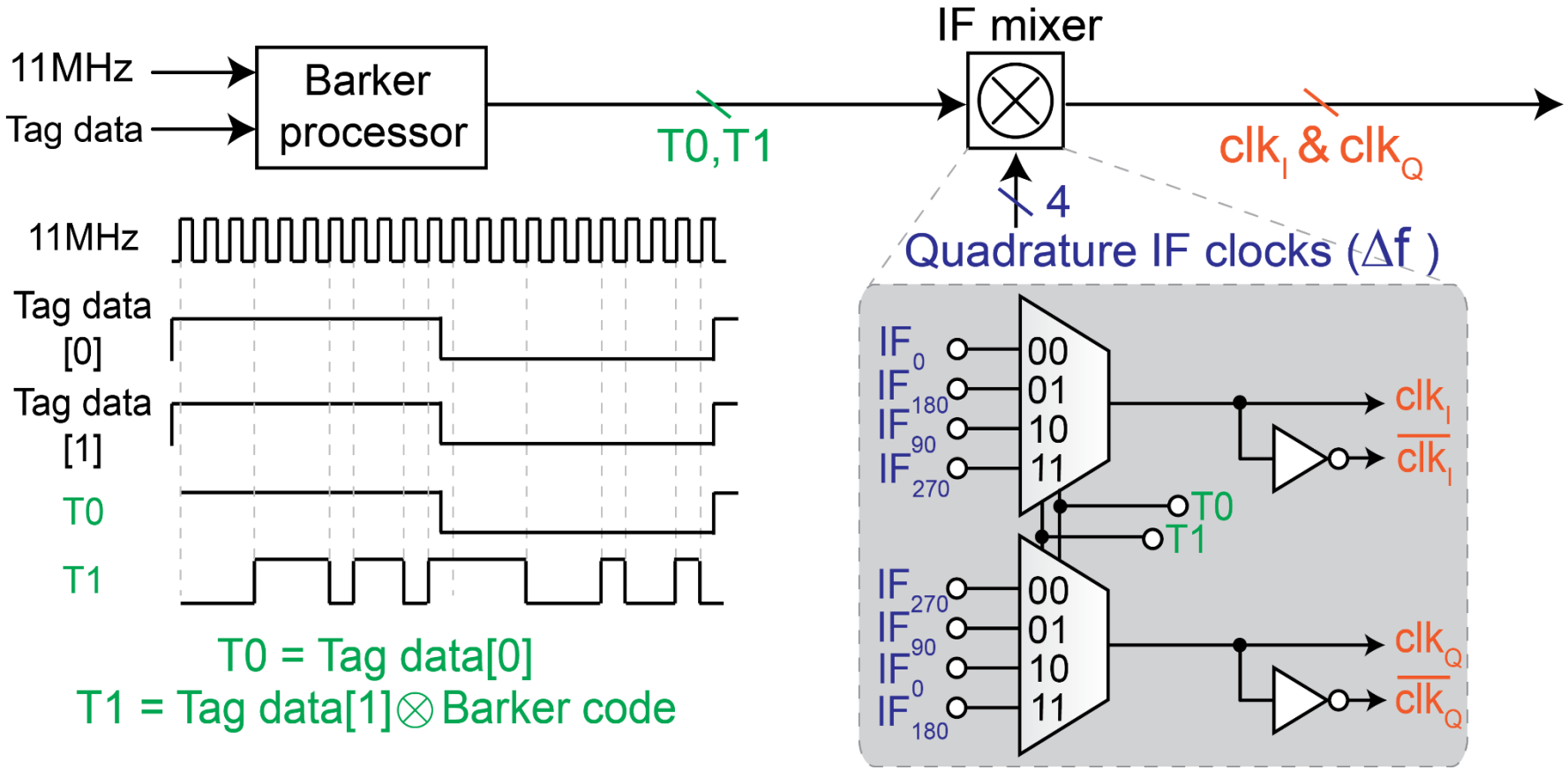


Backscatter (SSB QPSK)



Step1: Generate Barker code modulated data with on-chip 11MHz clock

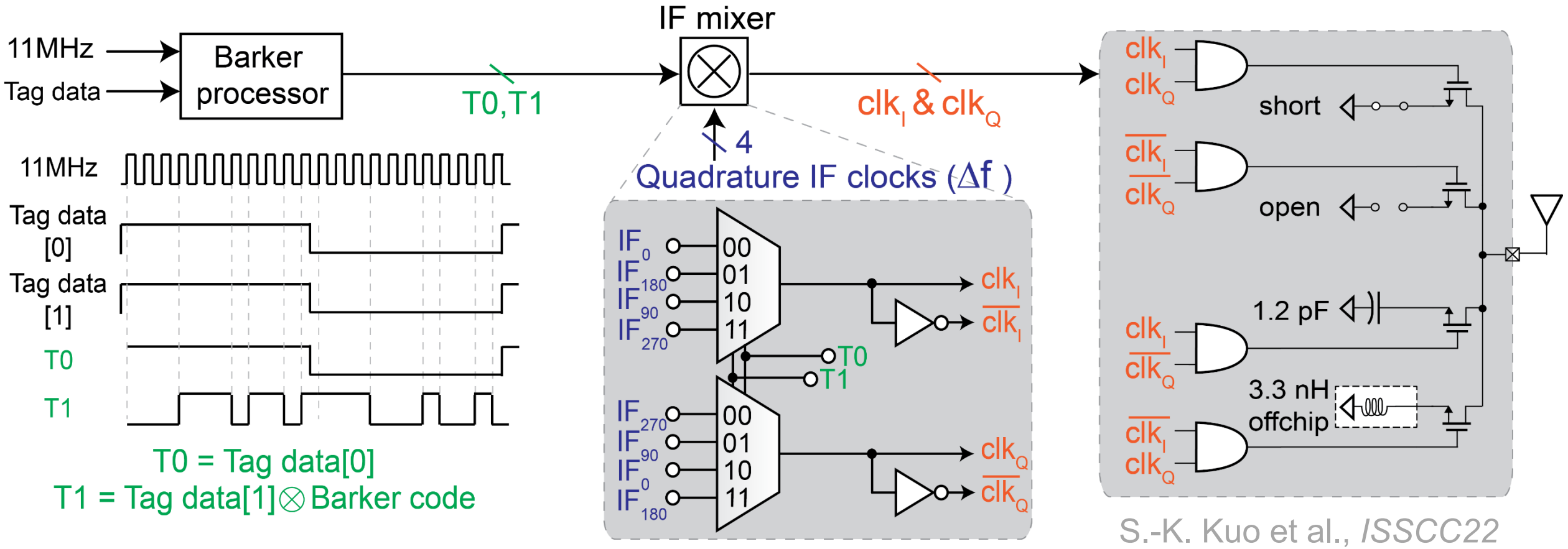
Backscatter (SSB QPSK)



Step1: Generate Barker code modulated data with on-chip 11MHz clock

Step2: Up-convert IQ data to IF via SSB digital mixer

Backscatter (SSB QPSK)



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Step1: Generate Barker code modulated data with on-chip 11MHz clock

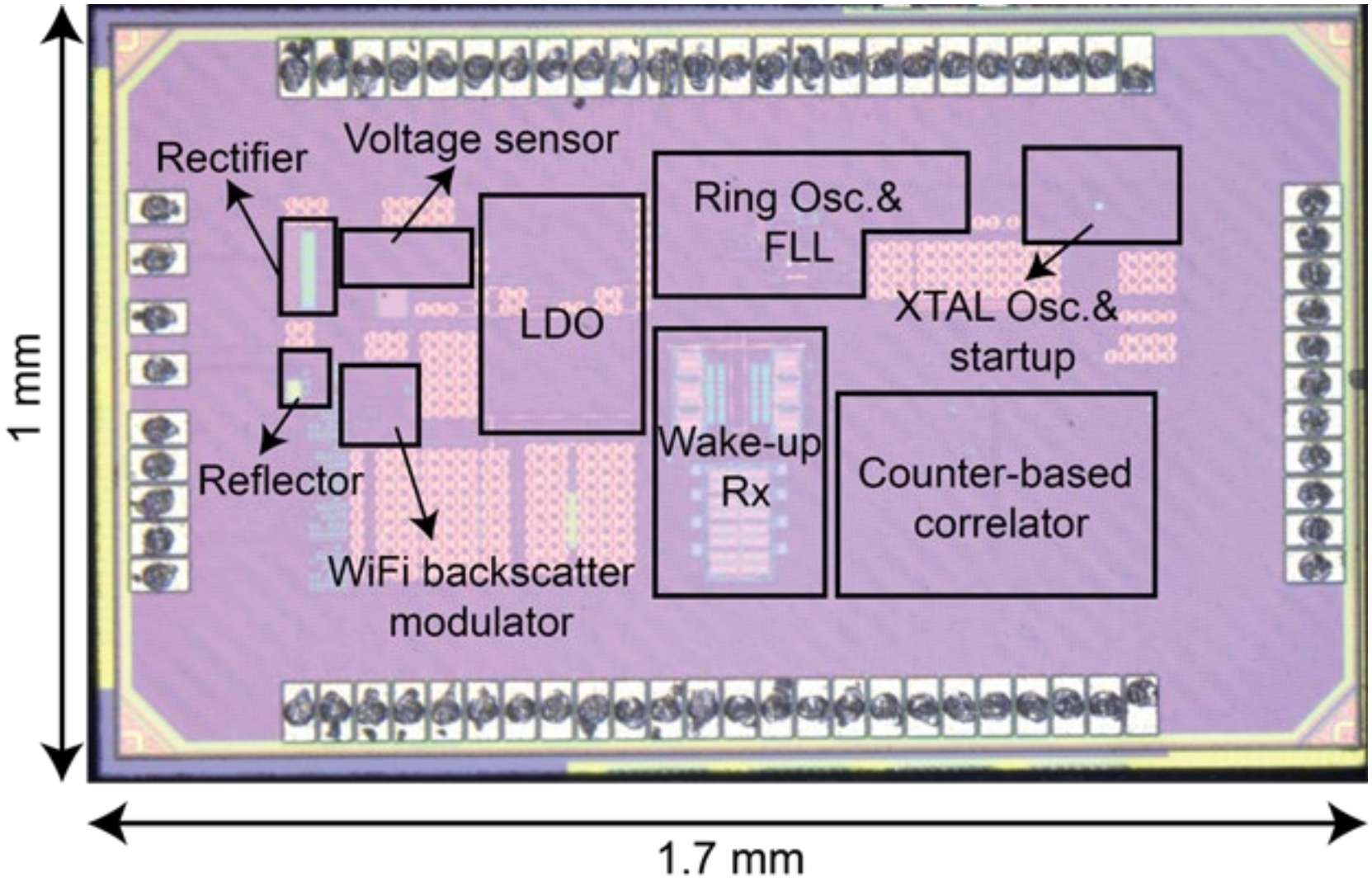
Step2: Up-convert IQ data to IF via SSB digital mixer

Step3: Quadrature IF clocks drive SP4T reflector

Outline

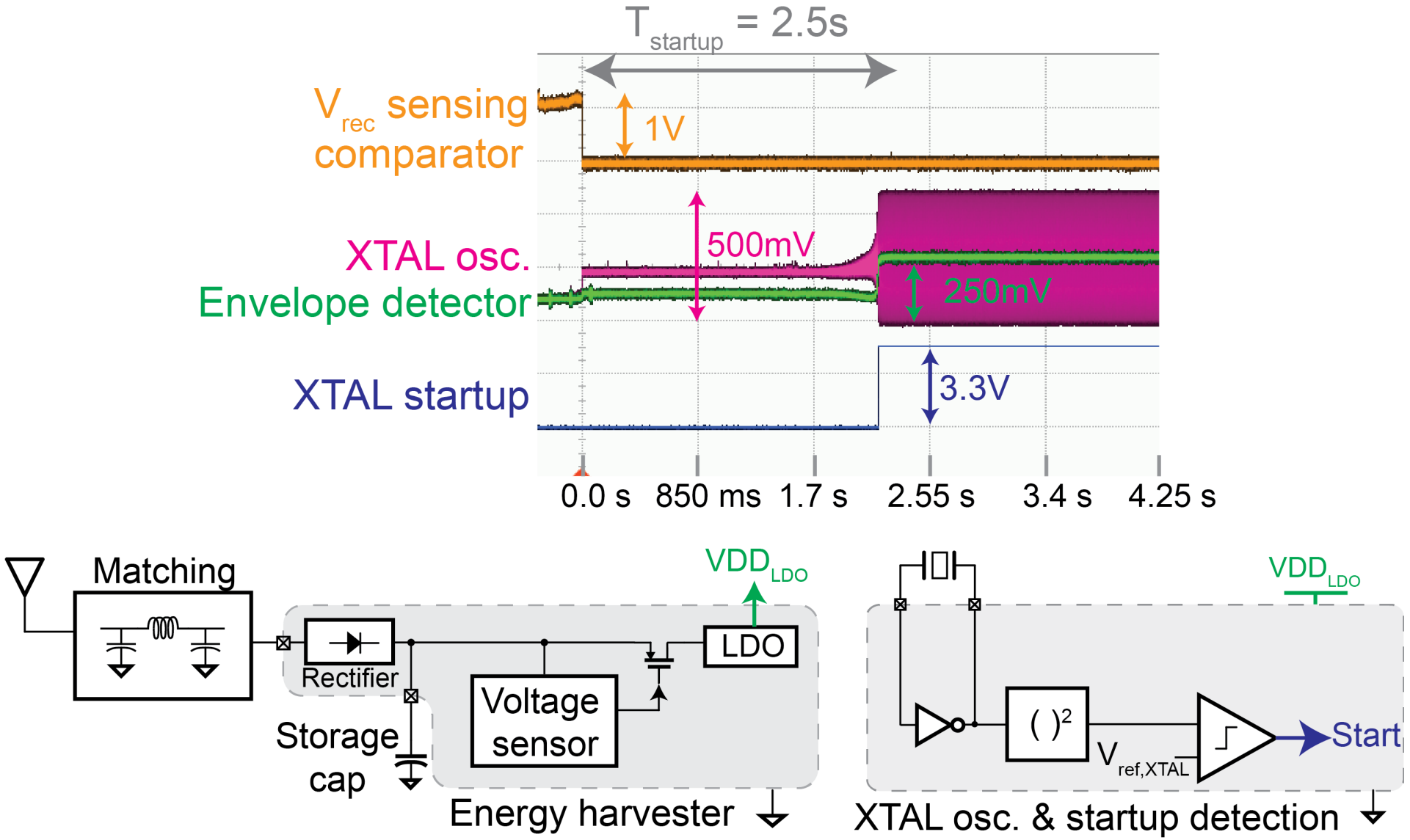
- Motivation
- Prior-art and proposed BLE-to-WiFi backscatter scheme
- Proposed single-device-interrogated backscatter chip
- Measurement results
- Conclusion

Die Micrograph

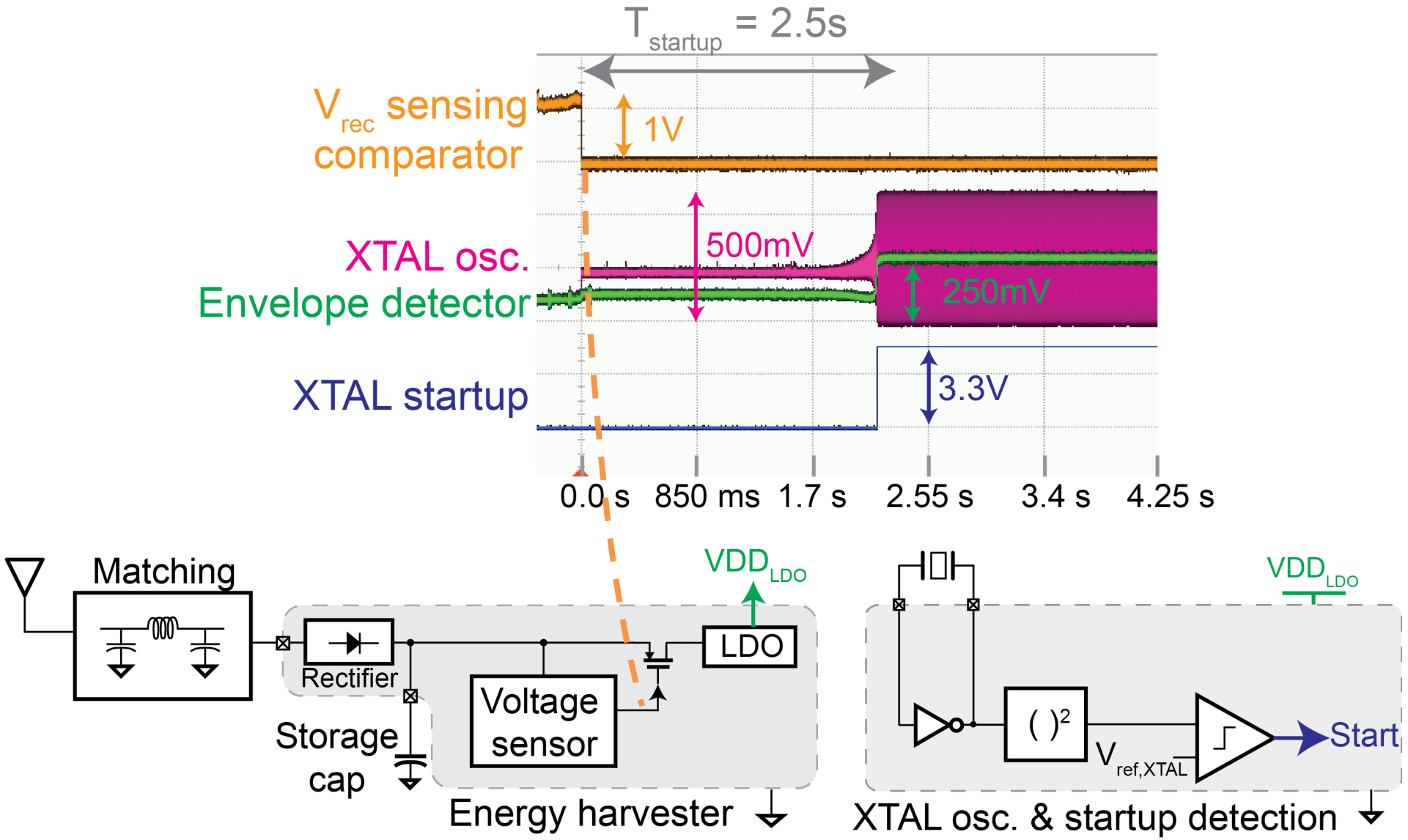


- 65nm CMOS
- 0.43mm^2 active area

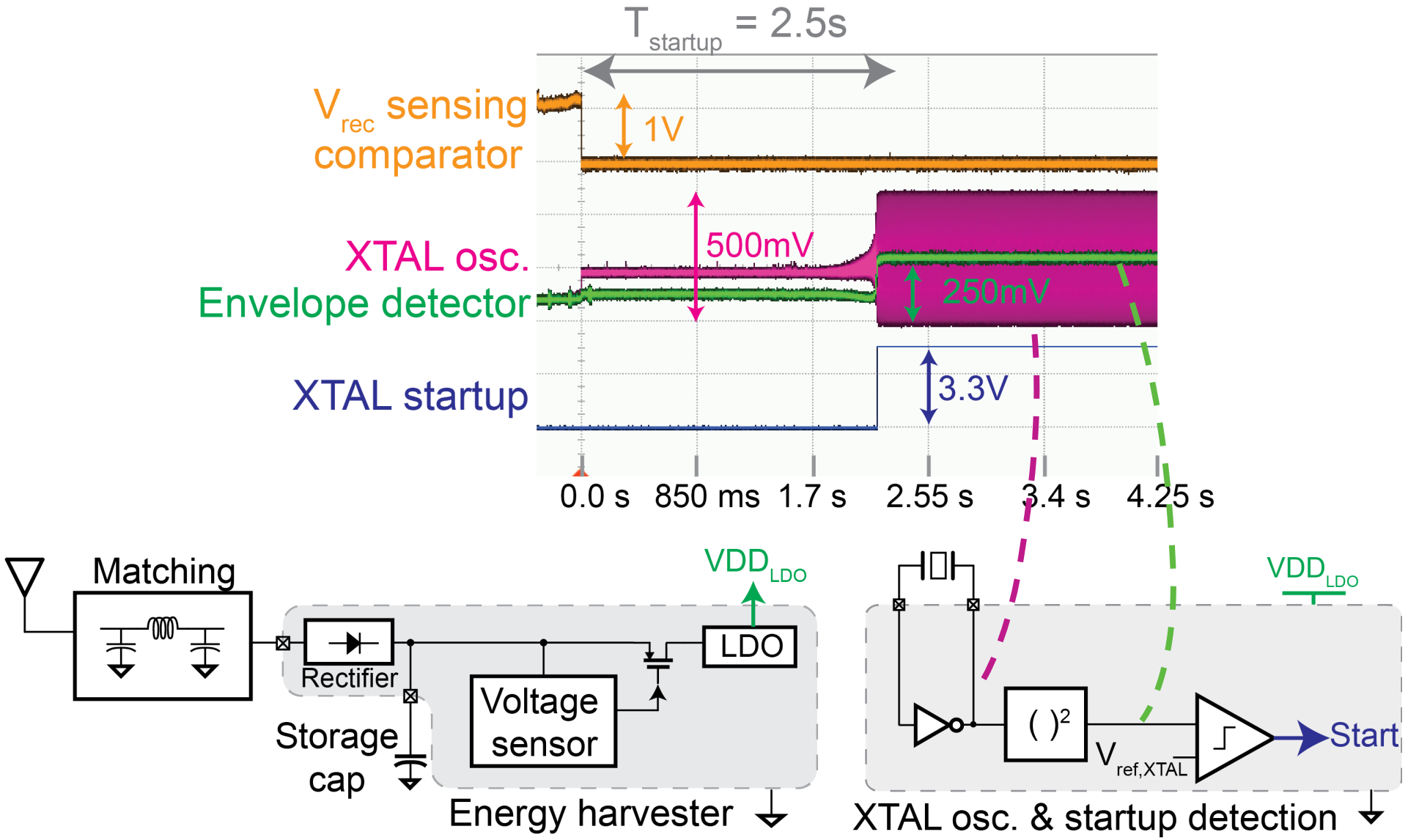
XTAL Startup Transients



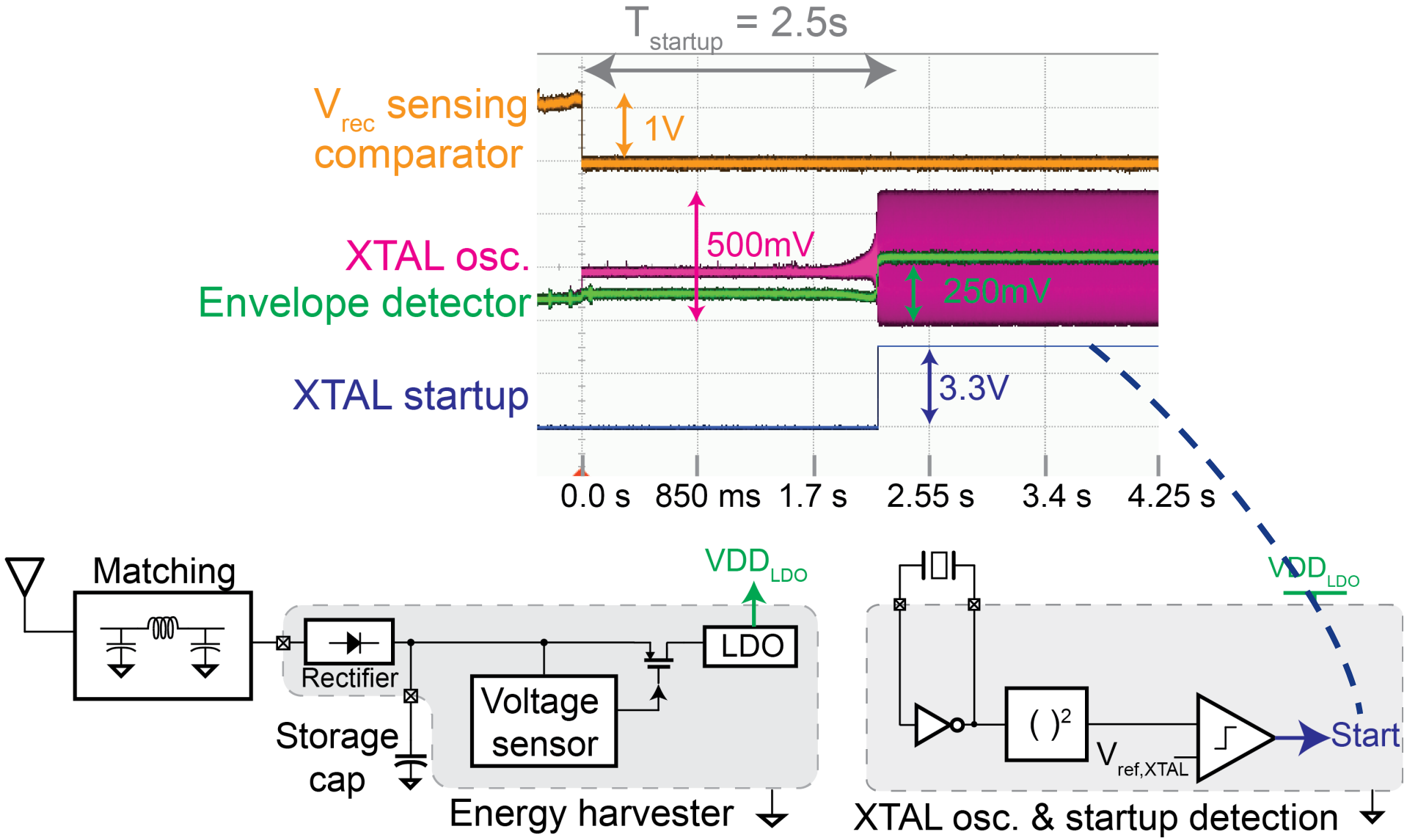
XTAL Startup Transients



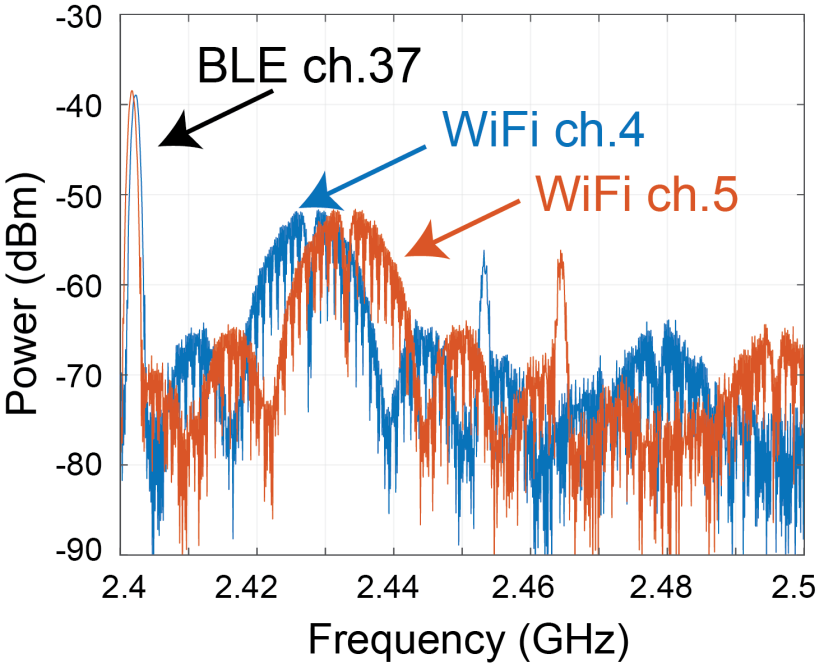
XTAL Startup Transients

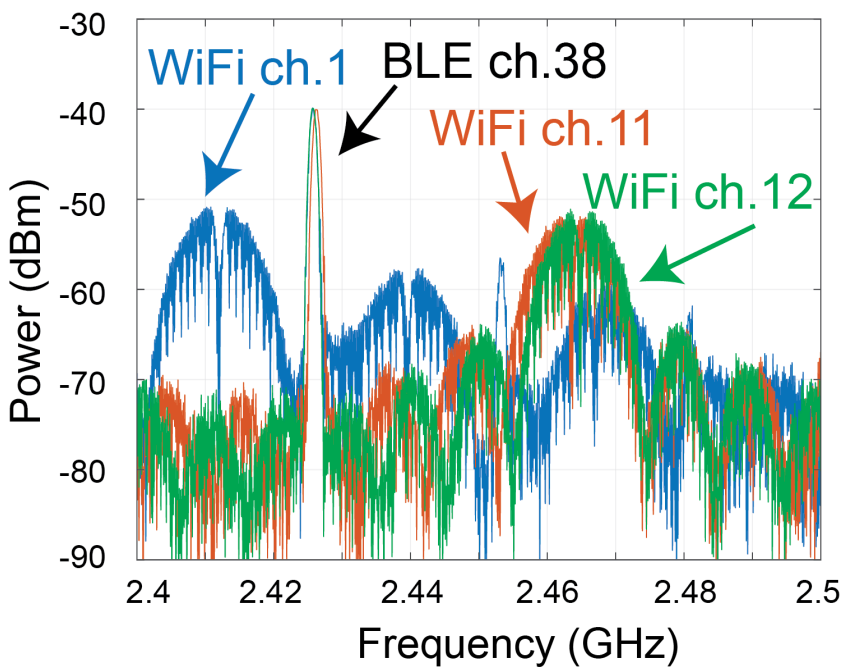


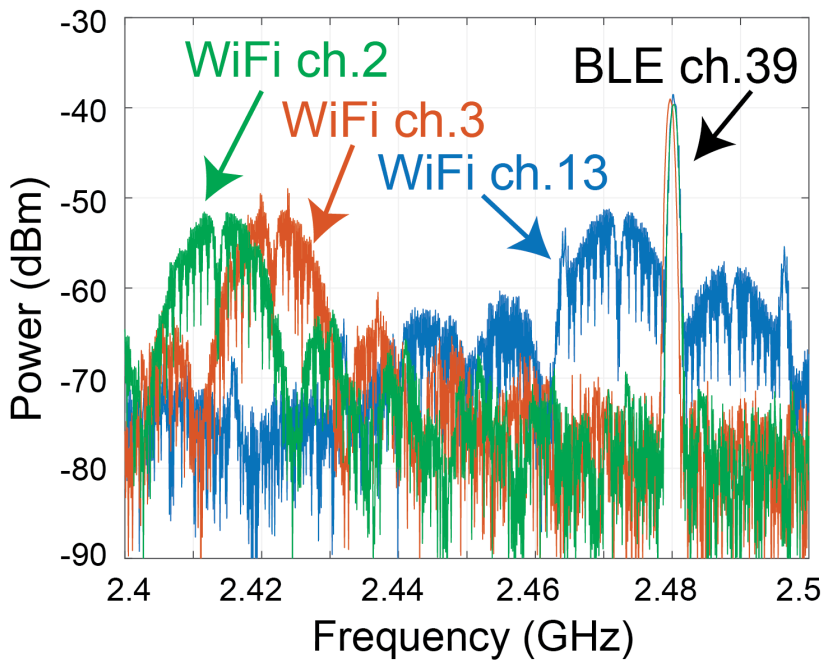
XTAL Startup Transients



Measured Spectra

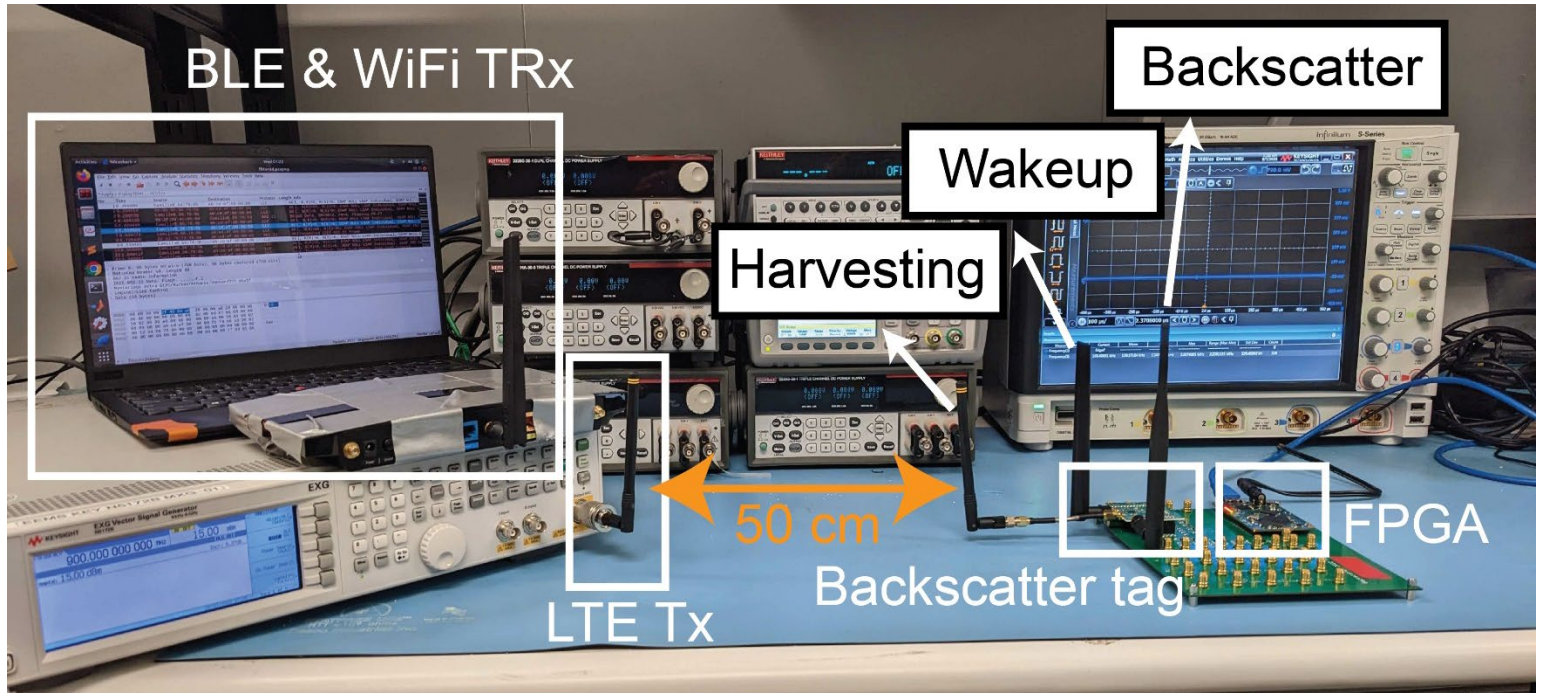


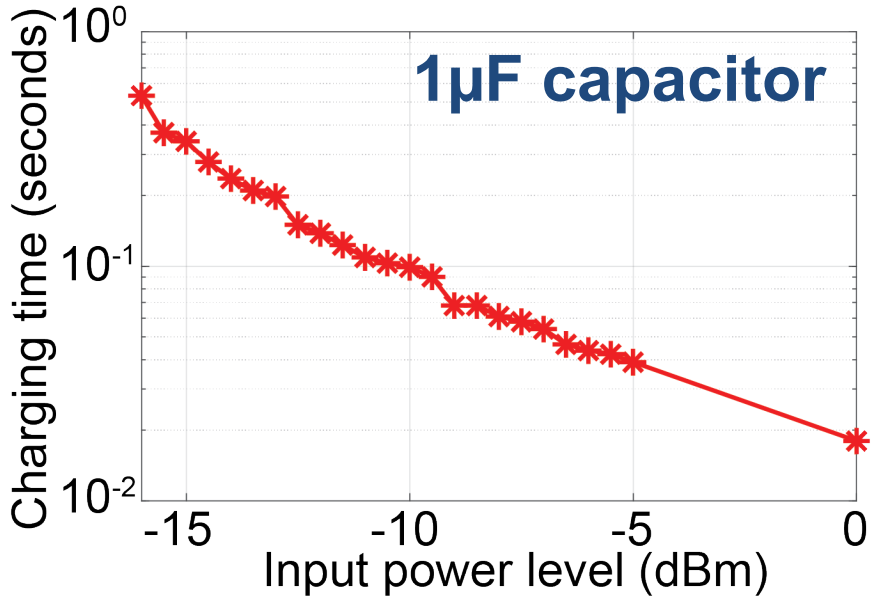


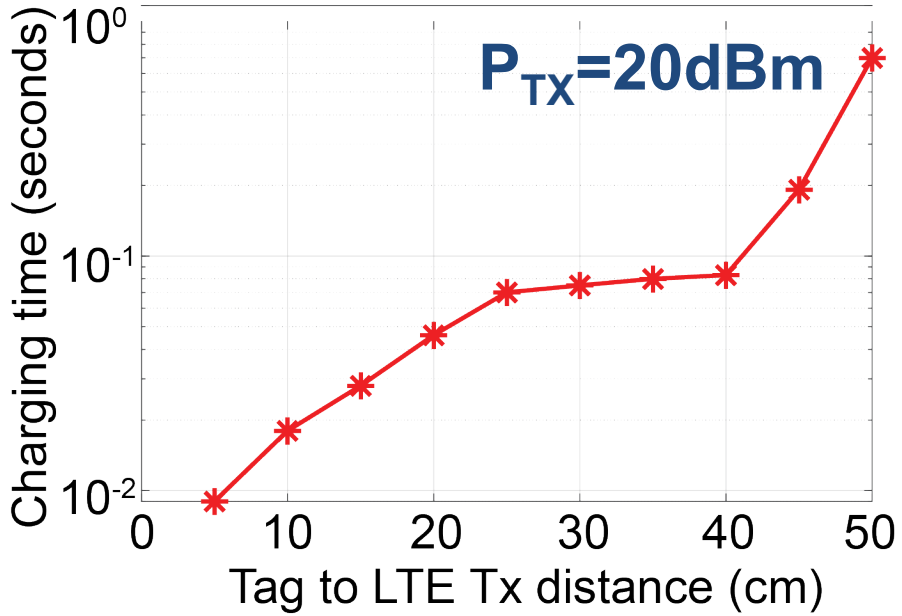


Incident BLE tones can be translated to different WiFi channels

Wireless Energy Harvesting Measurement

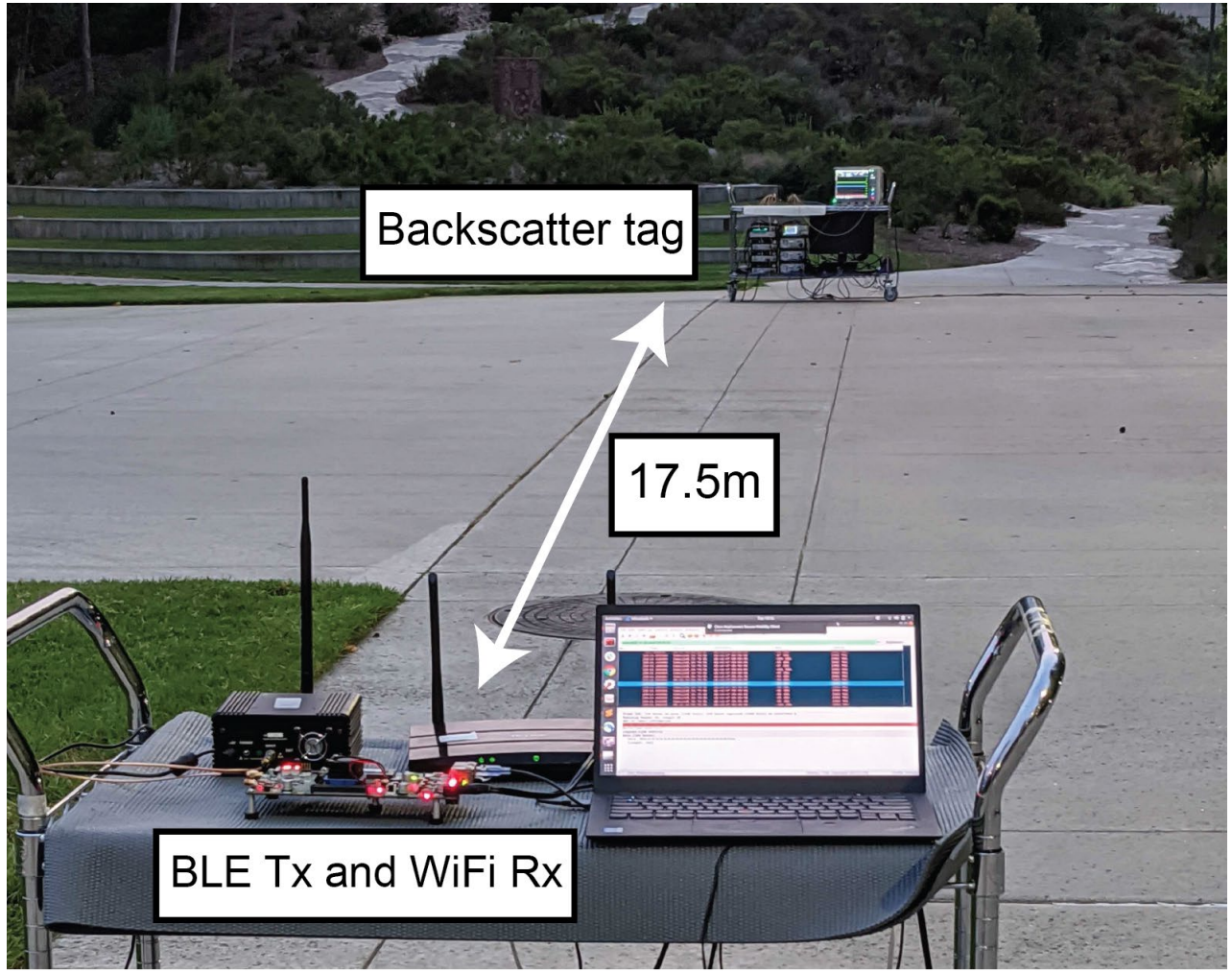






Charging time <1sec before backscattering when distance is within 50 cm

Range w/o energy harvesting



- Tag-to-access-point backscatter range = 17.5m when battery powered
- The system operating range is limited by the energy harvesting process instead of backscattering

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Comparison

	VLSI 2021 Lin [3]	ISSCC 2020 Wang [1]	ISSCC 2021 Meng [2]	ISSCC 2022 Kuo [4]	This work
Technology	180 nm	65 nm	65 nm	65 nm	65 nm
Core area (mm^2)	1.62	0.34	0.41	0.42	0.43
Backscatter scheme	Tone to WiFi 802.11b	SSB WiFi 802.11b to WiFi 802.11b			SSB BLE-to-WiFi 802.11b
Max data rate	1 Mbps	2 Mbps			2 Mbps

Tone generator is required

Two APs are required

Single-device operation

Comparison

* Backscatter freq.=25MHz when another divider is enabled

	VLSI 2021 Lin [3]	ISSCC 2020 Wang [1]	ISSCC 2021 Meng [2]	ISSCC 2022 Kuo [4]	This work
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Max data rate	1 Mbps	2 Mbps			2 Mbps
On-chip backscatter frequency tunability	No f_{RO}=11MHz	Yes* f_{RO}=50MHz	Yes* f_{RO}=50MHz	Yes* f_{RO}=50MHz	Yes f_{RO}=33~253MHz

Only generates an 11MHz clock that requires a dedicated tone which is not BLE-synthesizable

Only 25/50MHz frequency shift between Ch,1,6,11

Supports 8 BLE-to-WiFi schemes

Comparison

* Backscatter freq.=25MHz when another divider is enabled

	VLSI 2021 Lin [3]	ISSCC 2020 Wang [1]	ISSCC 2021 Meng [2]	ISSCC 2022 Kuo [4]	This work
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Core area (mm^2)	1.62	0.34	0.41	0.42	0.43
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On-chip backscatter frequency tunability	No f_{RO}=11MHz	Yes* f_{RO}=50MHz	Yes* f_{RO}=50MHz	Yes* f_{RO}=50MHz	Yes f_{RO}=33~253MHz
Wake-up power (μW)	0.15	2.8	4.5	5.5	4.5
Backscatter communication power (μW)	2.5	28	32	39	11~45 for f_{RO}=33~253MHz

Only supports 11MHz tone-to-WiFi case

Comparison

* Backscatter freq.=25MHz when another divider is enabled

	VLSI 2021 Lin [3]	ISSCC 2020 Wang [1]	ISSCC 2021 Meng [2]	ISSCC 2022 Kuo [4]	This work
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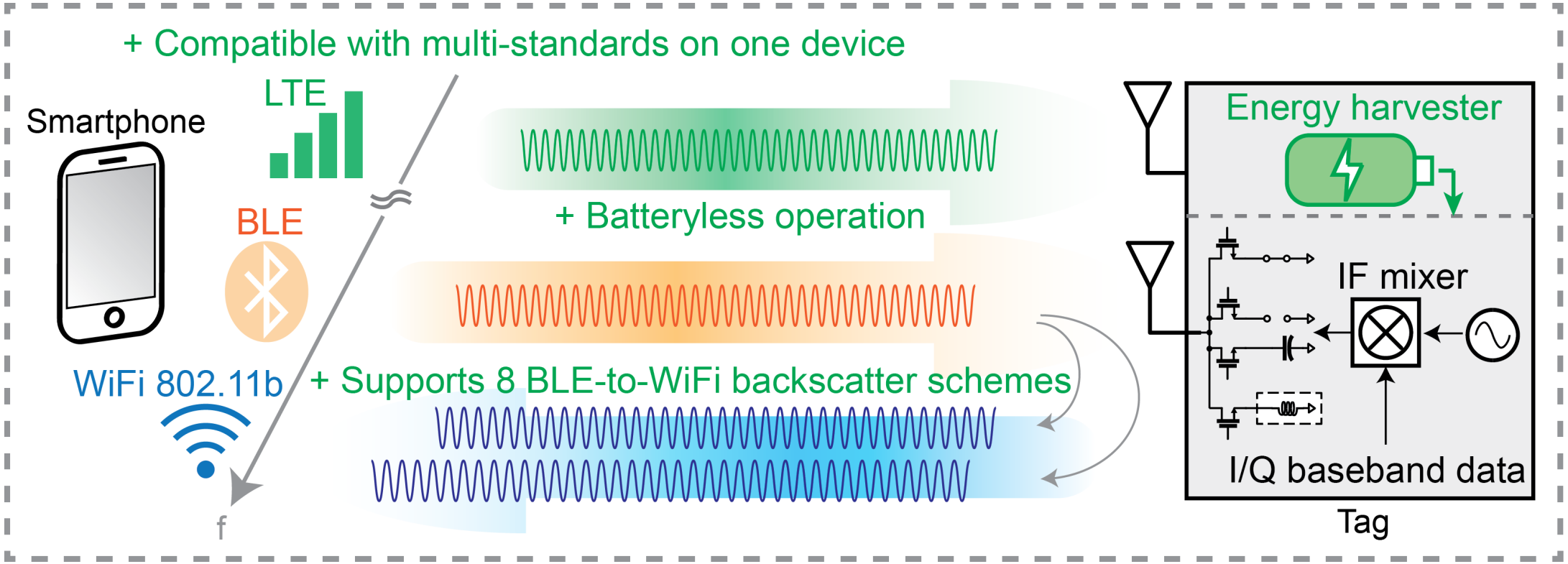
Backscatter communication power (μW)	2.5	28	32	39	11~45 for f_{RO}=33~253MHz
Self-sustainability	No	No	No	No	Yes

Conclusion



Acknowledgement: This work was supported in part by the National Science Foundation (NSF) under Grant No. 1923902 and UC San Diego Center for Wearable Sensors

Thanks for your attention!