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PowerPhone: Unleashing the Acoustic Sensing Capability of Smartphones

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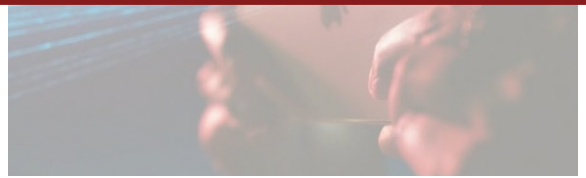
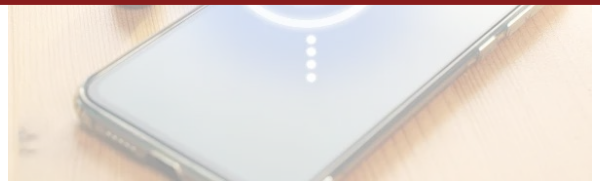
Wireless Sensing on Smartphones

Wireless sensing brings more intelligence to smartphones

Acoustic sensing is the *most extensively* studied sensing modality



LiDAR sensing



UWB sensing

Acoustic sensing

Advantage One: Wide Availability on Smartphones

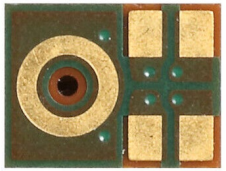
Dedicated modules

LiDAR sensor

UWB sensor

Ubiquitous modules

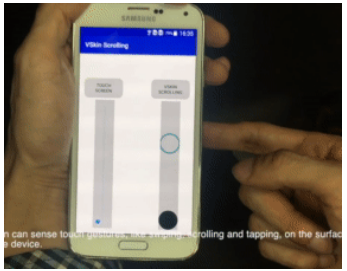
Speaker



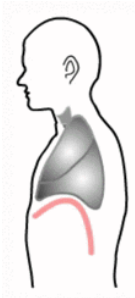
Microphone

Advantage Two: Fine Sensing Granularity

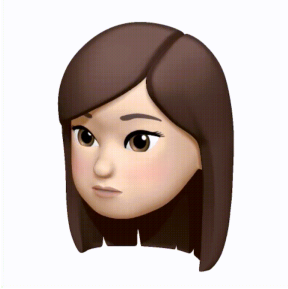
Acoustic signals enable applications that support fine sensing granularity



Finger tracking



Respiration monitoring

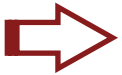


Eye blink detection

Centimeter level → Millimeter level → Submillimeter level

Fundamental Limitation

Acoustic sensing performance is constrained by the limited sampling rate



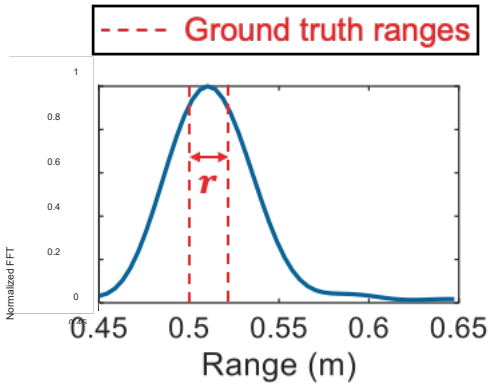
Human speaking and hearing frequency
< 20 *kHz*

Sampling rates for speaker and microphone
44.1 *kHz* or 48 *kHz*

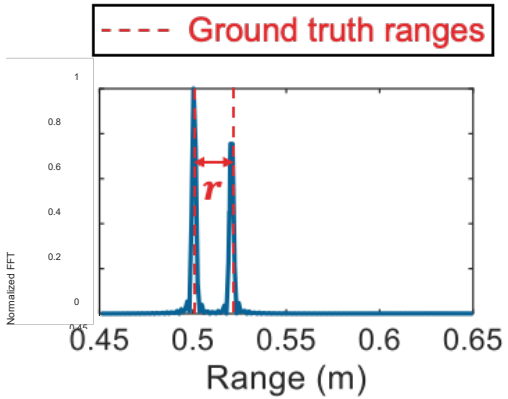
Great Benefits of Higher Sampling Rates

Increasing sampling rate can improve the **sensing resolution**

Sampling rate = 48 *kHz*
Two targets are indistinguishable



Sampling rate = 192 *kHz*
Two targets are distinguishable

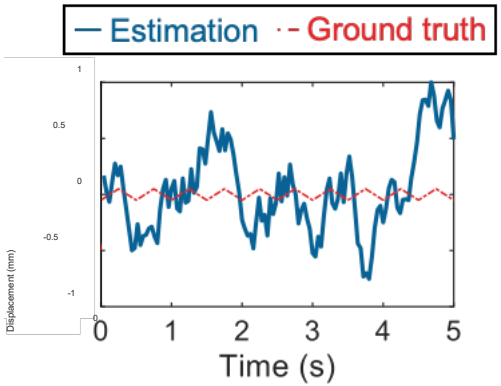


Great Benefits of Higher Sampling Rates

Increasing sampling rate can boost the **sensing granularity**

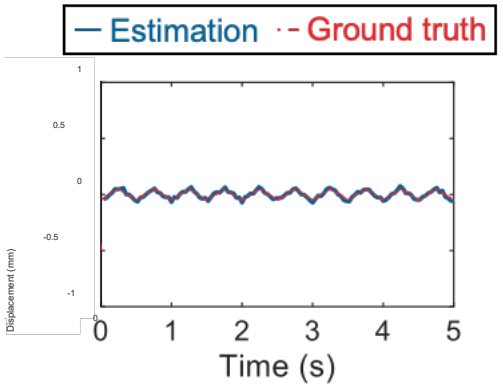
Sampling rate = 48 *kHz*

Cannot capture 0.1 *mm* displacement



Sampling rate = 192 *kHz*

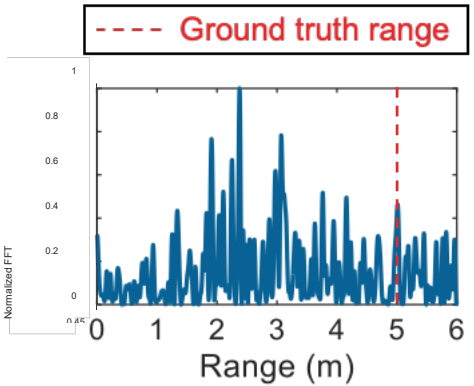
Successfully capture 0.1 *mm* displacement



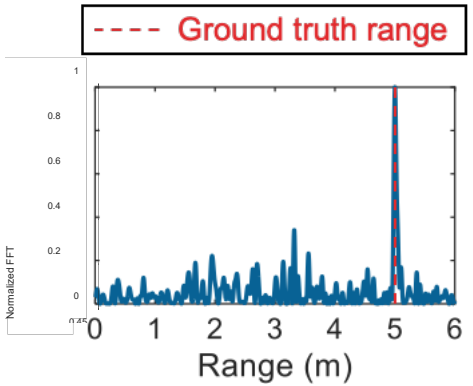
Great Benefits of Higher Sampling Rates

Increasing sampling rate can increase the **sensing range**

Sampling rate = 48 *kHz*
Cannot sense a target at 5 m



Sampling rate = 192 *kHz*
Successfully sense the target at 5 m



Opportunities Hidden in Smartphone Hardware

We analyzed more than **100** smartphones and found their hidden capabilities

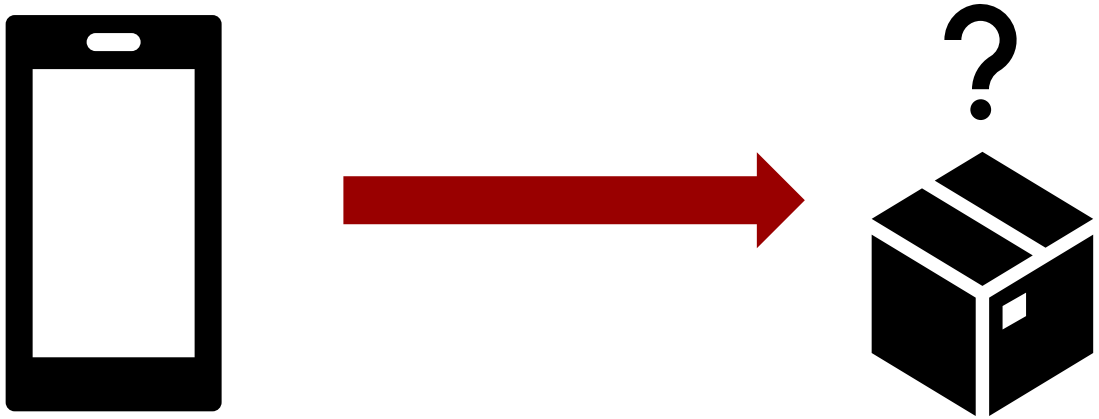
Brand	Lineup	# of Models	Audio Codec	RX f_s	Speaker Amplifier	TX f_s
Google	Pixel 4	1	Knowles IA8505	192 *kHz*	Cirrus Logic CS35L36	384 *kHz*
Google	Pixel 4a/5/5a	3	Realtek RT5514	192 *kHz*	Cirrus Logic CS35L41	192 *kHz*
Samsung	Galaxy S21 lineup (Exynos)	4	Exynos 2100 (integrated)	384 *kHz*	Cirrus Logic CS35L41	192 *kHz*
Samsung	Galaxy A50 lineup	2	Exynos 9610 (integrated)	384 *kHz*	Cirrus Logic CS35L41	192 *kHz*
Samsung	Galaxy A10/A20/A30/A40 lineup	10	Samsung COD3035x	192 *kHz*	Silicon Mitus SMA1301	192 *kHz*
Samsung	Galaxy S9 lineup (Snapdragon)	2	Qualcomm WCD9341	192 *kHz*	Maxim MAX98512	192 *kHz*
Samsung	Galaxy S10 lineup (Exynos)	5	Cirrus Logic CS47L93	192 *kHz*	Cirrus Logic CS35L40	192 *kHz*
Xiaomi	Redmi K40 lineup	4	Qualcomm WCD9380	192 *kHz*	Cirrus Logic CS35L41	192 *kHz*
Xiaomi	Mi 9/10/11/12/13 lineup	24	Qualcomm WCD93xx	192 *kHz*	Cirrus Logic CS35L41	192 *kHz*
Xiaomi	Redmi Note 8/8T/9Pro lineup	3	Qualcomm WCD937x	192 *kHz*	TI TAS2562	96 *kHz*
Huawei	P40 lineup	3	HiSilicon Hi6405	384 *kHz*	TI TAS2564	192 *kHz*
Huawei	Mate20/30/40, P30, Nova6/7 lineup	24	HiSilicon Hi6xxx series	192 *kHz*	NXP TFA9874	96 *kHz*
ASUS	Zenfone 9	1	Qualcomm WCD9380	192 *kHz*	Qualcomm WSA8835	384 *kHz*
Motorola	Edge (2020)	1	Cirrus Logic CS47L35	192 *kHz*	Cirrus Logic CS35L41	192 *kHz*
Sony	Xperia 1/5 II/III, Xperia 10 lineup	6	Qualcomm WCD93xx	192 *kHz*	Cirrus Logic CS35L41	192 *kHz*
Vivo	iQOO Neo3 5G	1	Qualcomm WCD9341	192 *kHz*	Maxim MAX98928	48 *kHz*
OnePlus	OnePlus 6 lineup	2	Qualcomm WCD9341	192 *kHz*	Maxim MAX98928	48 *kHz*
OnePlus	OnePlus 9 lineup	3	Qualcomm WCD9385	192 *kHz*	NXP TFA98xx series	48 *kHz*
Oppo	Realme X50 lineup	4	Qualcomm WCD9385	192 *kHz*	NXP TFA98xx series	48 *kHz*

Can we break the audio sampling rate limits of a smartphone, to unleash its hidden acoustic sensing capability?

Introducing PowerPhone

- A pure software reconfiguration
- Support higher sampling rates (E.g., 192 *kHz*)
- No extra hardware required

First Challenge: Black Box Hardware Structure

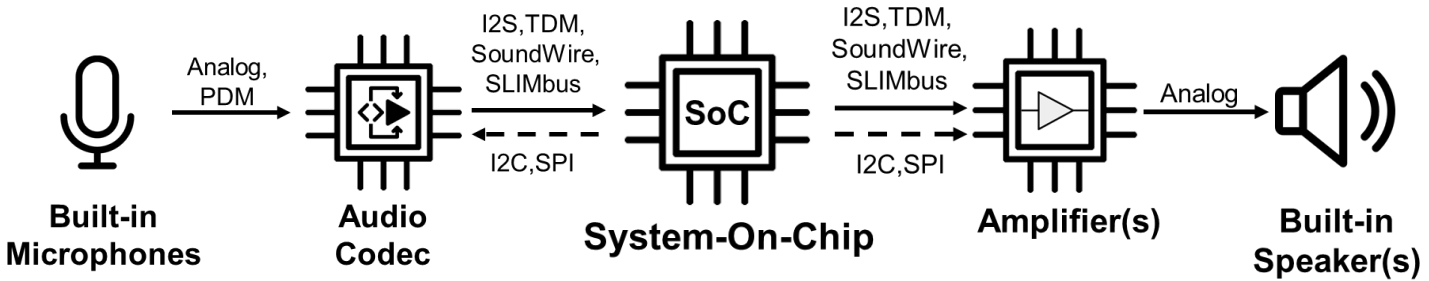


Hardware Fundamentals

- Electric schematics are proprietary, but the Linux Kernel are open-source
- We reverse-engineered smartphones through the Device-Tree-Overlays (DTOs) in their Linux kernel
- DTO allows us to know the hardware topology inside the smartphones without physically teardown

Hardware Fundamentals

- We summarize an audio hardware topology based on 100+ smartphones

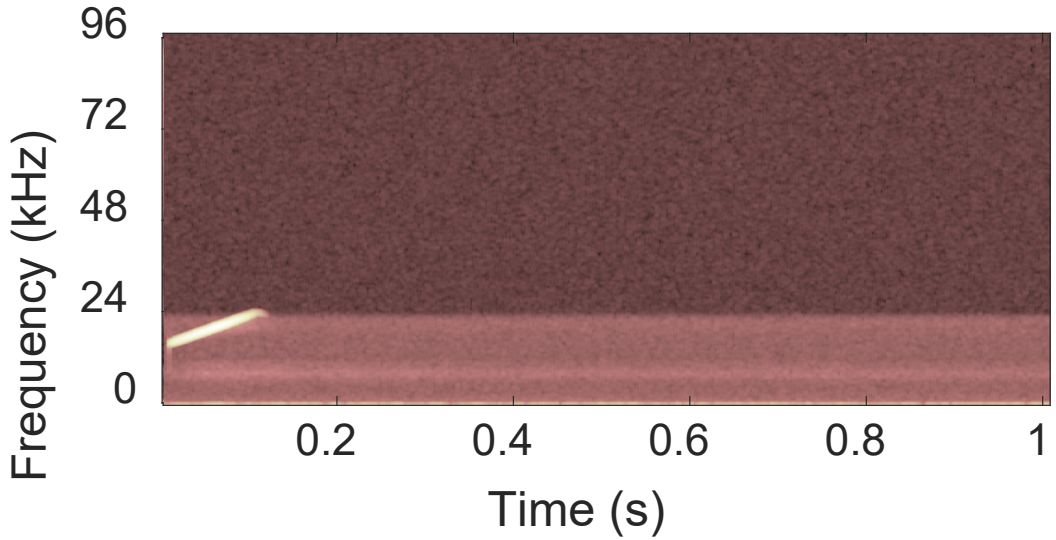


Driver Reconfiguration

- Configure the Phase-Lock Loop (PLL) to generate correct leading bit-clock
- Modify the registers inside codec and amplifier through SPI or I2C to support 192 kHz sampling rates
- Change Direct-Memory-Access (DMA) bit-rate and memory mapping size

Second Challenge:

Sampling Rates Remain at 48 *kHz*



Analysis

Multi-layer Signal Chain

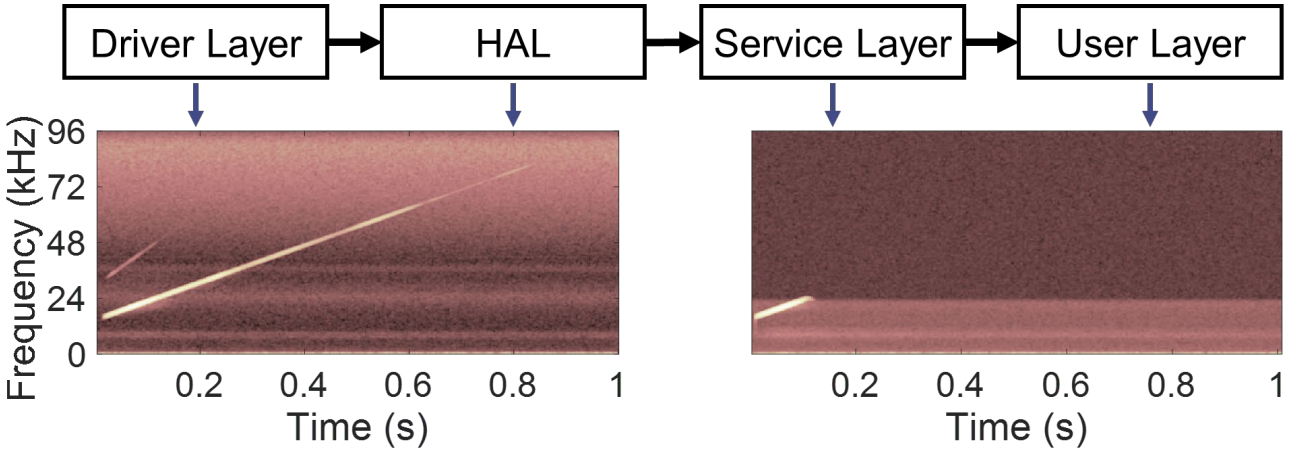
- Android OS has many layers in its audio chain
- We summarized them into four layers
  - Linux Kernel Driver Layer
  - Hardware Abstraction Layer
  - System Service Layer
  - User Layer (Public API)
- **We need to figure out which layer down-sampled the audio stream**

Our Solution: Layer-By-Layer Analysis

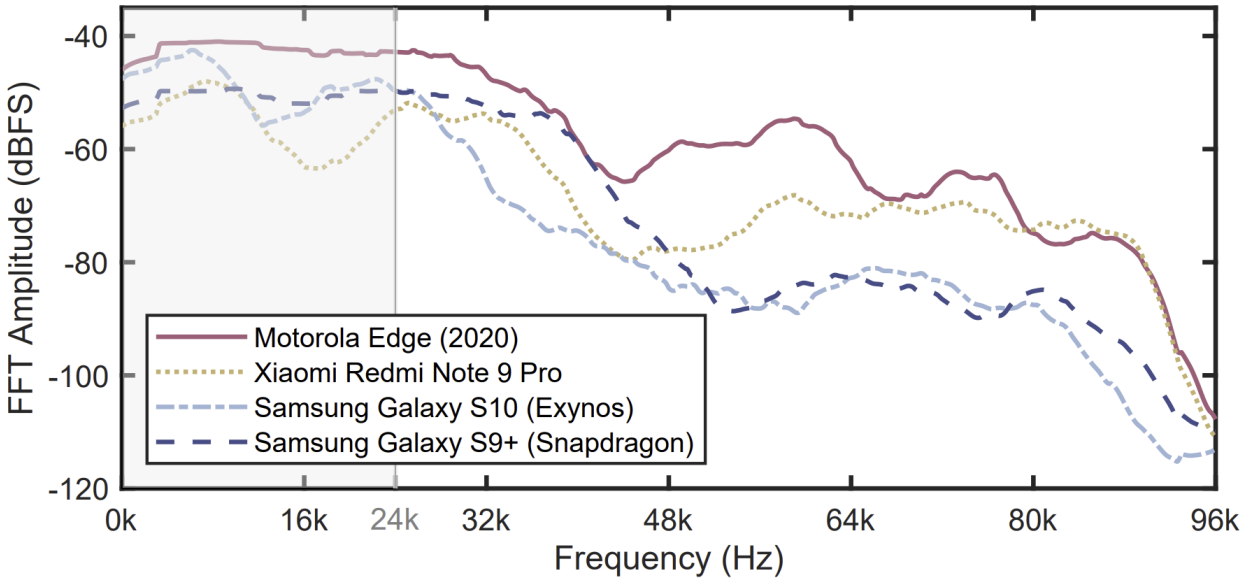
- Find out who down-sampled the audio stream is not trivial, especially the HAL is in binary form
- To access the output of the Linux Kernel Driver, we ported Ubuntu Touch OS to the smartphone
- To access the output of the HAL and System Service Layer, we compiled and built our own Android OS based on LineageOS

Our Findings

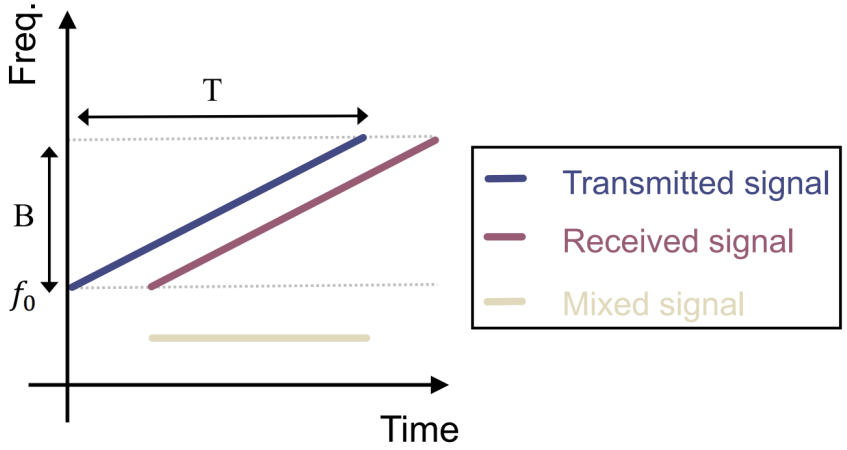
- We found that **System Service Layer** down-sampled the audio
- We fixed such behavior by changing hard-coded configuration files

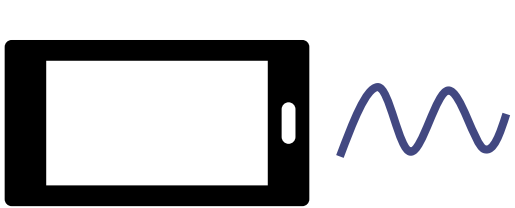


Frequency Responses

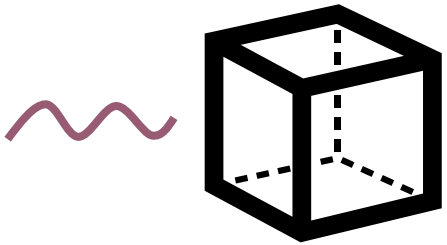


Chirp Signals



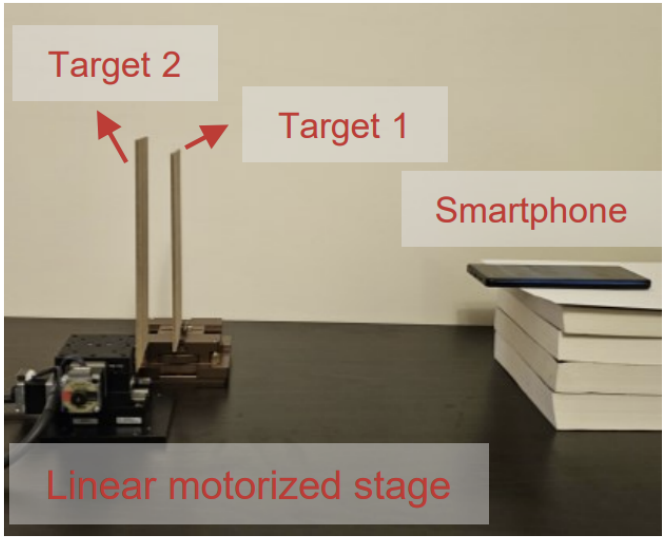


Smartphone

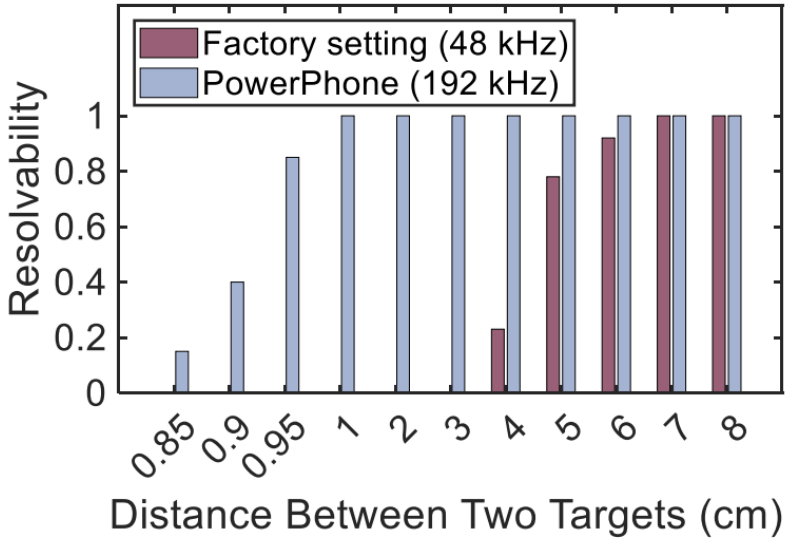


Target

Resolution Benchmark

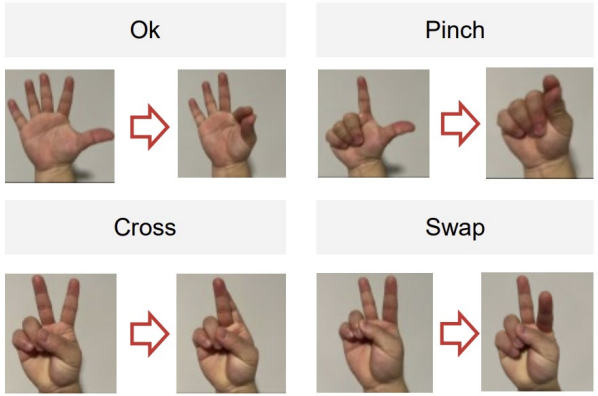


Experiment Setup

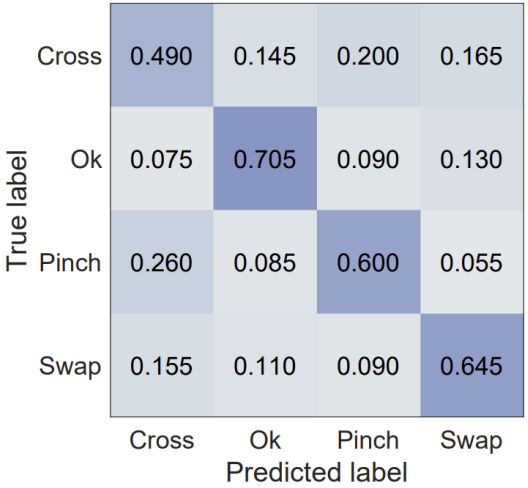


Results

Resolution Field Study



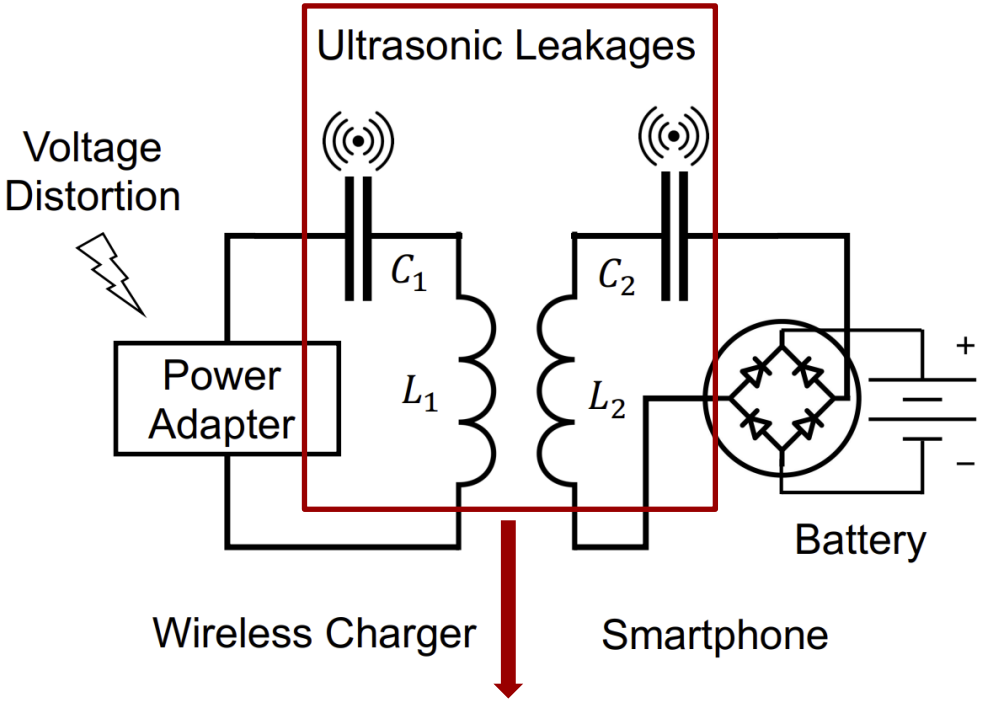
Gestures

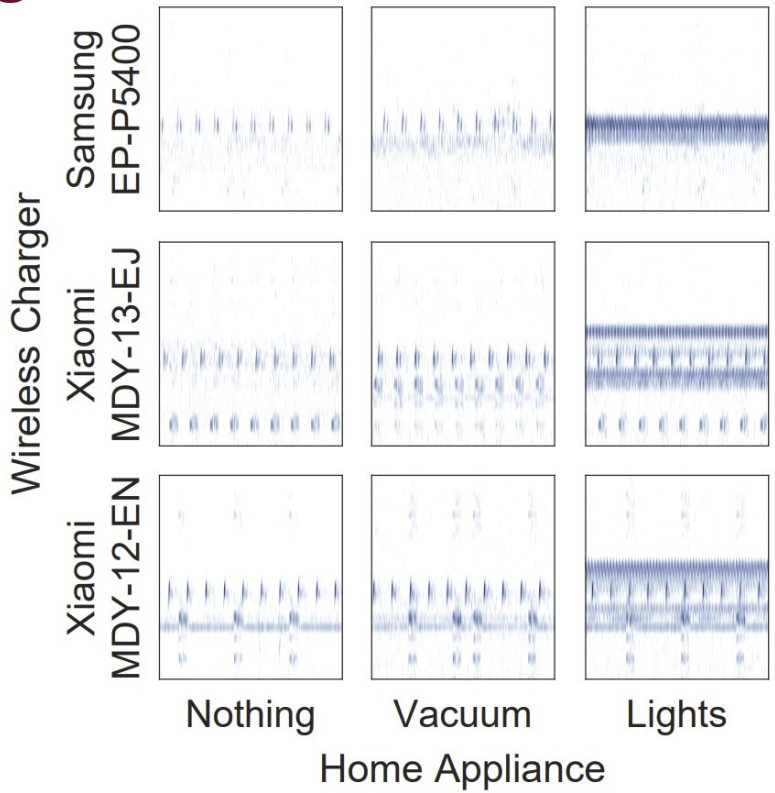


Factory Settings (48 kHz)

PowerPhone (192 kHz)

New Application: Wireless Charger Leakages

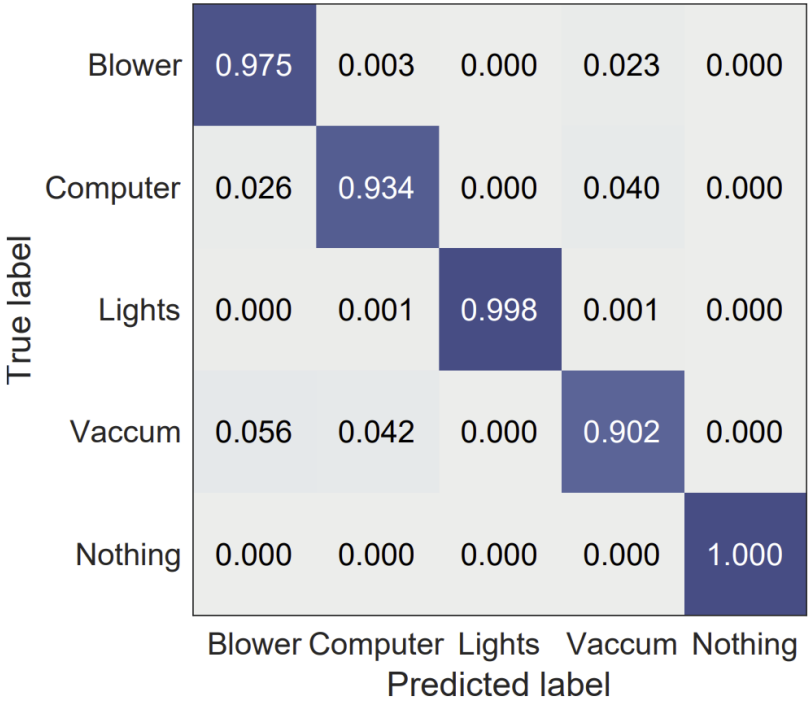




- Leakages from capacitors and inductors

New Application: Results

- Classification using Vision Transformer (ViT) network
- Overall accuracy: 96.2%



Conclusion

- Reconfigured smartphone sampling rates to 192kHz and open-sourced implementation
- Enhanced sensing resolution (1 cm), granularity (2 um), and range (6 m)
- Enabling many new ultrasonic sensing applications, e.g., home appliance monitoring

Check Our Website!

- Step-by-step instruction, source codes, system images, etc.
- Future updates / new supported smartphones.
- https://powerphone.github.io

POWERPHONE

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COMPUTING FOR THE COMMON GOOD

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