UMassAmherst | Manning College of Information & Computer Sciences

PowerPhone: Unleashing the Acoustic Sensing Capability of Smartphones

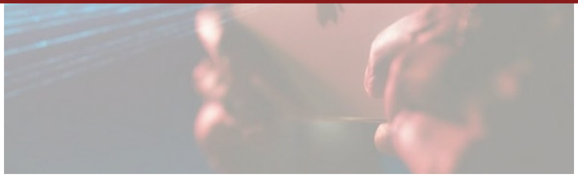
Shirui Cao*, Dong Li*, Sunghoon Ivan Lee†, Jie Xiong†

ACM MobiCom 2023

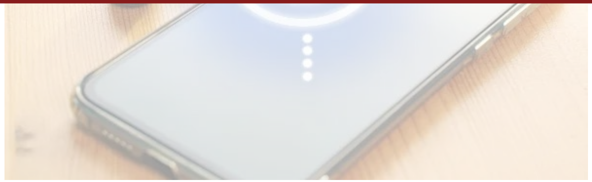
Wireless Sensing on Smartphones

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

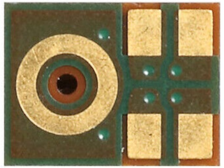
Dedicated modules

LiDAR sensor

UWB sensor

Ubiquitous modules

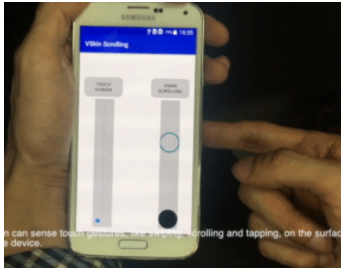
Speaker



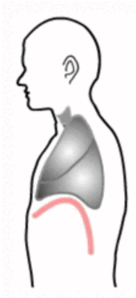
Microphone

Advantage Two: Fine Sensing Granularity

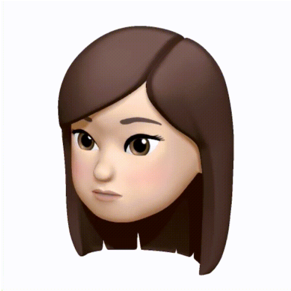
Acoustic signals enable applications that support fine sensing granularity



Finger tracking



Respiration monitoring

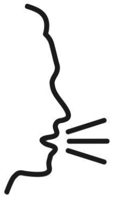


Eye blink detection

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*

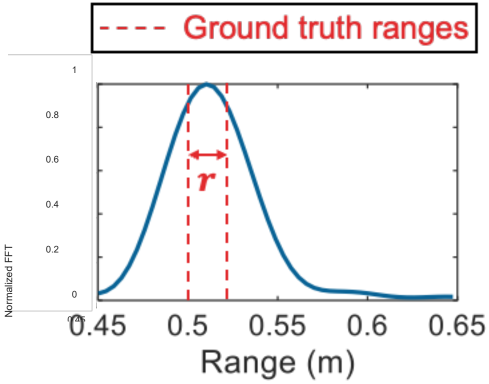
Sampling rates for speaker and microphone

44.1 *kHz* or 48 *kHz*

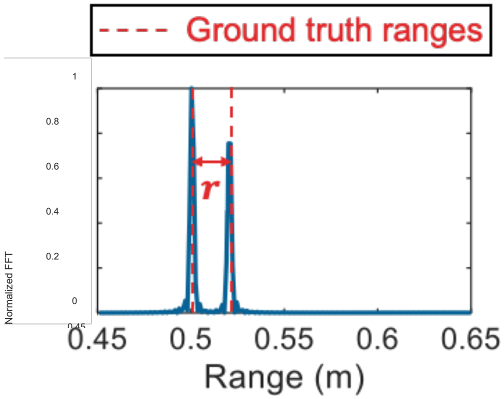
Great Benefits of Higher Sampling Rates

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

Sampling rate = 48 *kHz*
Two targets are indistinguishable



Sampling rate = 192 *kHz*
Two targets are distinguishable

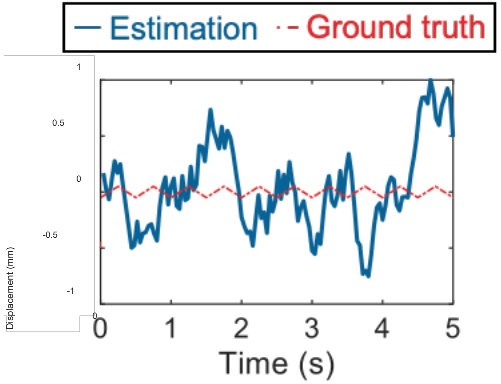


Great Benefits of Higher Sampling Rates

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

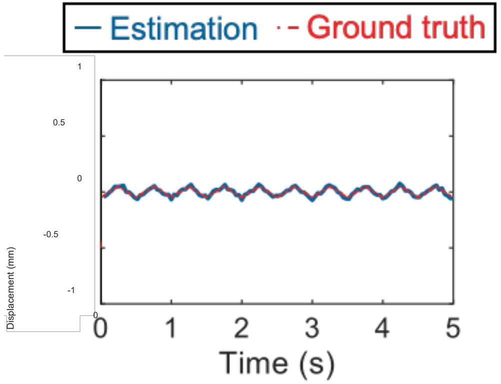
Sampling rate = 48 *kHz*

Cannot capture 0.1 *mm* displacement



Sampling rate = 192 *kHz*

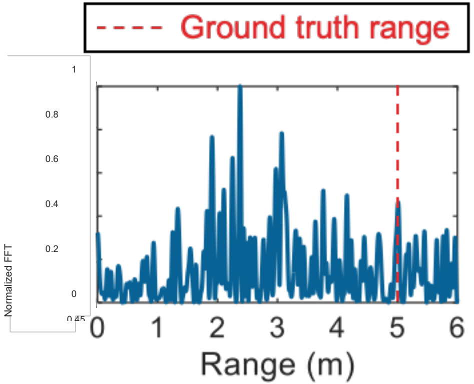
Successfully capture 0.1 *mm* displacement



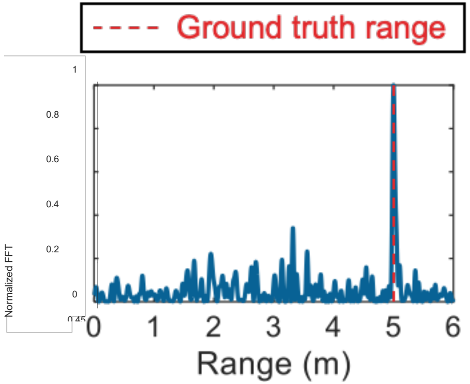
Great Benefits of Higher Sampling Rates

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*

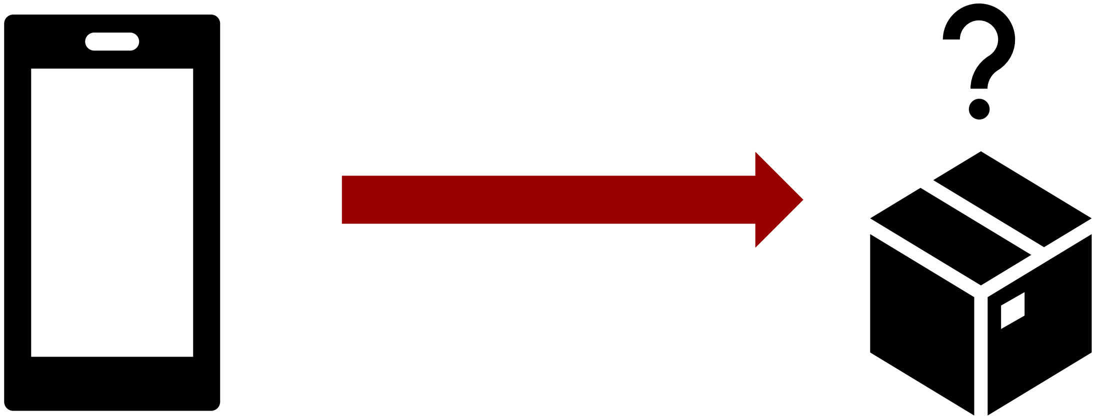
Can we break the audio sampling rate limits of a smartphone, to unleash its hidden acoustic sensing capability?

Introducing PowerPhone

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

POWERPHONE

First Challenge:
Black Box Hardware Structure

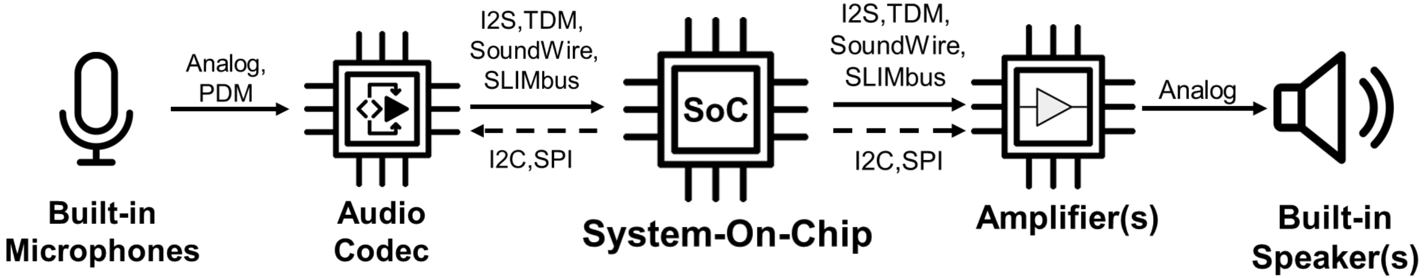


Hardware Fundamentals

- 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

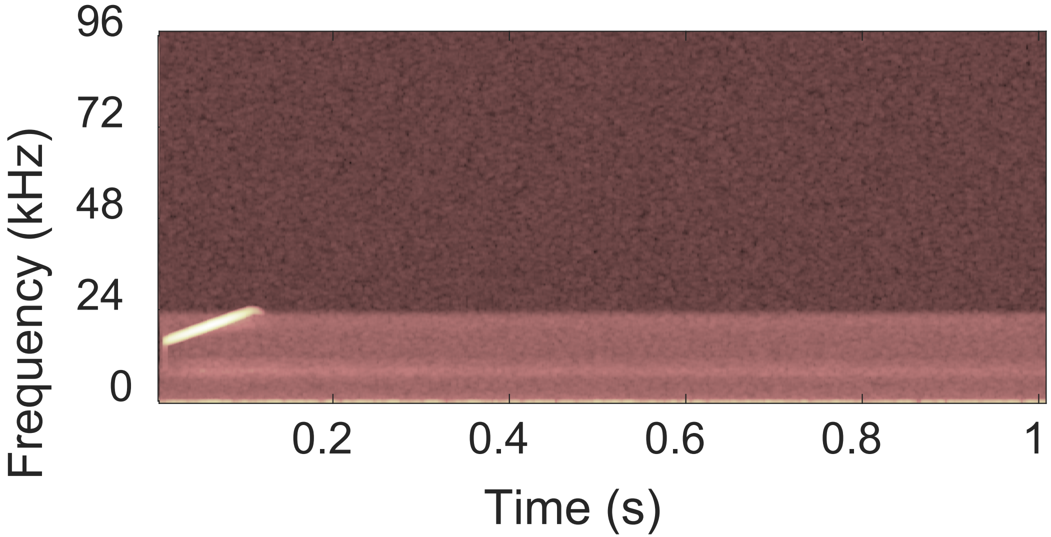
- We summarize an audio hardware topology based on 100+ smartphones



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

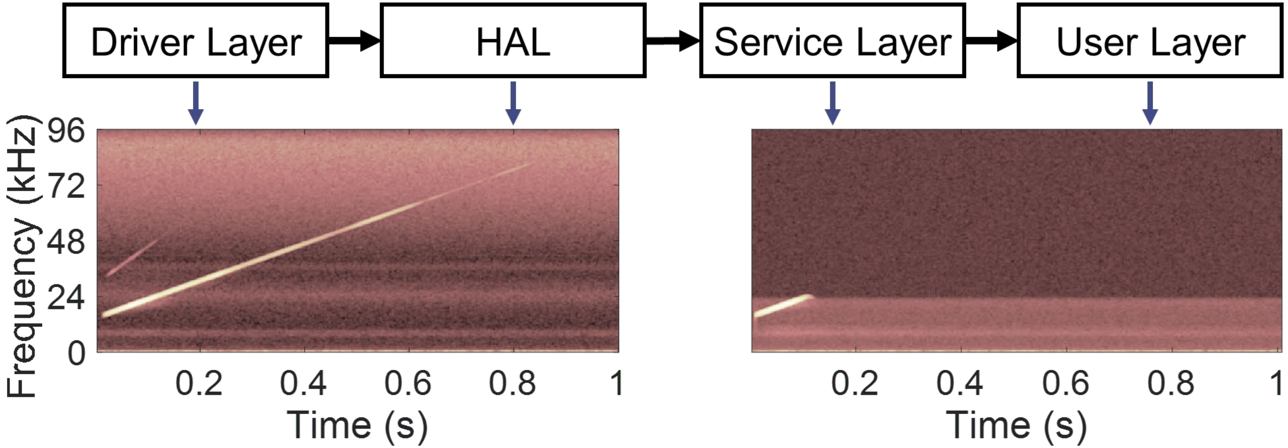
- Android OS has many layers in its audio chain
- We summarized them into four layers
  - Linux Kernel Driver Layer
  - Hardware Abstraction Layer
  - System Service Layer
  - User Layer (Public API)
- **We need to figure out which layer down-sampled the audio stream**

Our Solution: Layer-By-Layer Analysis

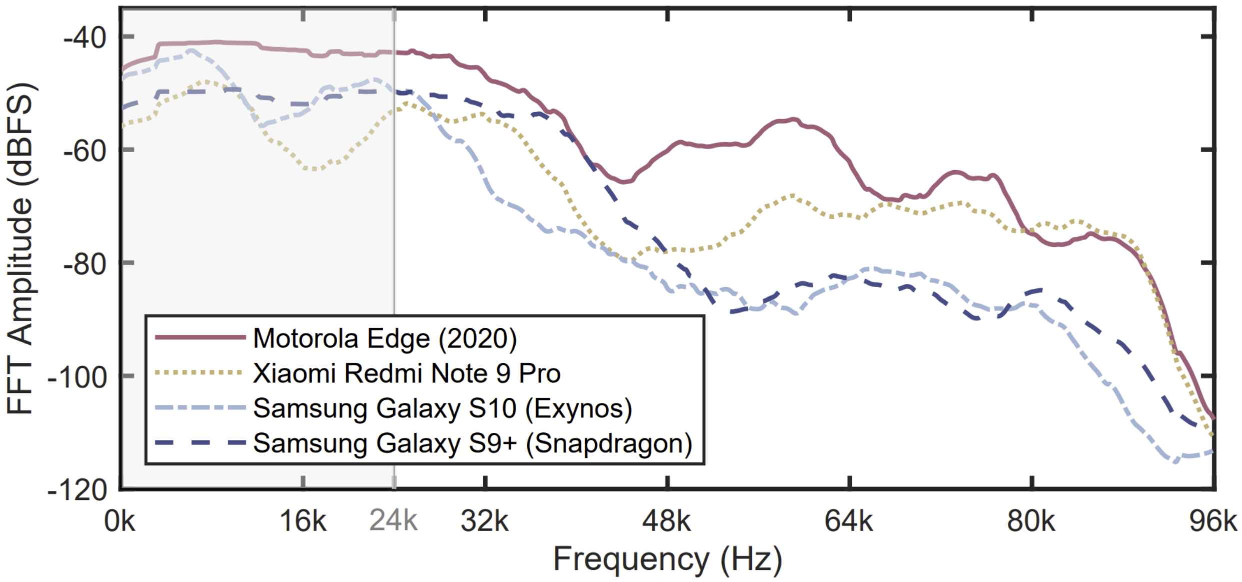
- Find out who down-sampled the audio stream is not trivial, especially the HAL is in binary form
- To access the output of the Linux Kernel Driver, we ported Ubuntu Touch OS to the smartphone
- To access the output of the HAL and System Service Layer, we compiled and built our own Android OS based on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

Our Findings

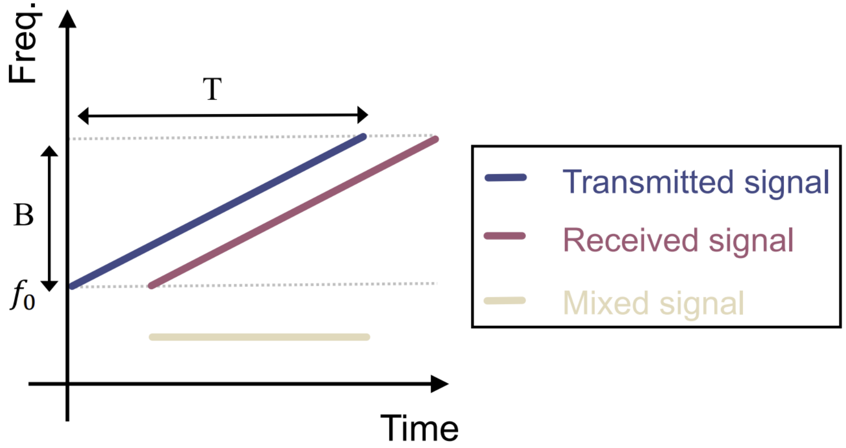
- We found that **System Service Layer** down-sampled the audio
- We fixed such behavior by changing hard-coded configuration files

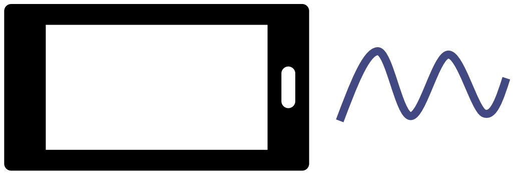


Frequency Responses

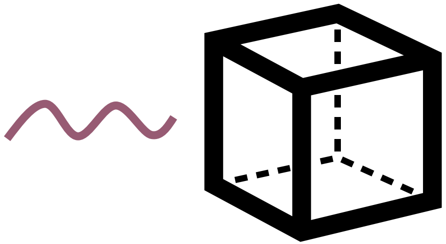


Chirp Signals



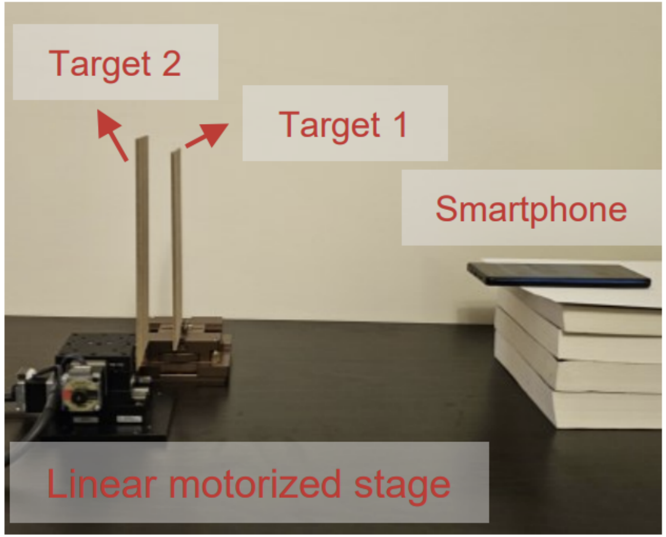


Smartphone

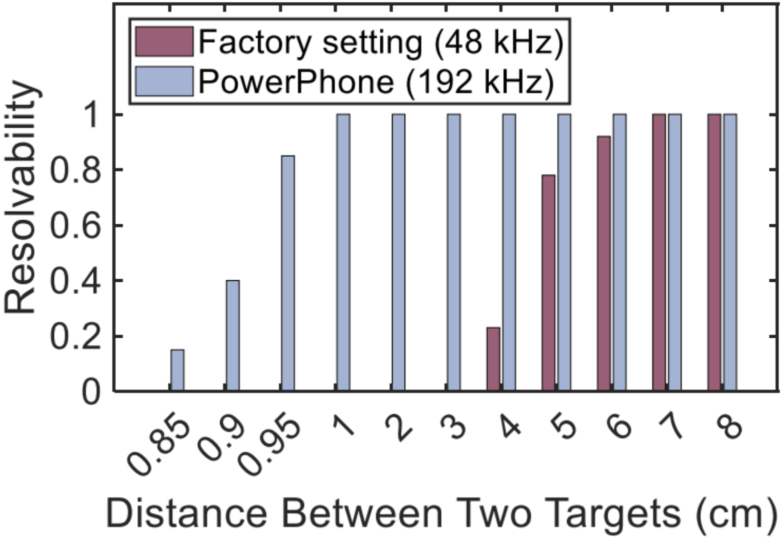


Target

Resolution Benchmark

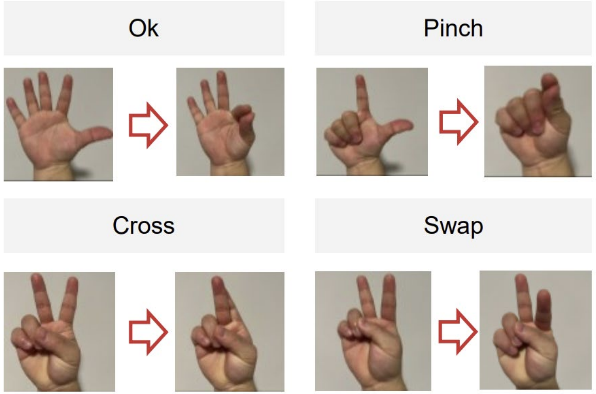


Experiment Setup



Results

Resolution Field Study



Gestures

True label \ Predicted label	Cross	Ok	Pinch	Swap
Cross	0.490	0.145	0.200	0.165
Ok	0.075	0.705	0.090	0.130
Pinch	0.260	0.085	0.600	0.055
Swap	0.155	0.110	0.090	0.645

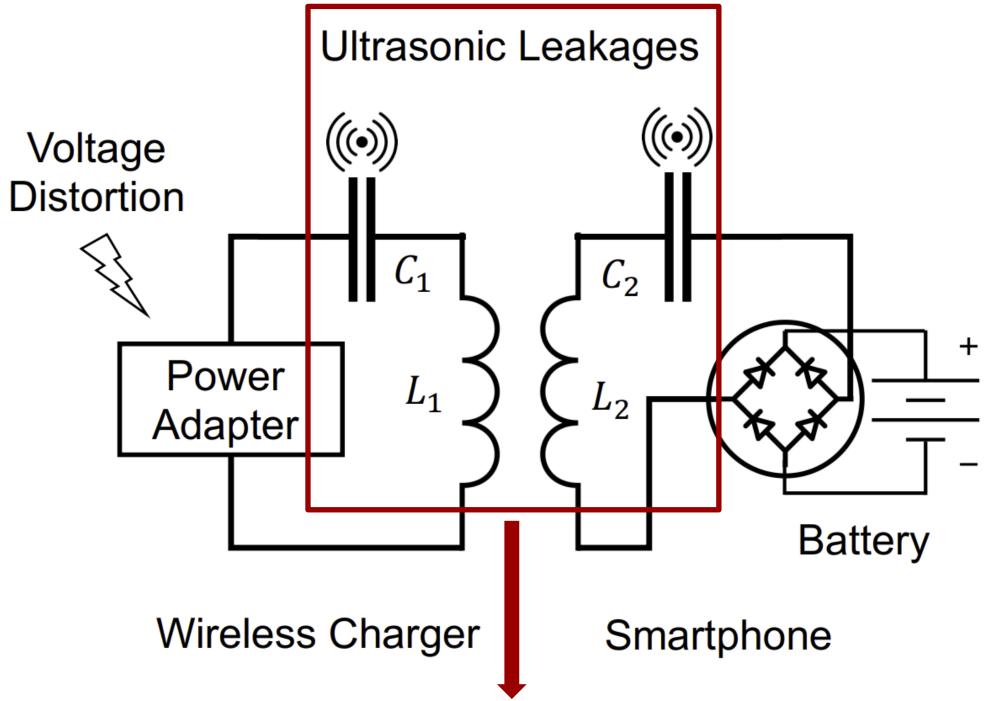
Factory Settings (48 kHz)

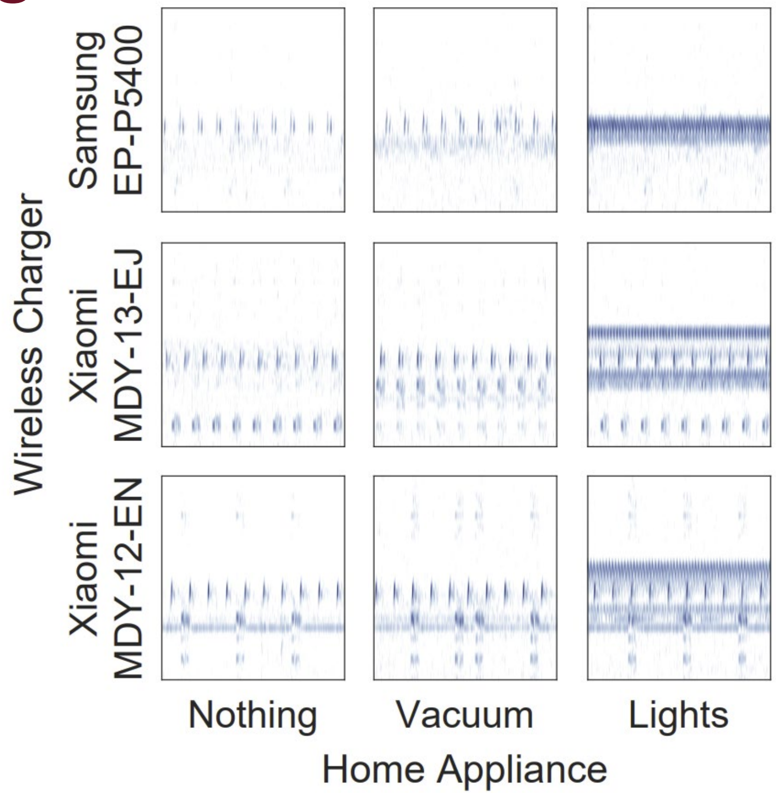
True label \ Predicted label	Cross	Ok	Pinch	Swap
Cross	0.865	0.075	0.035	0.025
Ok	0.045	0.925	0.020	0.010
Pinch	0.010	0.045	0.920	0.025
Swap	0.035	0.005	0.060	0.900

PowerPhone (192 kHz)

New Application: Wireless Charger Leakages

UMassAmherst | Manning College of Information & Computer Sciences





- Leakages from capacitors and inductors

New Application: Results

UMassAmherst | Manning College of Information & Computer Sciences

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

True label \ Predicted label	Blower	Computer	Lights	Vaccum	Nothing
Blower	0.975	0.003	0.000	0.023	0.000
Computer	0.026	0.934	0.000	0.040	0.000
Lights	0.000	0.001	0.998	0.001	0.000
Vaccum	0.056	0.042	0.000	0.902	0.000
Nothing	0.000	0.000	0.000	0.000	1.000

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

UMassAmherst | Manning College of Information & Computer Sciences

COMPUTING FOR THE COMMON GOOD

Shirui Cao
shiruicao@cs.umass.edu
github.com/charlescao460