Metamorph: Injecting Inaudible Commands into Over-the-air Voice Controlled Systems

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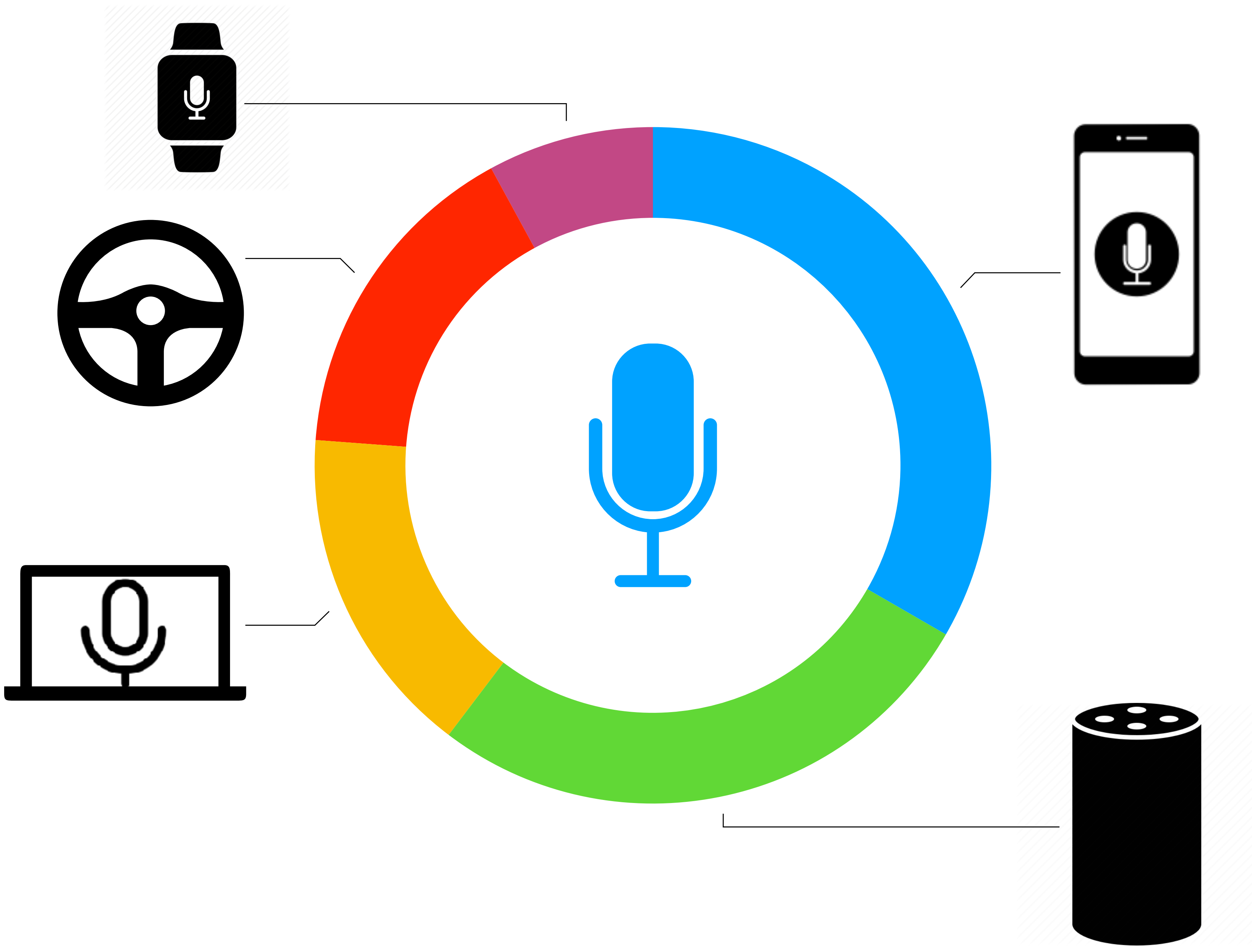
City University of Hong Kong

Microsoft

PRINCETON UNIVERSITY

Voice Assistants in Smart Home



Voice Assistants in Smart Home

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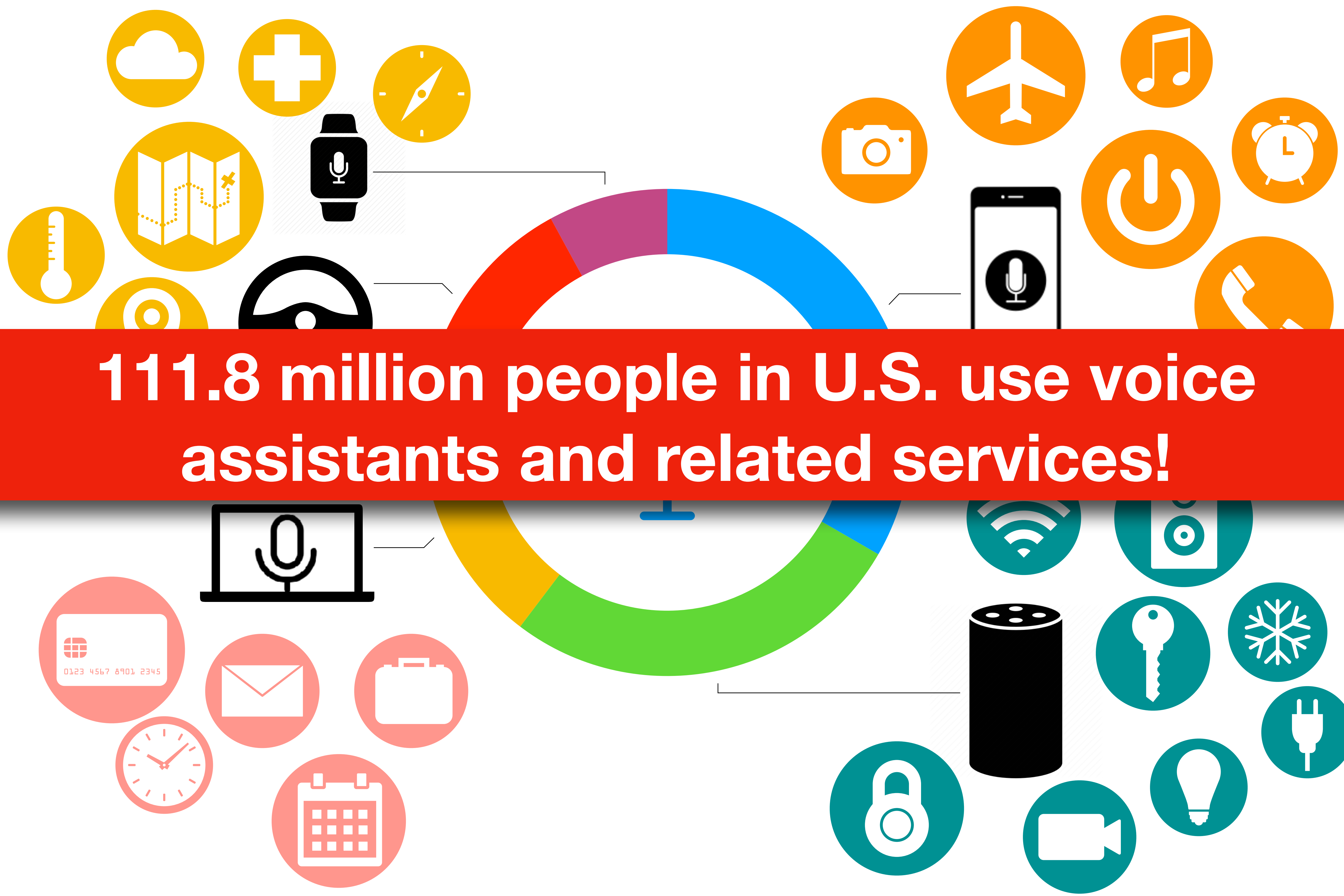
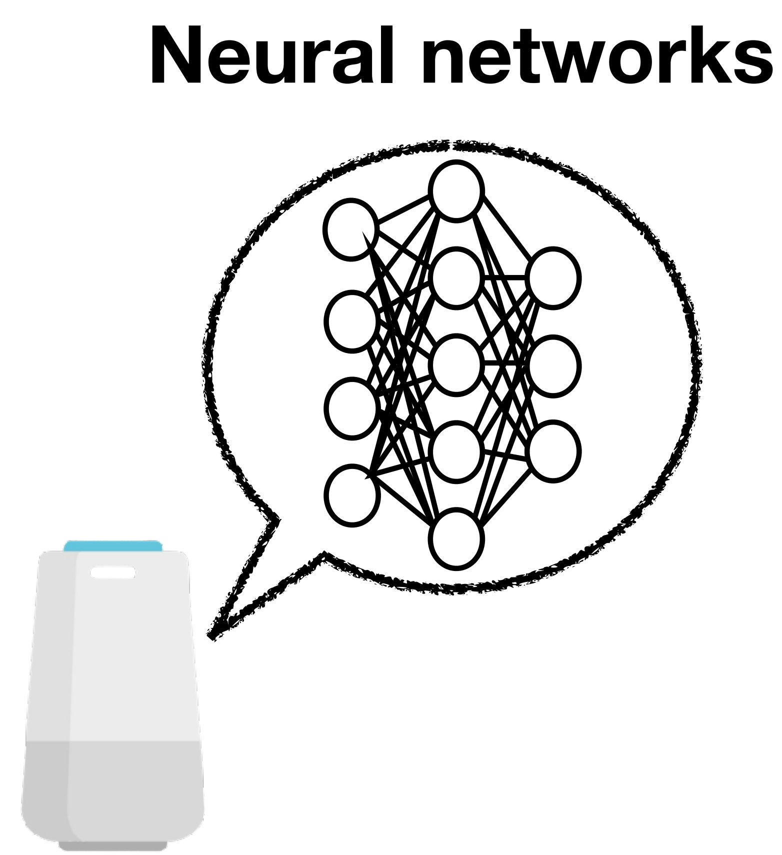


111.8 million people in U.S. use voice assistants and related services!

https://www.emarketer.com/content/us-voice-assistant-users-2019

Are they safe enough?

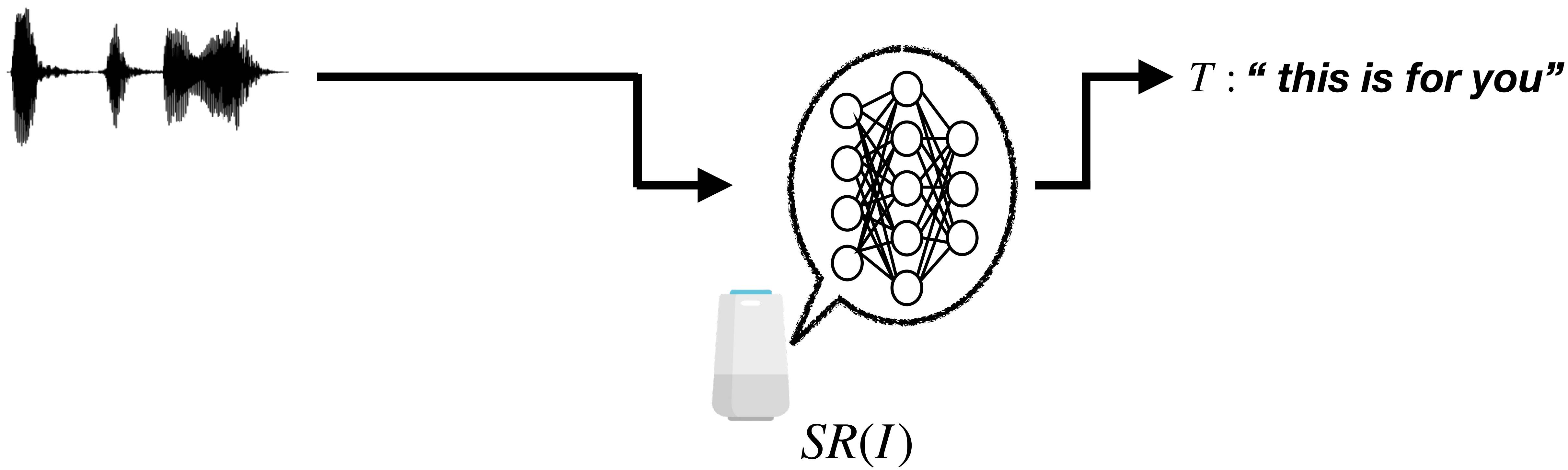
How to attack the voice assistant?



Speech Recognition Models (SR)

How to attack the voice assistant?

Audio Clip: I



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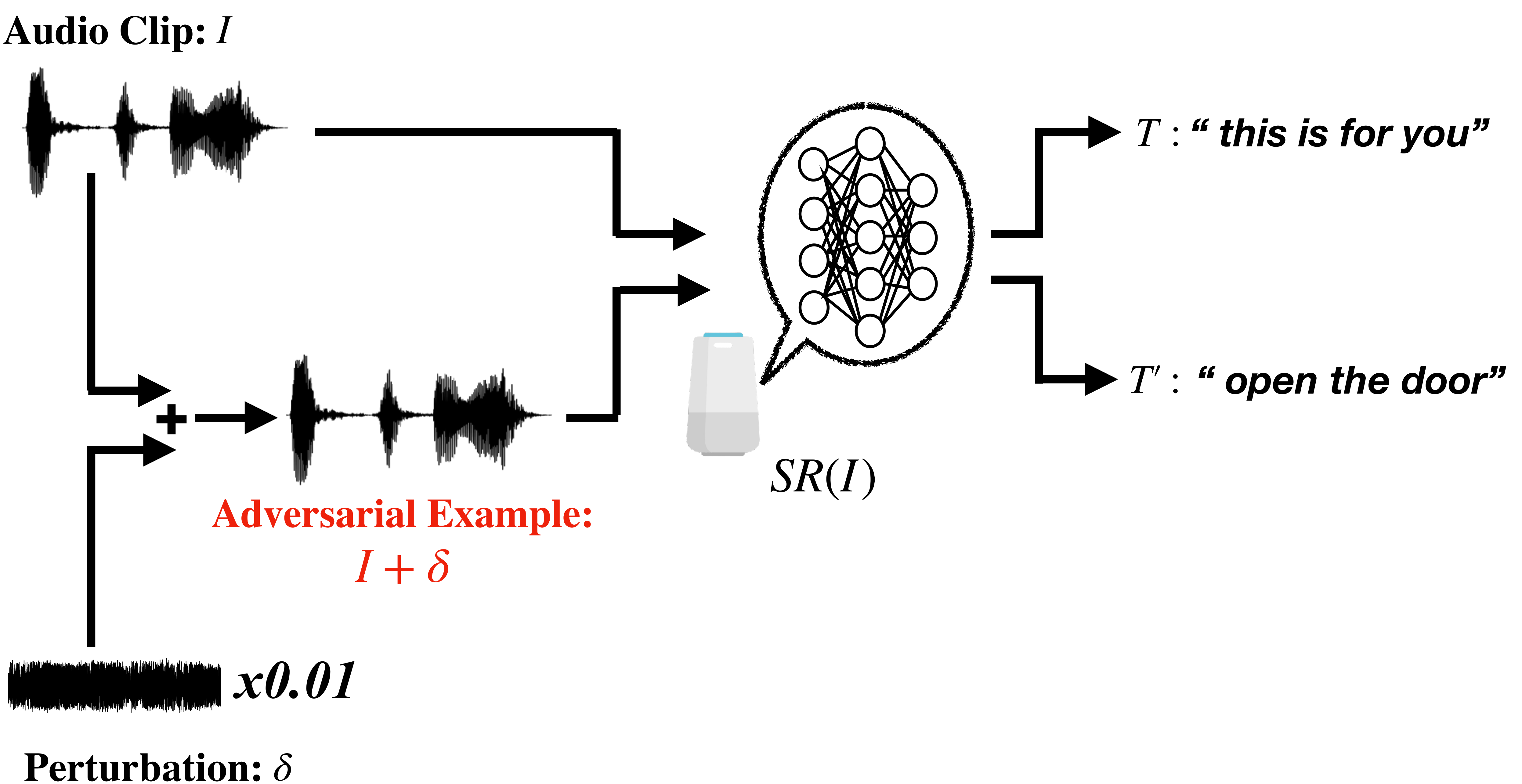

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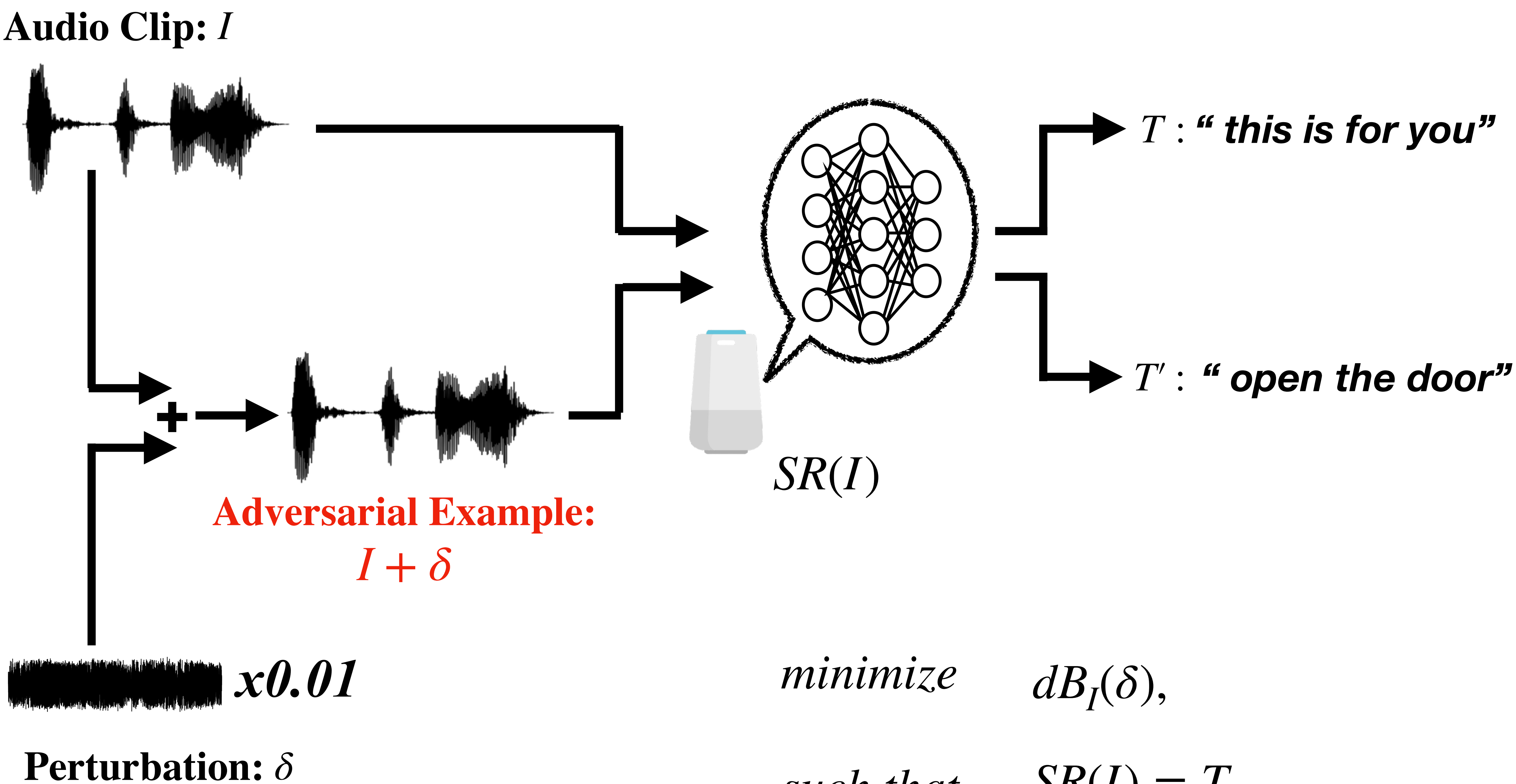


$$\begin{aligned} &\textit{minimize} && dB_I(\delta), \\ &\textit{such that} && SR(I) = T, \\ & && SR(I+\delta) = T' \end{aligned}$$

Nicholas Carlini et al. Audio Adversarial Examples, Deep Learning and Security Workshop, 2018

How to attack the voice assistant?

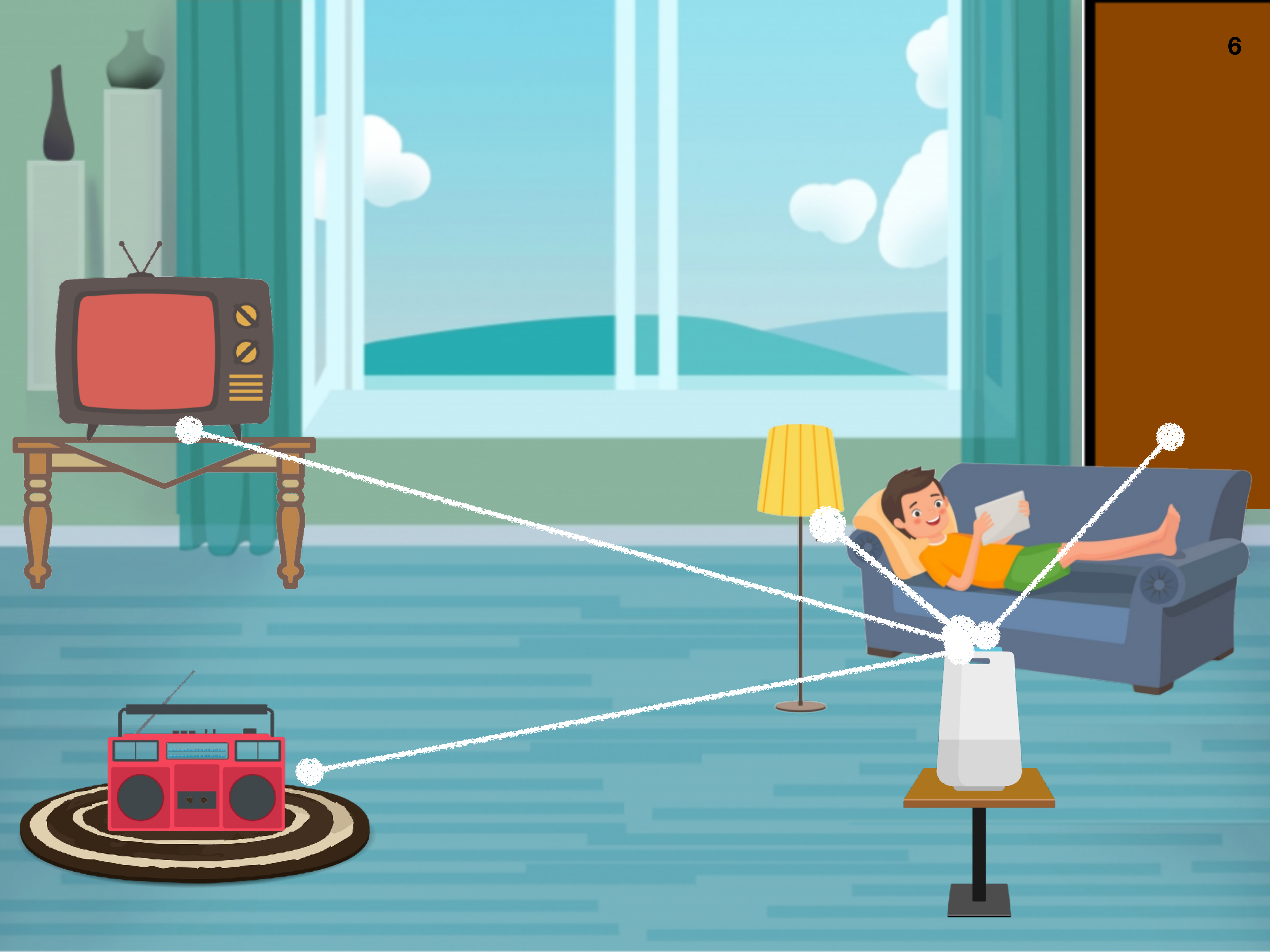
Audio Adversarial Attack

$x0.01$

Perturbation: δ

$$\begin{aligned} &\textit{minimize} && dB_I(\delta), \\ &\textit{such that} && SR(I) = T, \\ & && SR(I+\delta) = T' \end{aligned}$$

Nicholas Carlini et al. Audio Adversarial Examples, Deep Learning and Security Workshop, 2018

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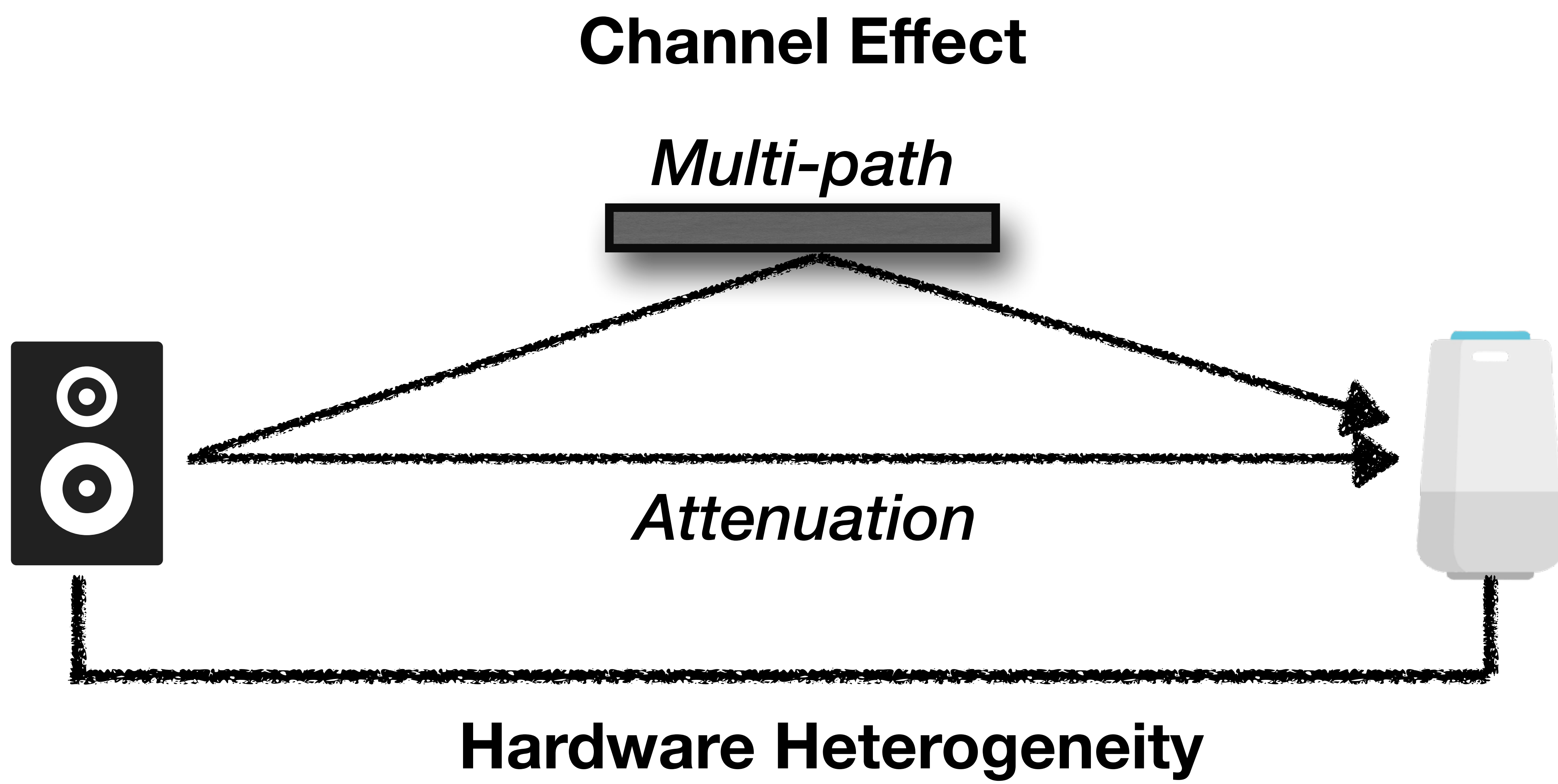
Is it a real threat? Yes!


Adversarial Example

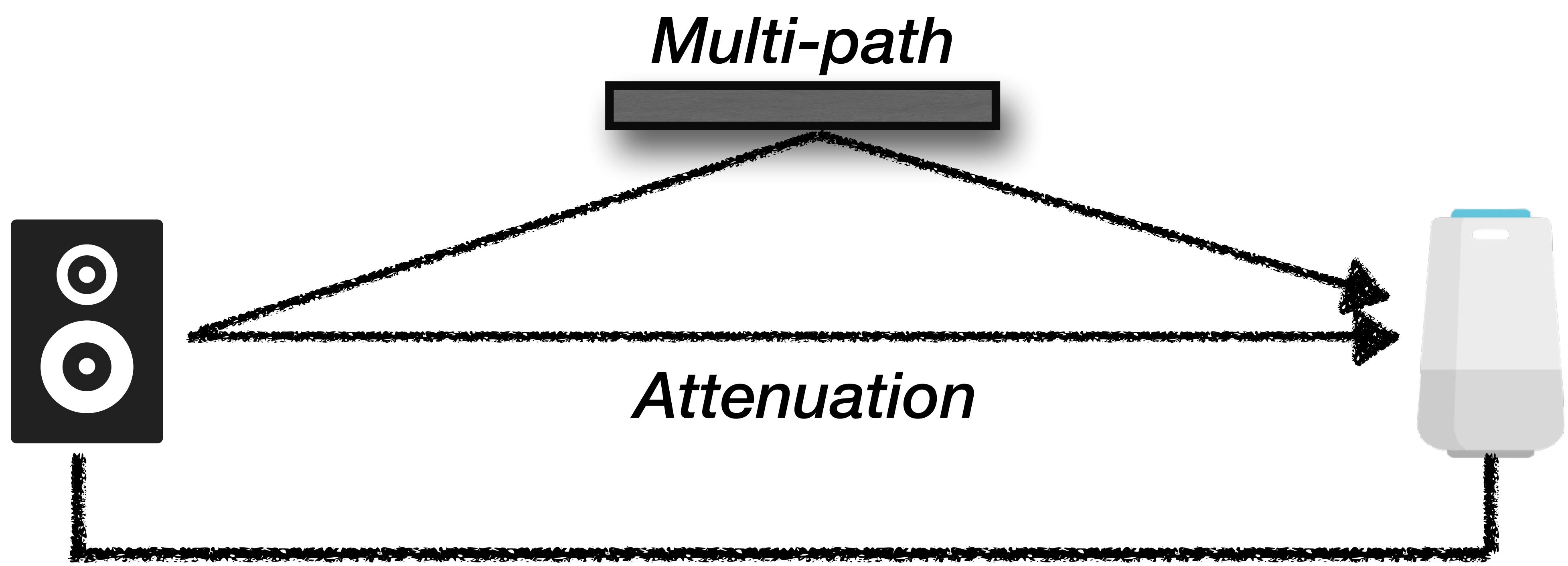

Adversarial Example
But, failed Over-the-air!

Challenge


Channel Effect
Multi-path
Attenuation
Hardware Heterogeneity

Challenge

Channel Effect



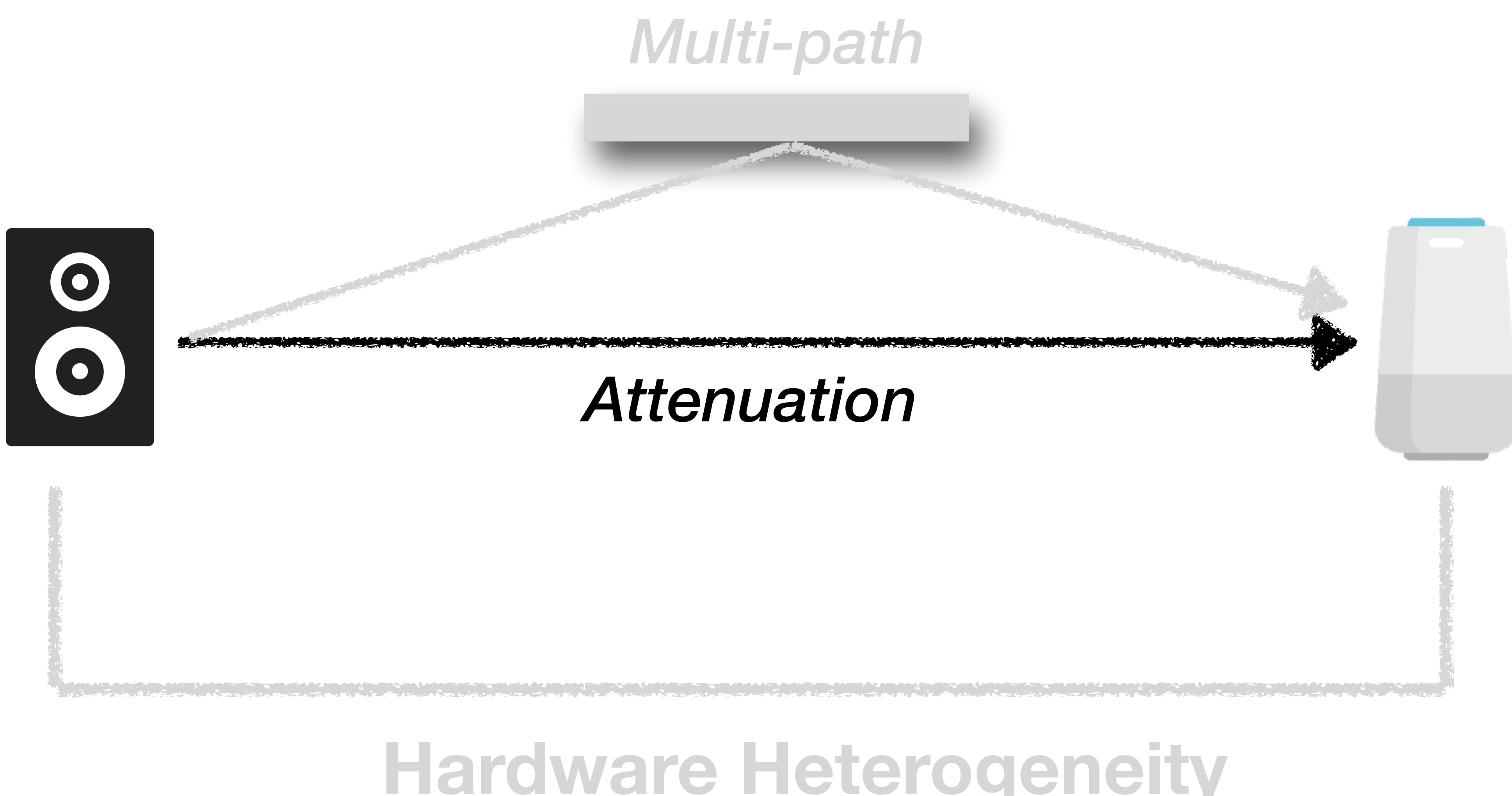
Hardware Heterogeneity

$$SR(I + \delta) \ \textbf{vs} \ SR(H(I + \delta))$$

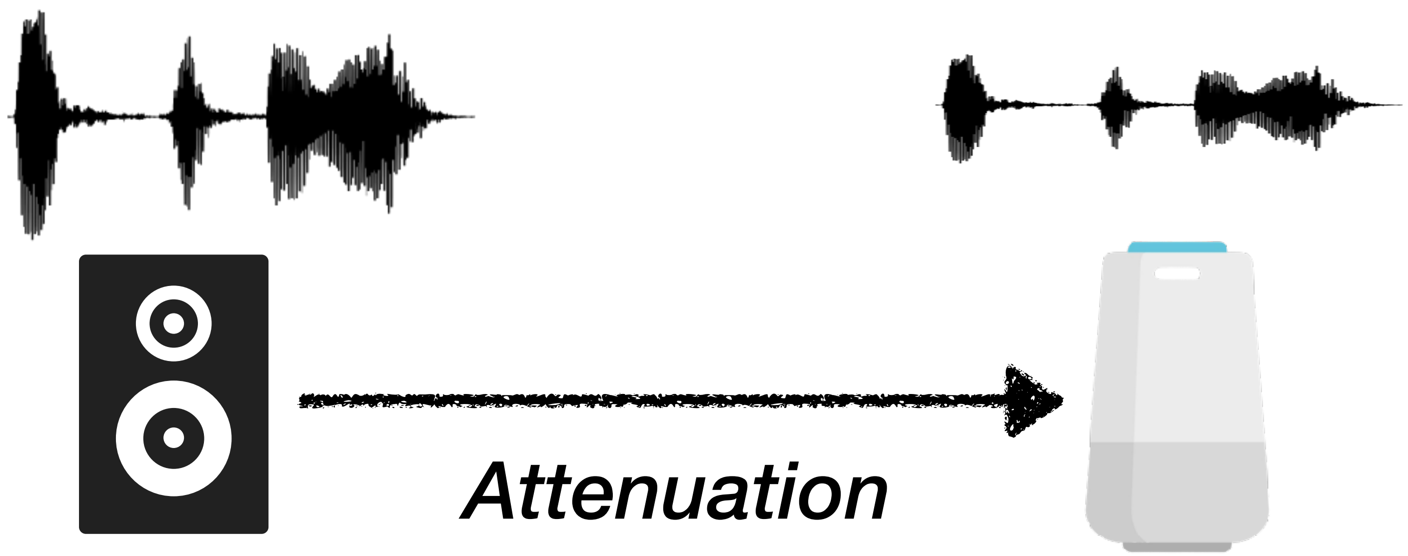
H is unknown in advance!

Understand Over-the-air Attack

Channel Effect



Attenuation



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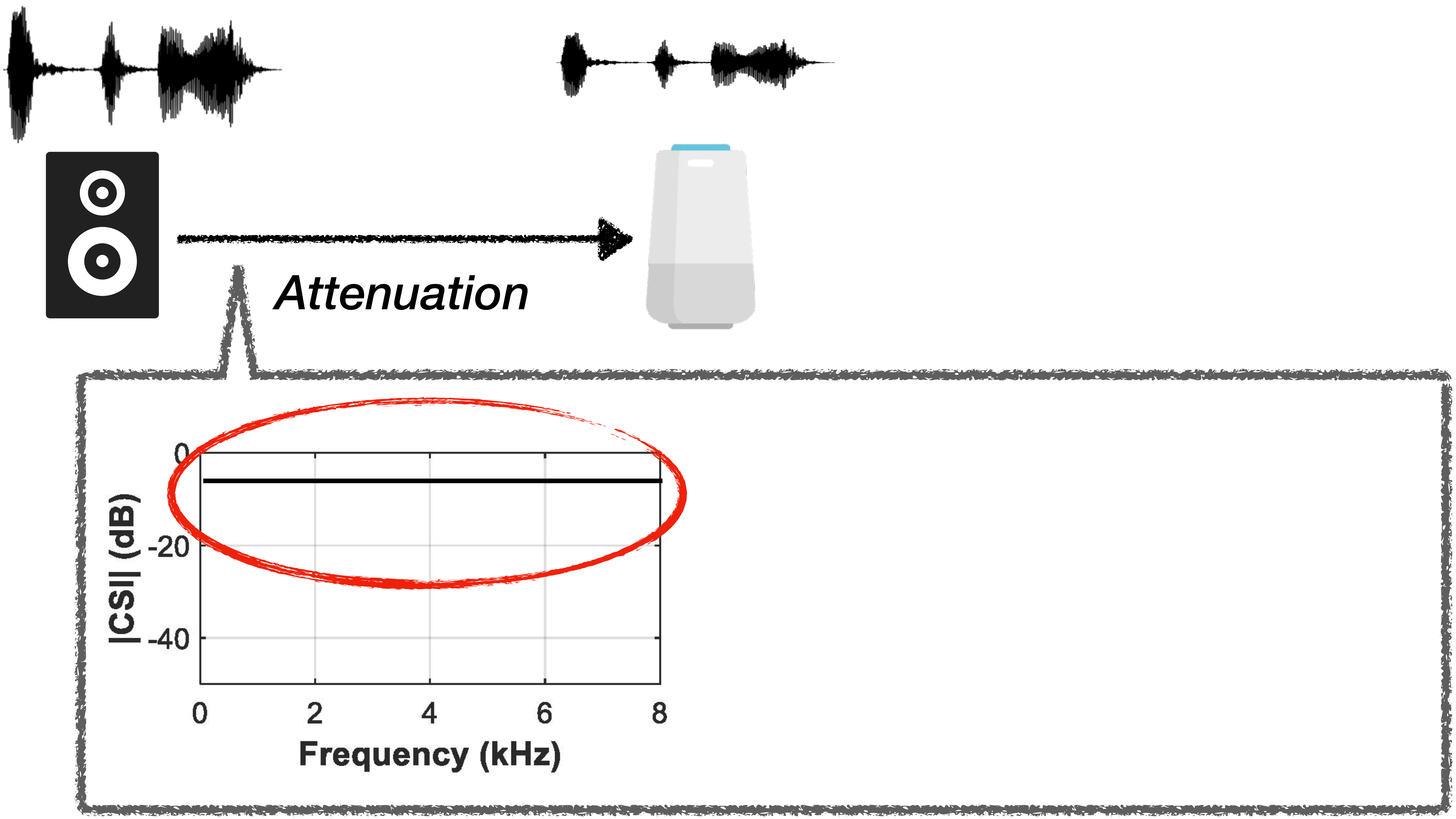

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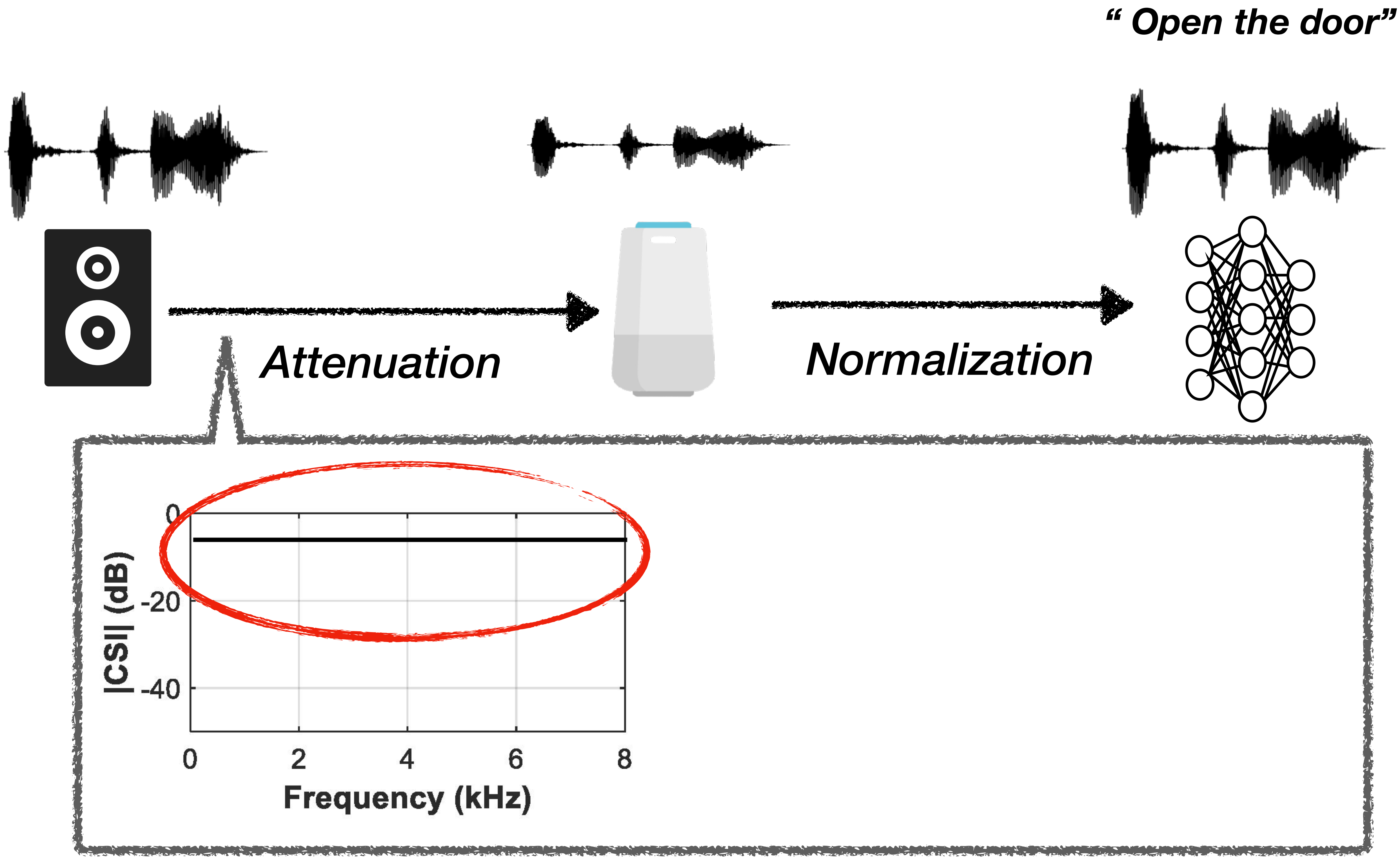
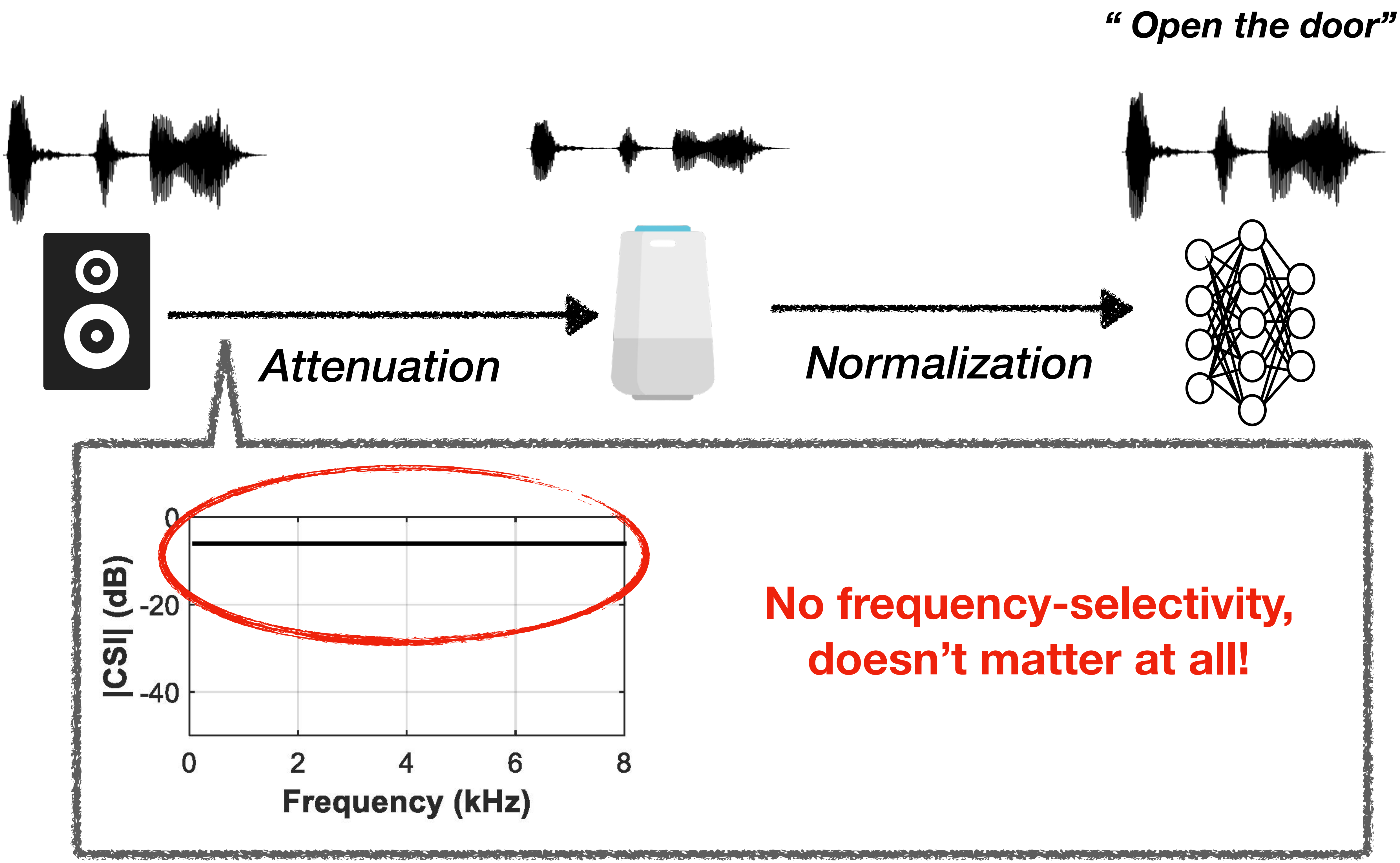
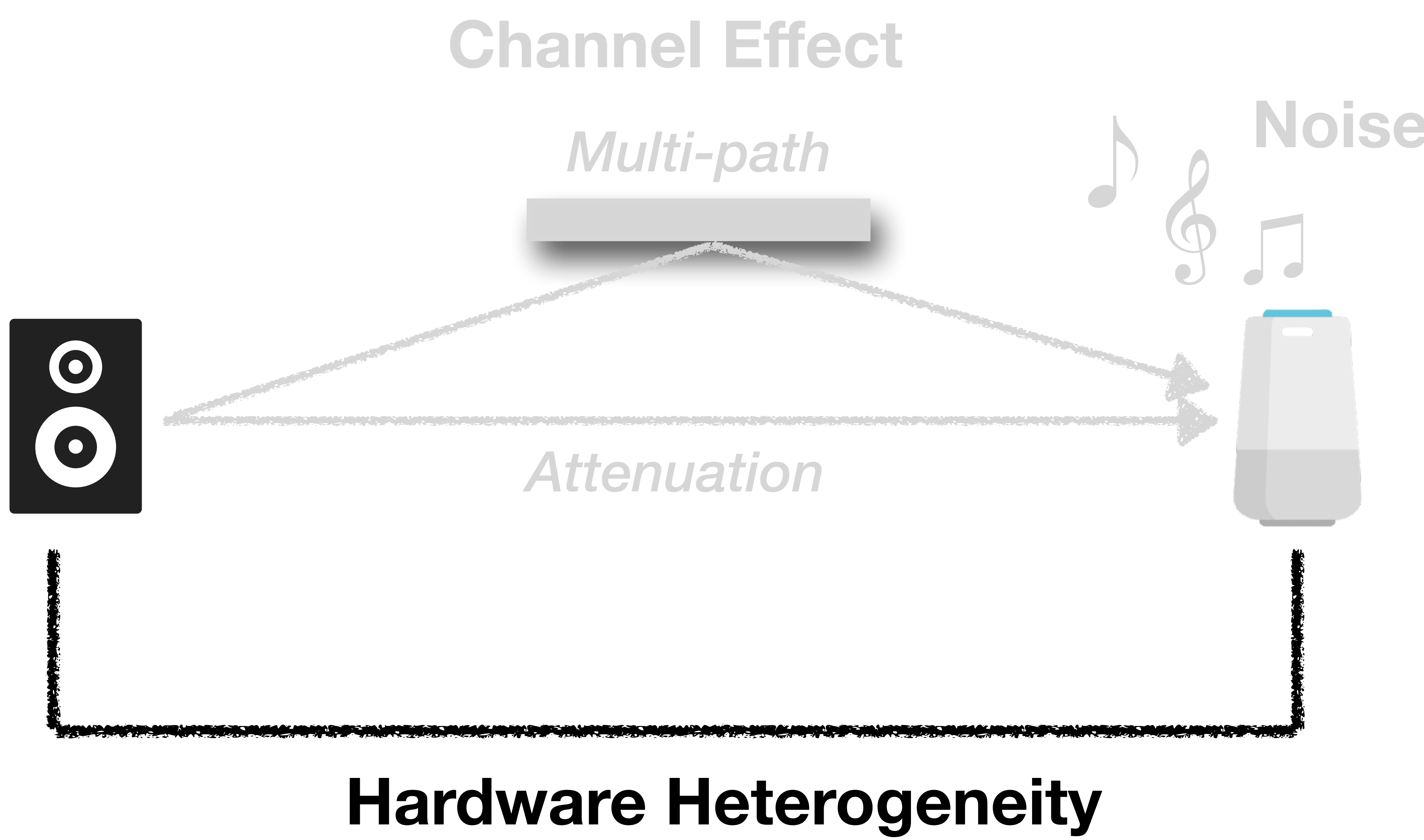


Attenuation

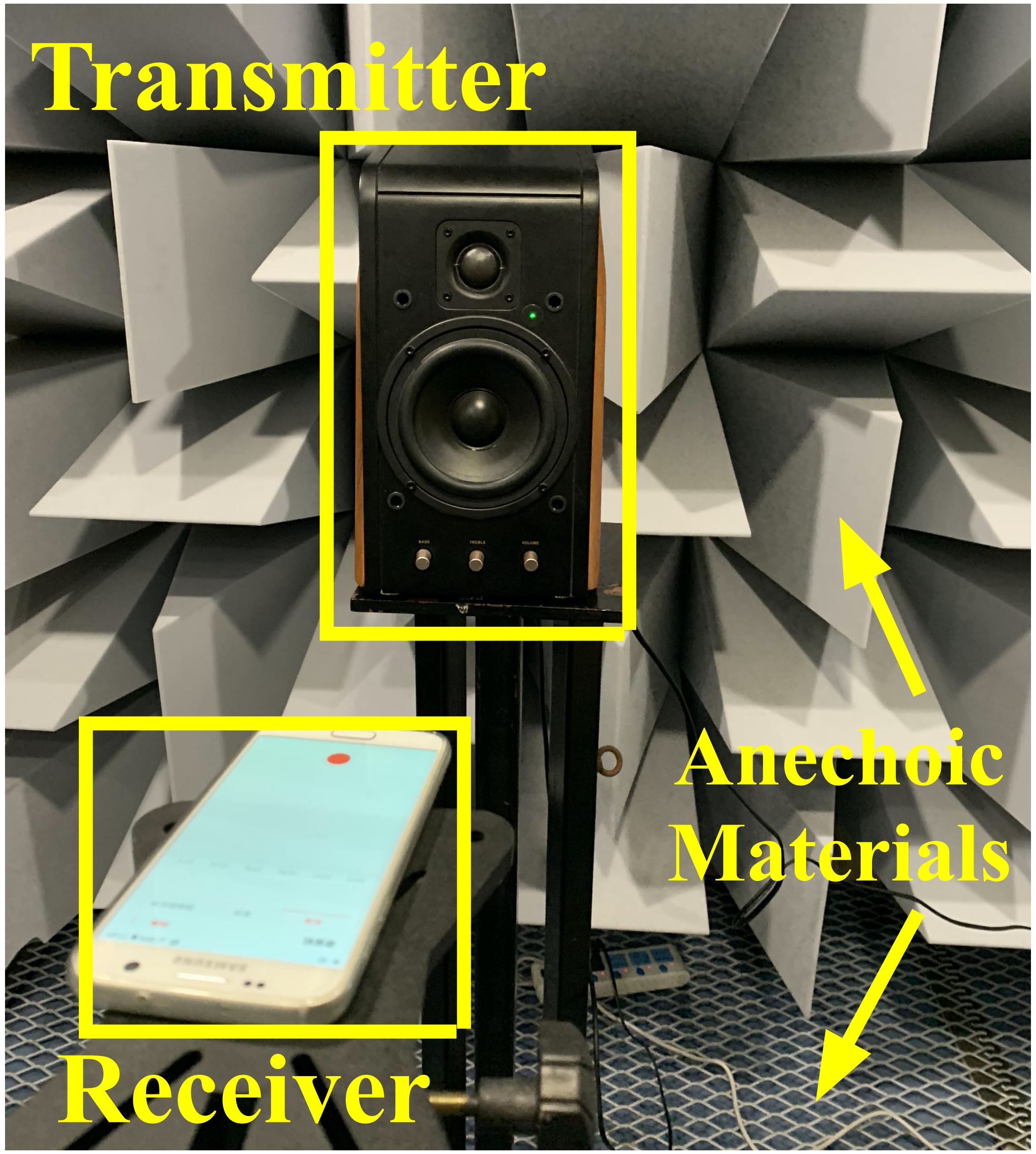


No frequency-selectivity, doesn’t matter at all!

Understand Over-the-air Attack

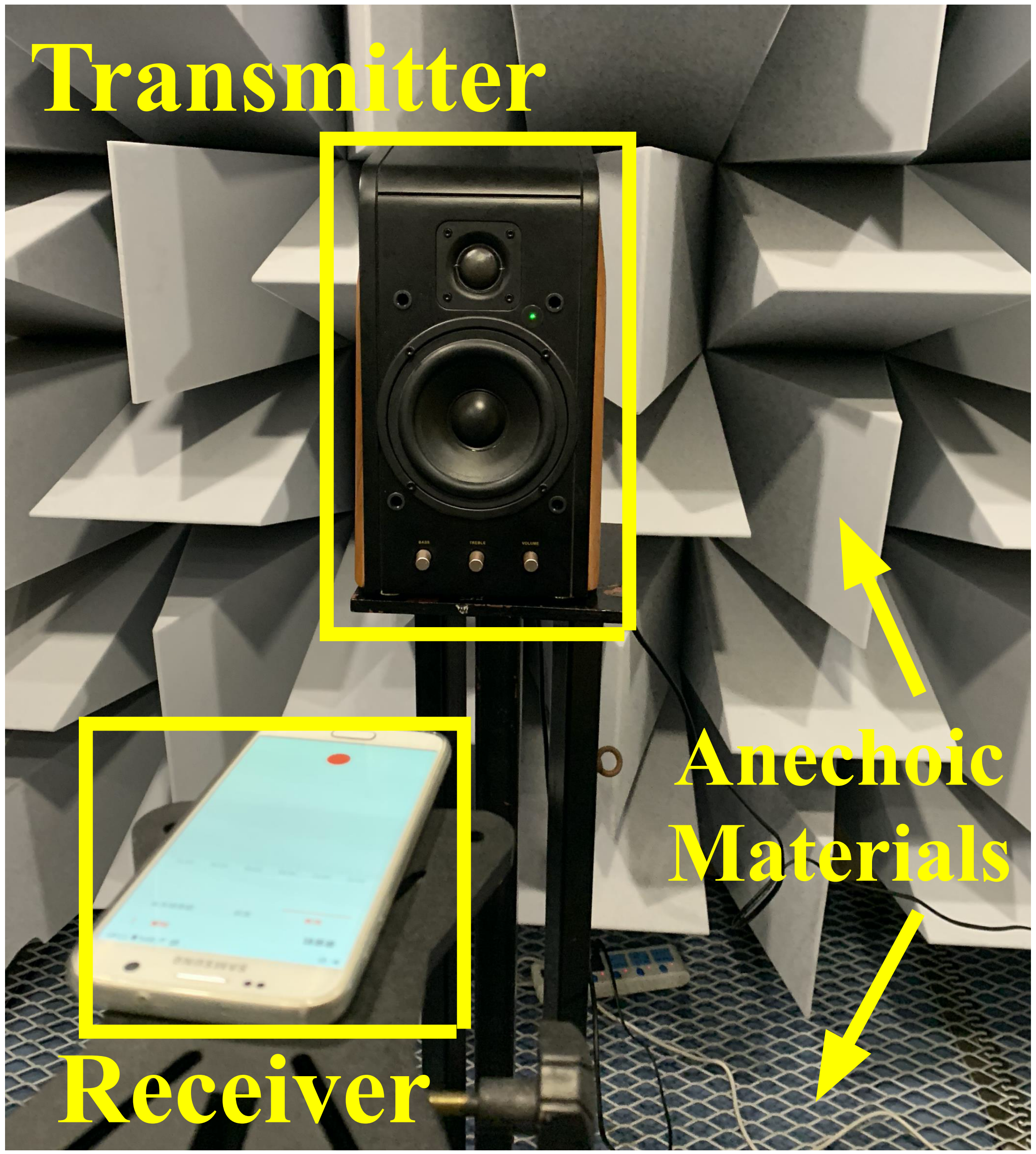


Hardware Heterogeneity

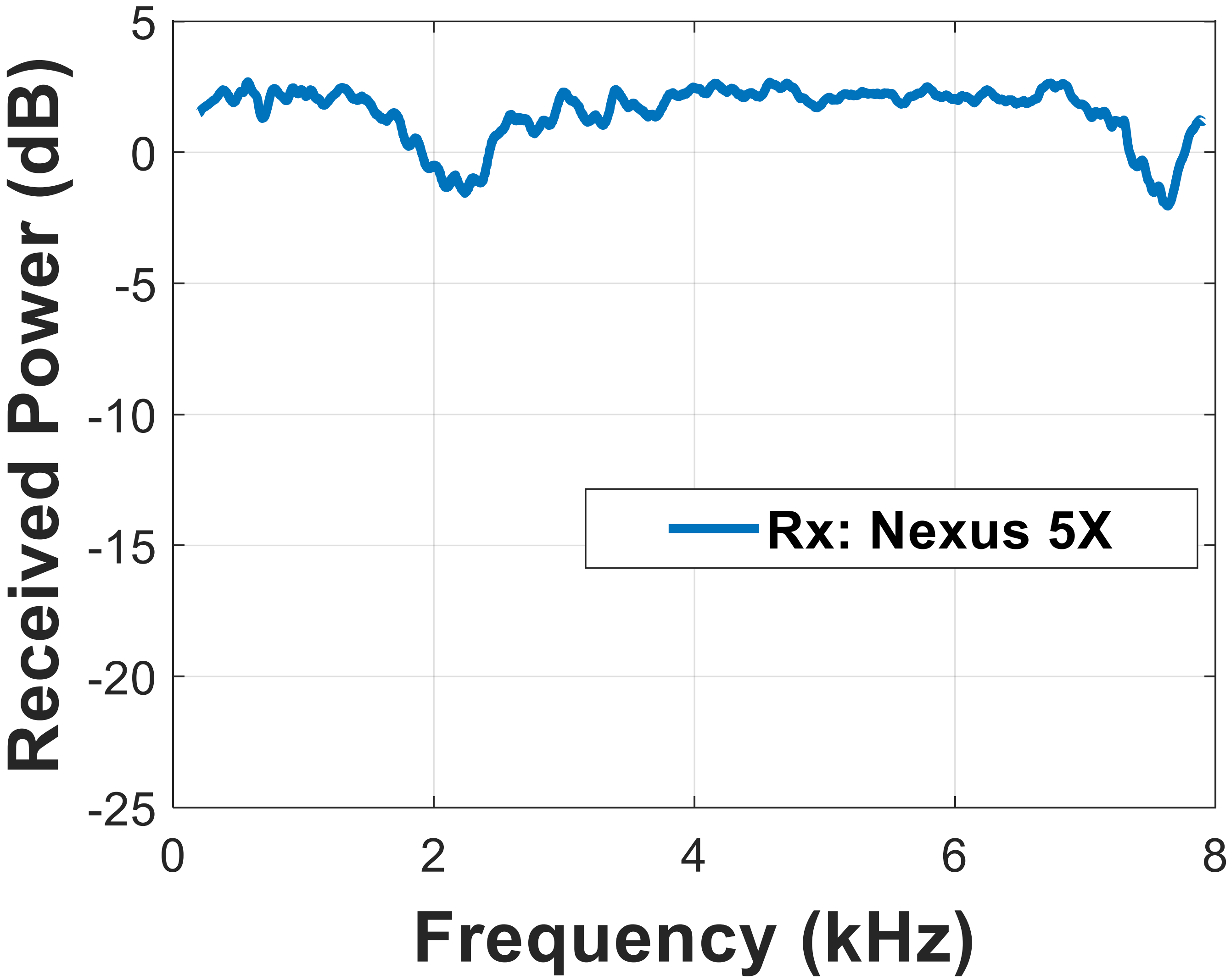


Anechoic Chamber Testing

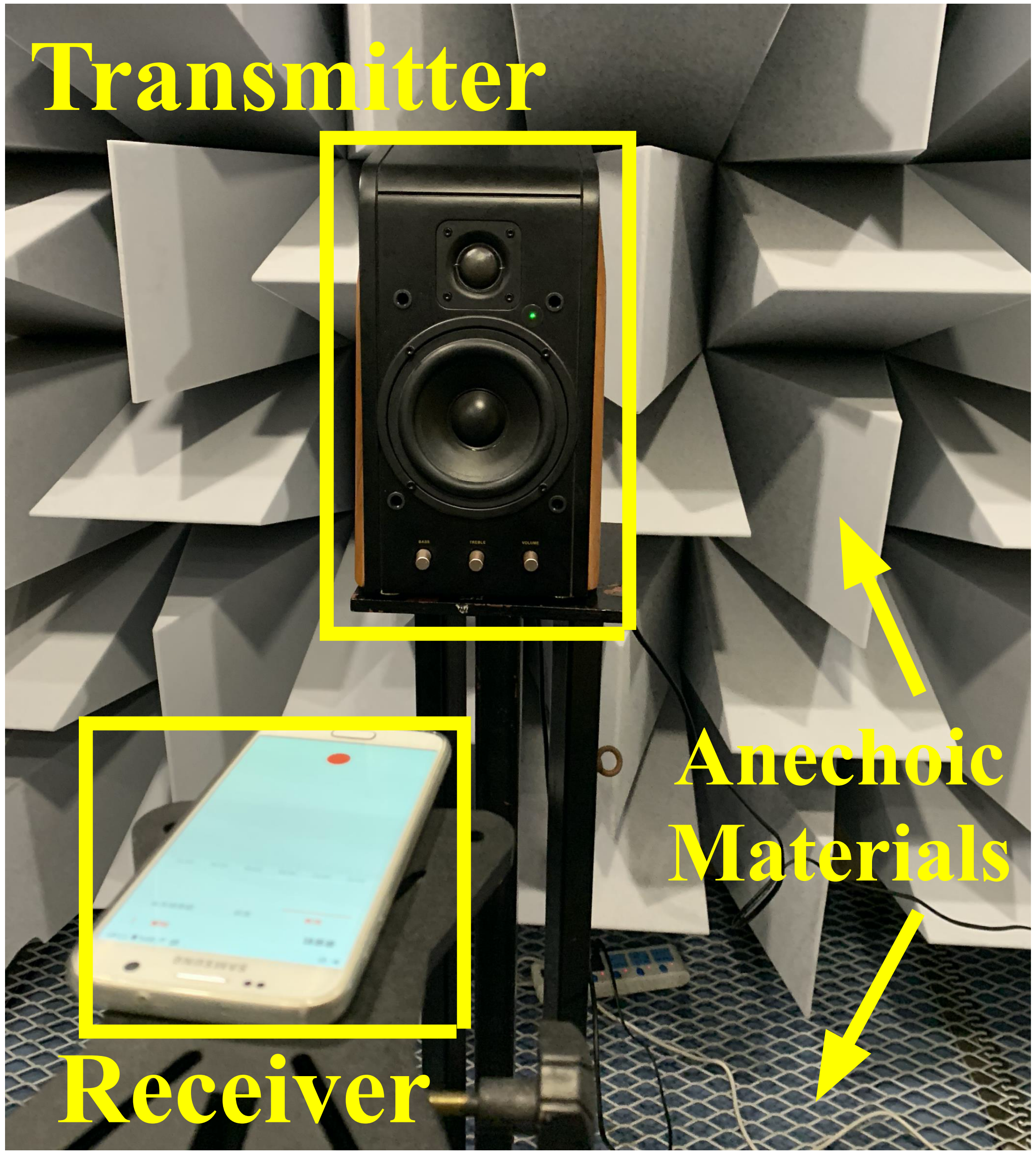
Hardware Heterogeneity



Anechoic Chamber Testing



Hardware Heterogeneity



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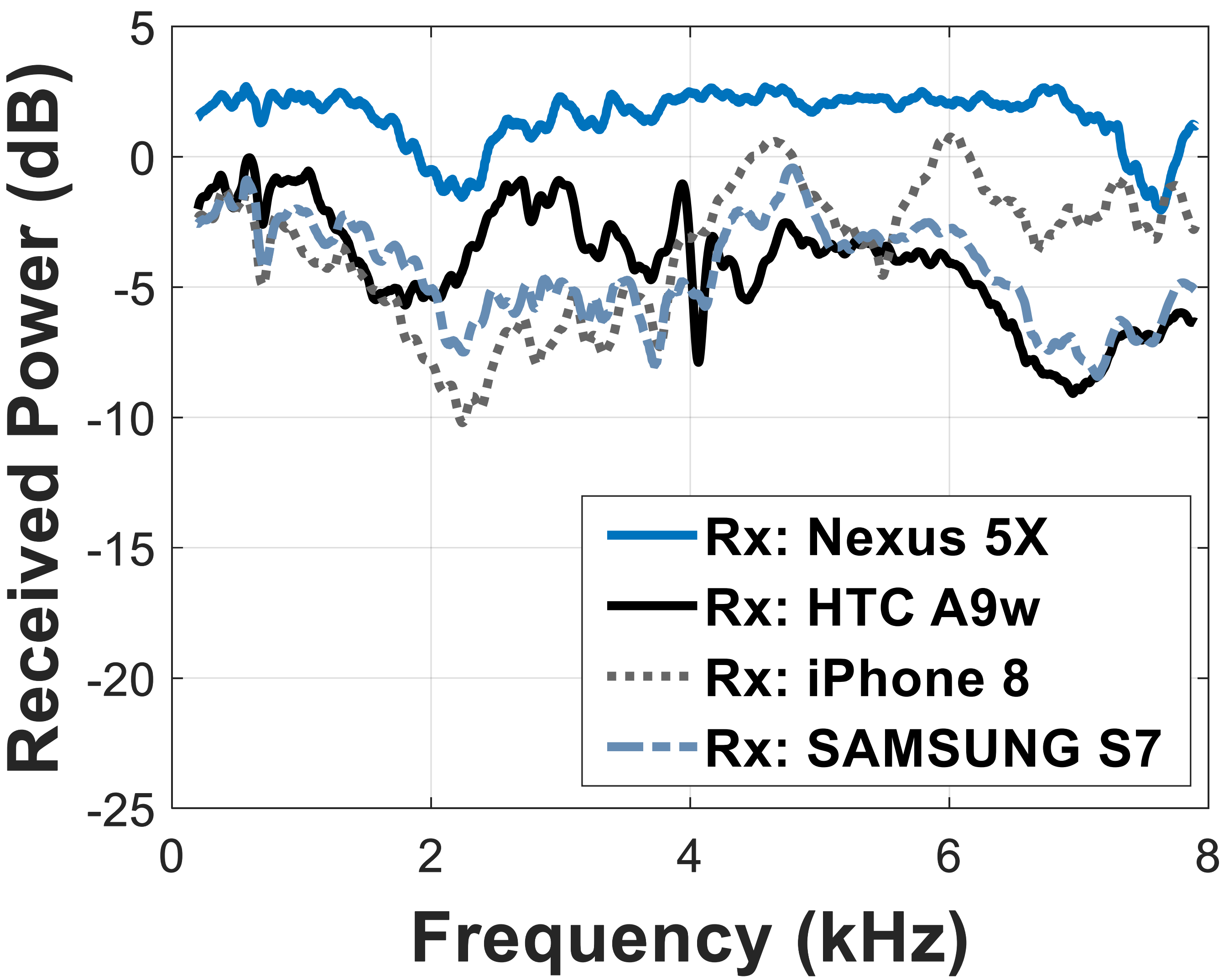
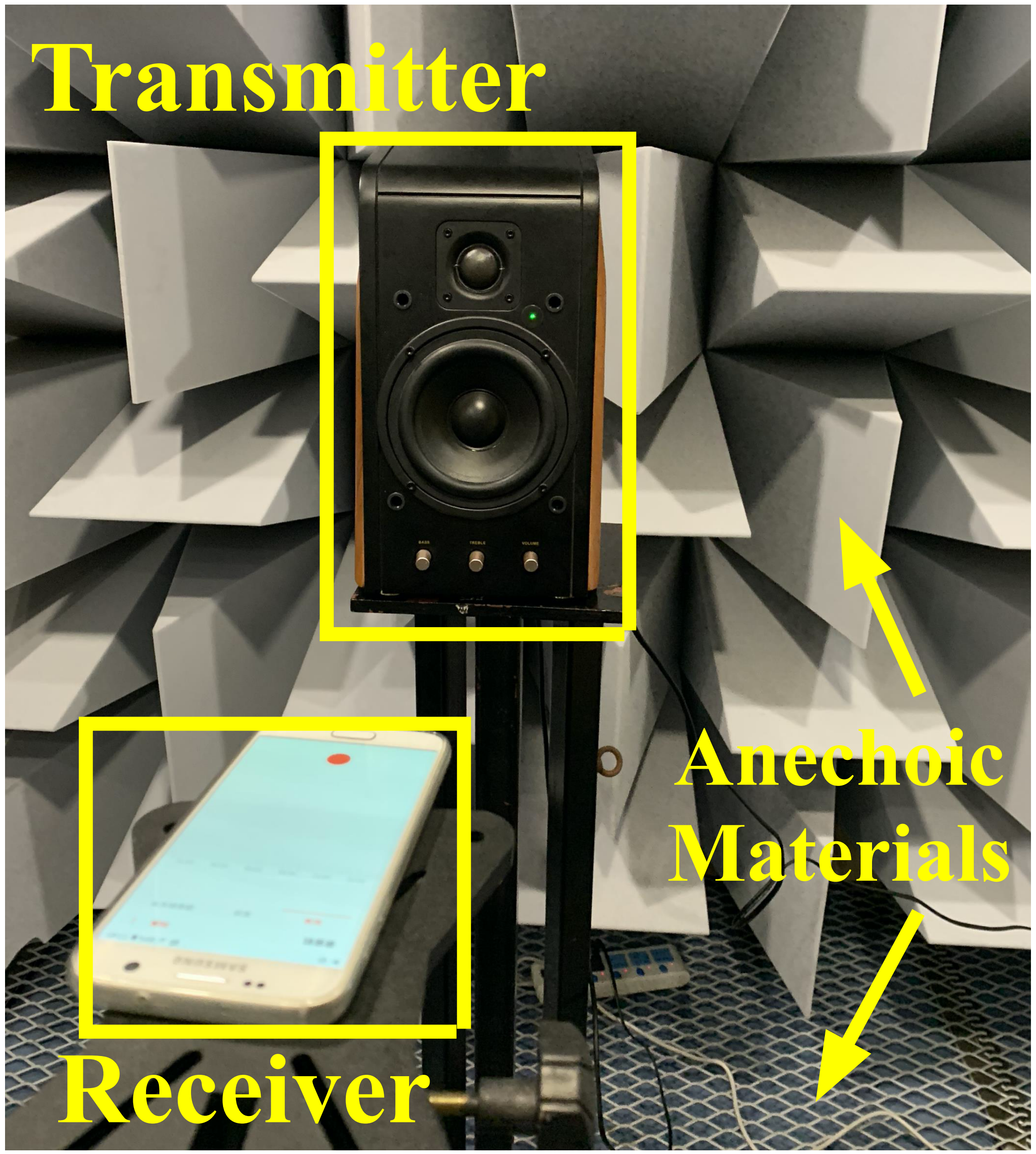
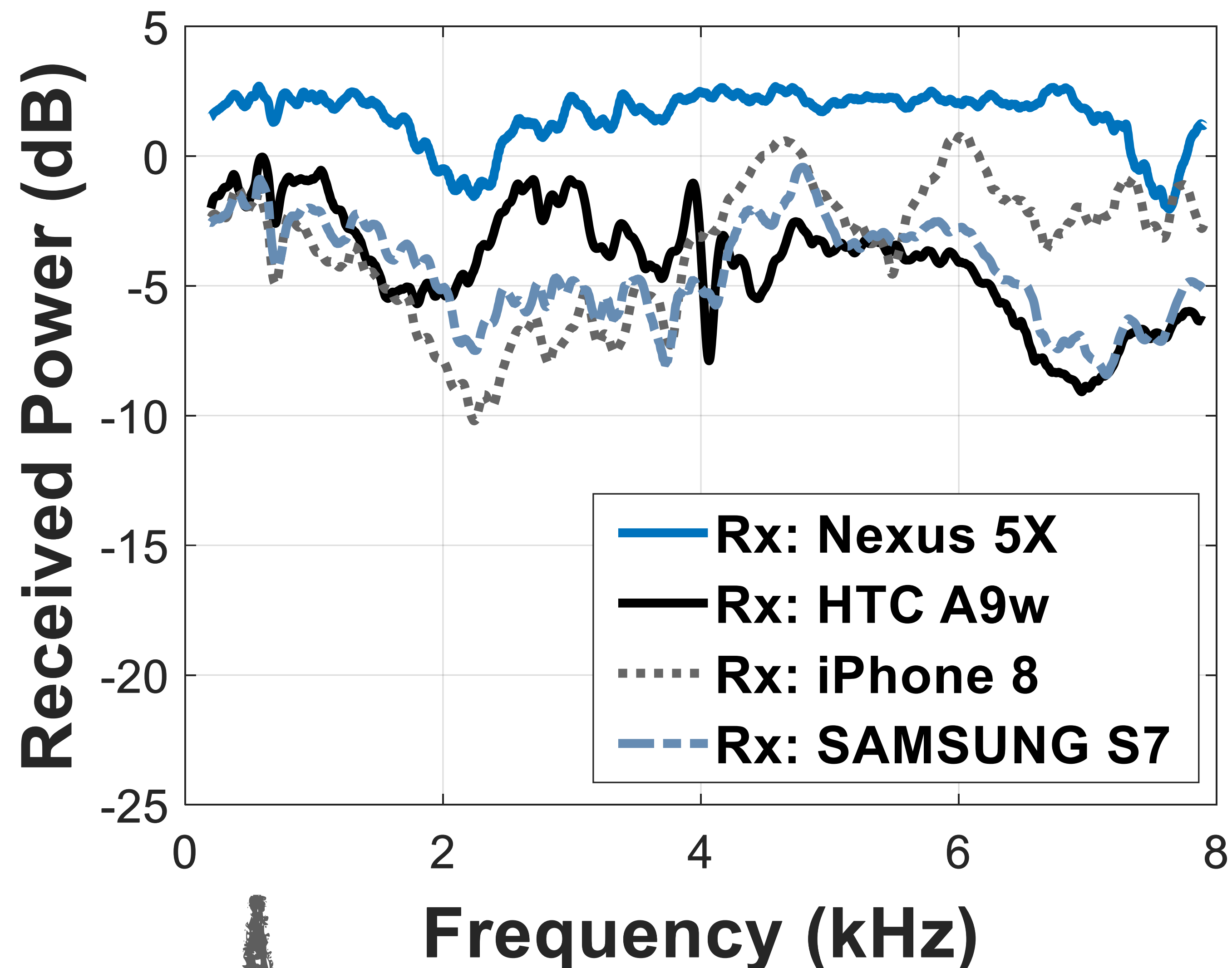


Hardware Heterogeneity

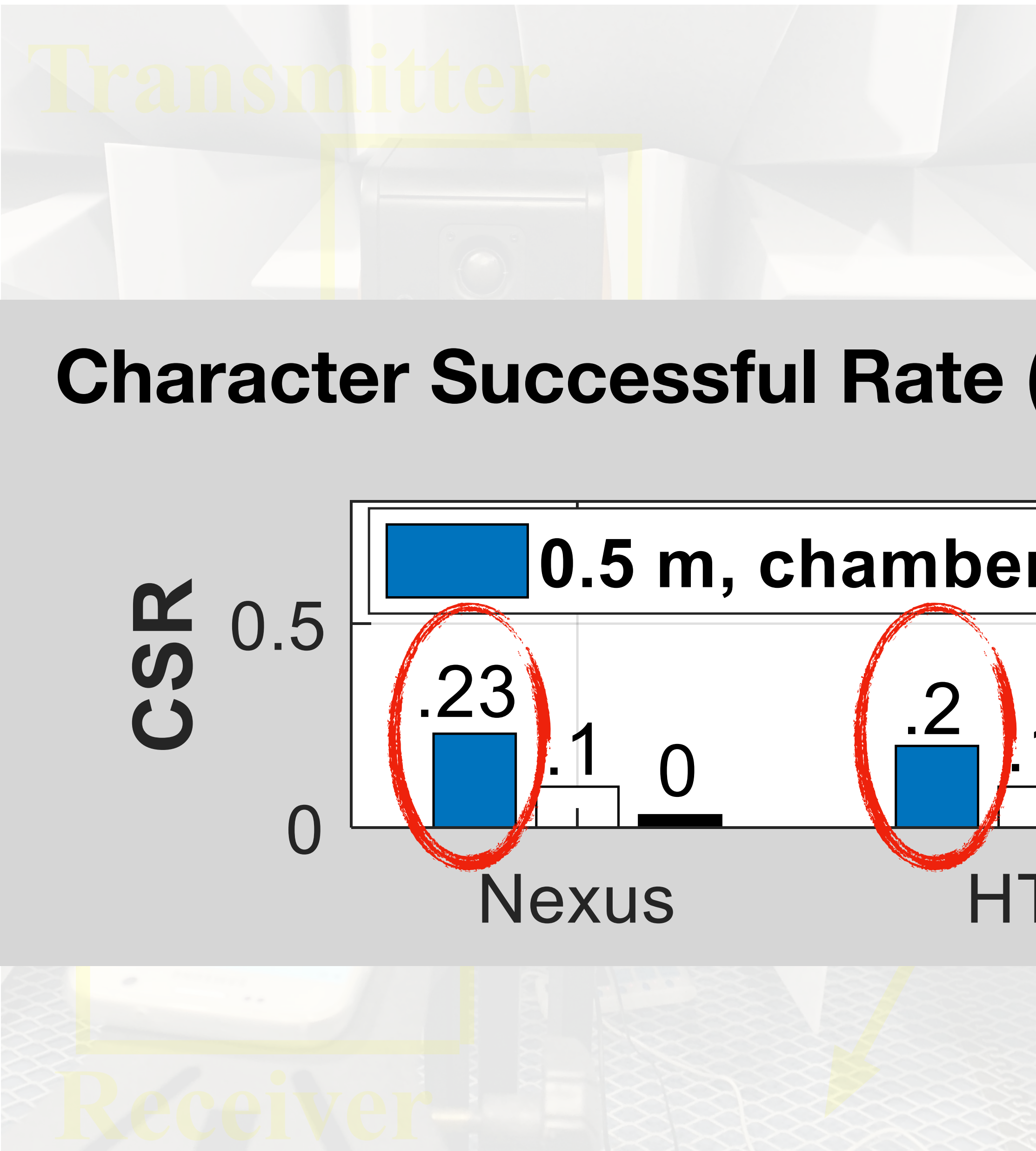


Anechoic Chamber Testing



Not strong, device's inherent feature, compensable!

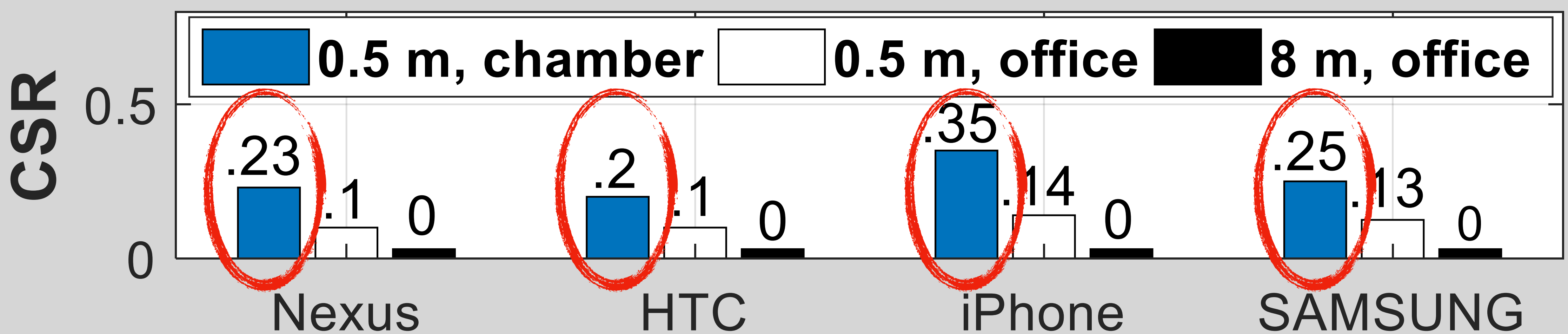
Hardware Heterogeneity



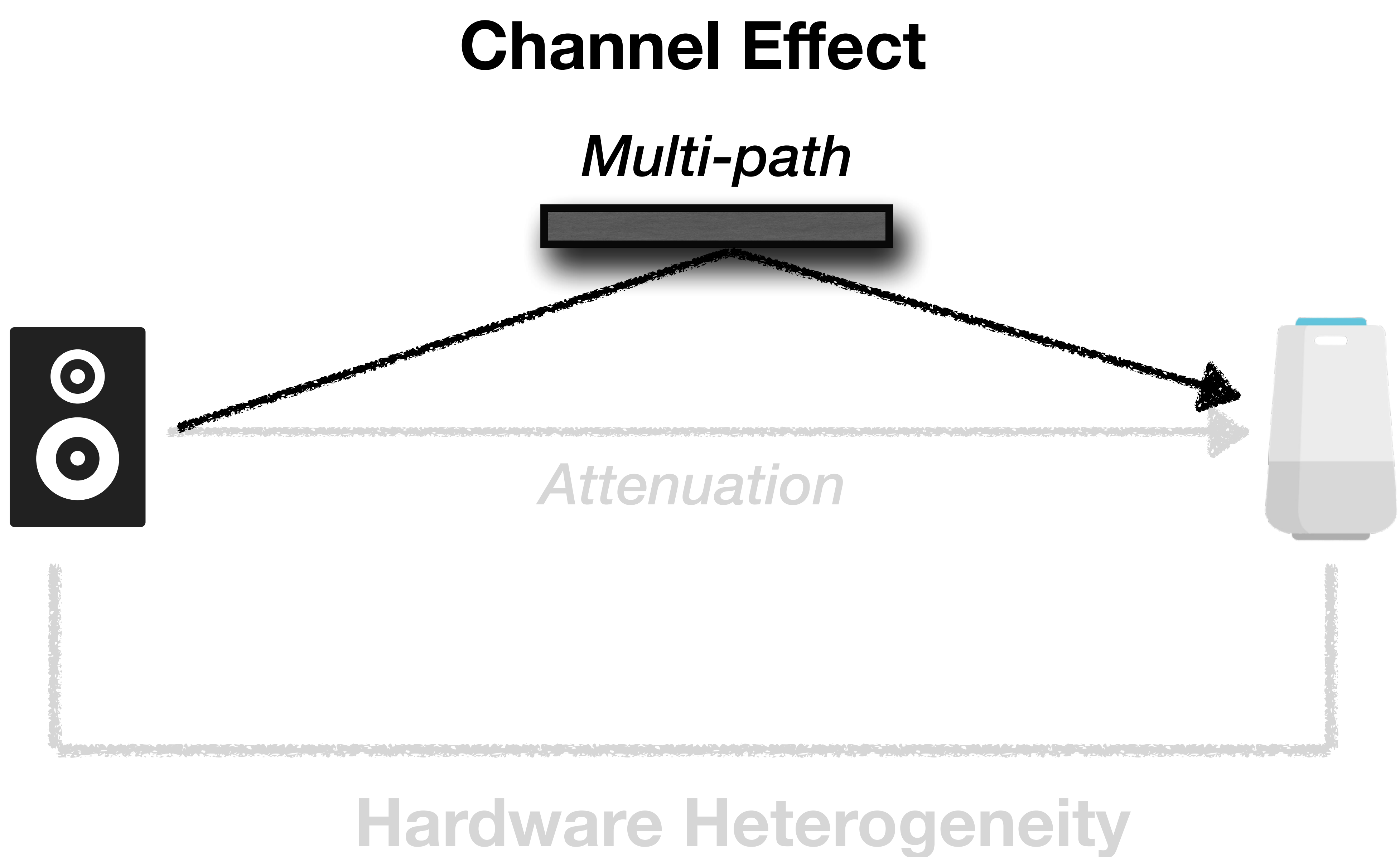
Anechoic Chamber Testing

Static, predictable and compensable!

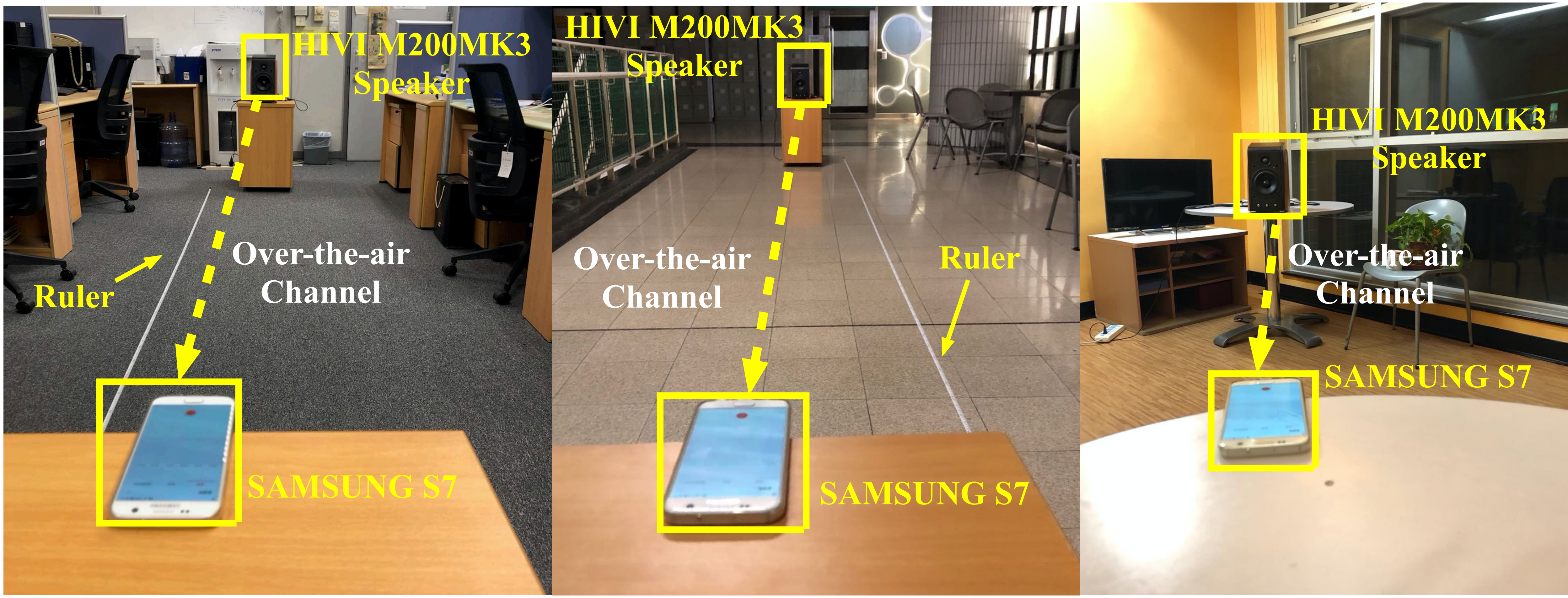
Character Successful Rate (CSR):



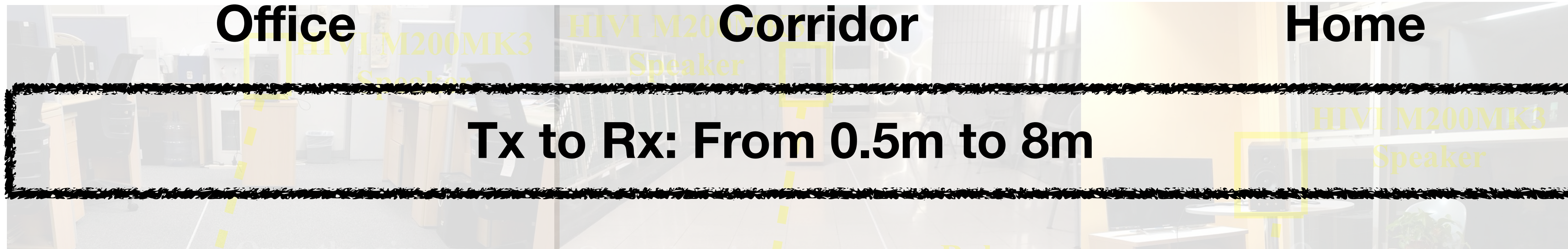
Understand Over-the-air Attack



Multi-path


HIVI M200MK3
Speaker
Over-the-air
Channel
Ruler
SAMSUNG S7
HIVI M200MK3
Speaker
Over-the-air
Channel
Ruler
SAMSUNG S7
HIVI M200MK3
Speaker
Over-the-air
Channel
SAMSUNG S7

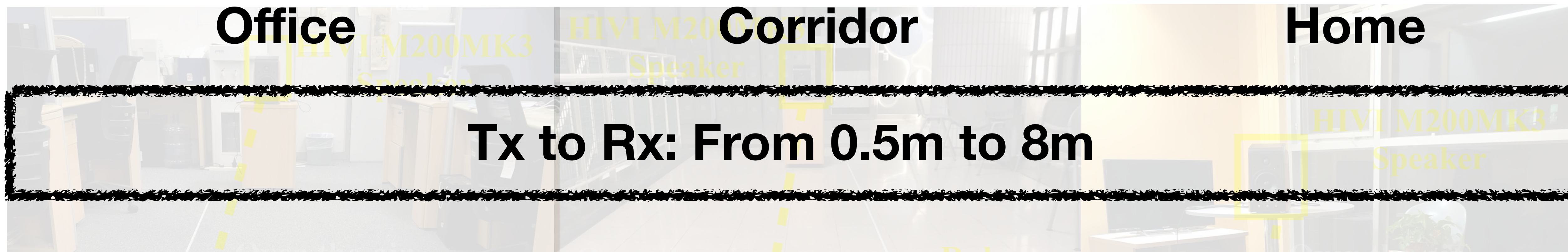
Multi-path: Near range

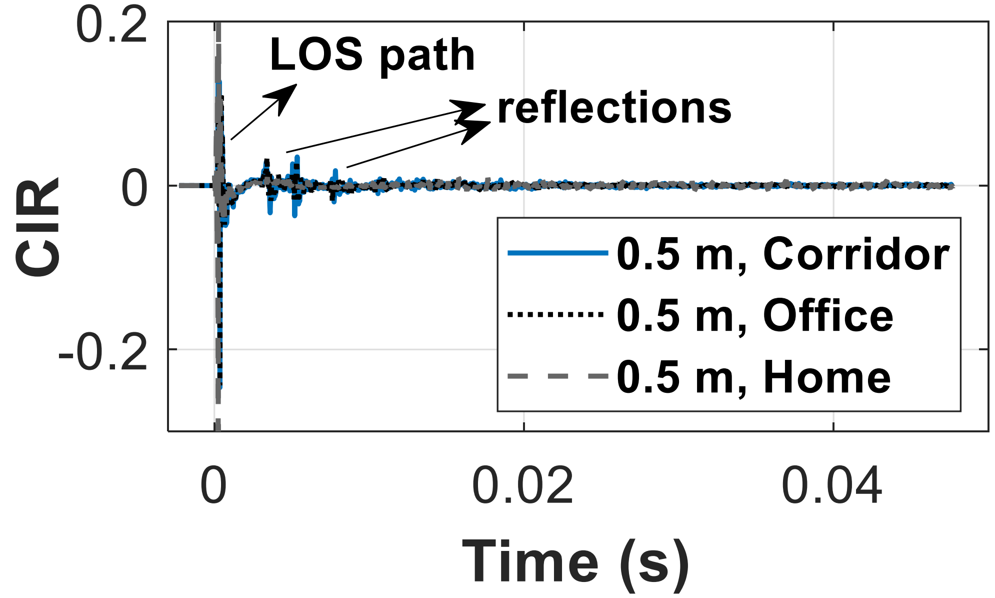


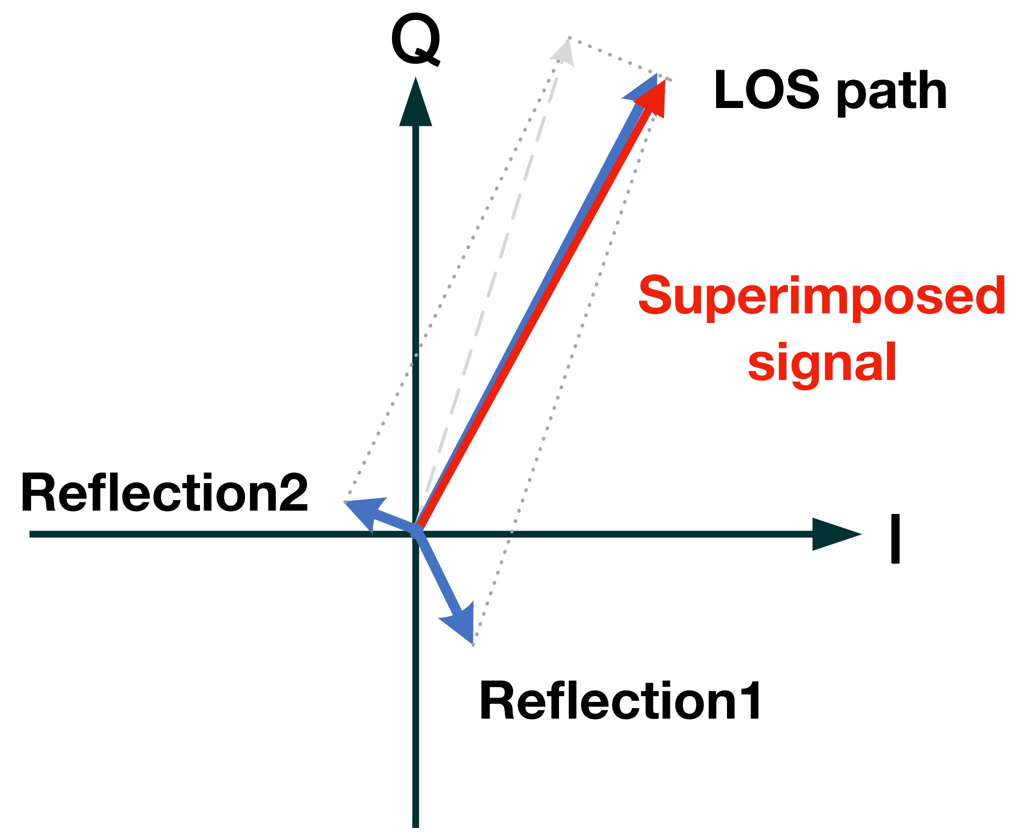
Office Corridor Home

Tx to Rx: From 0.5m to 8m

Multi-path: Near range







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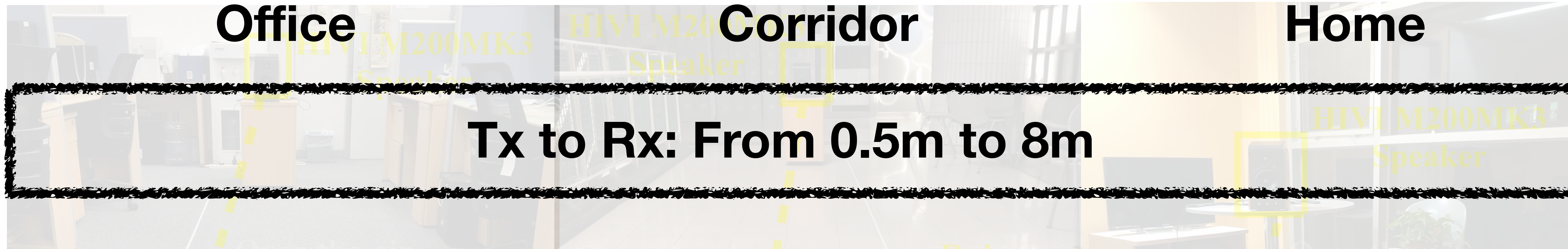
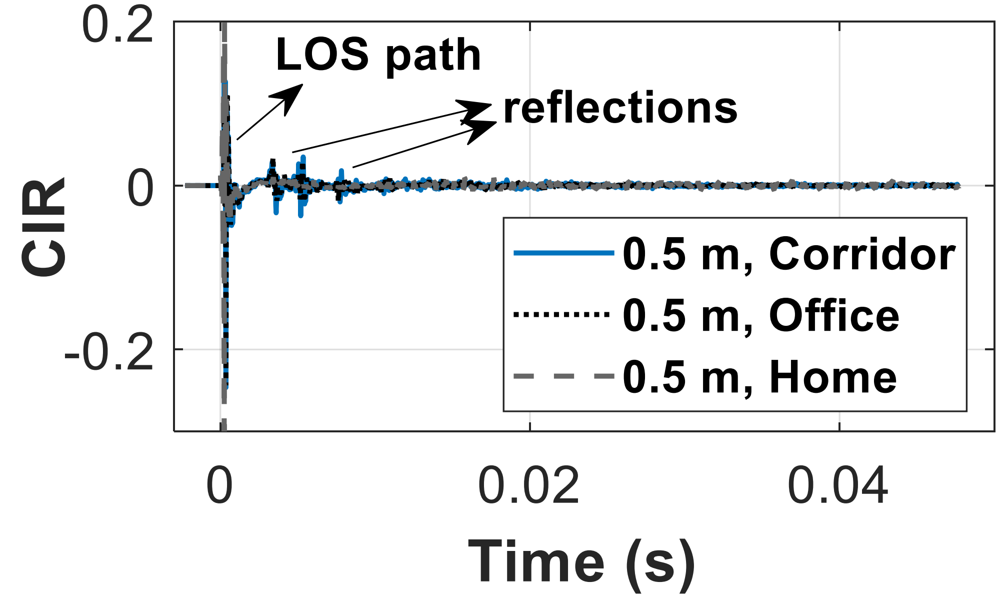
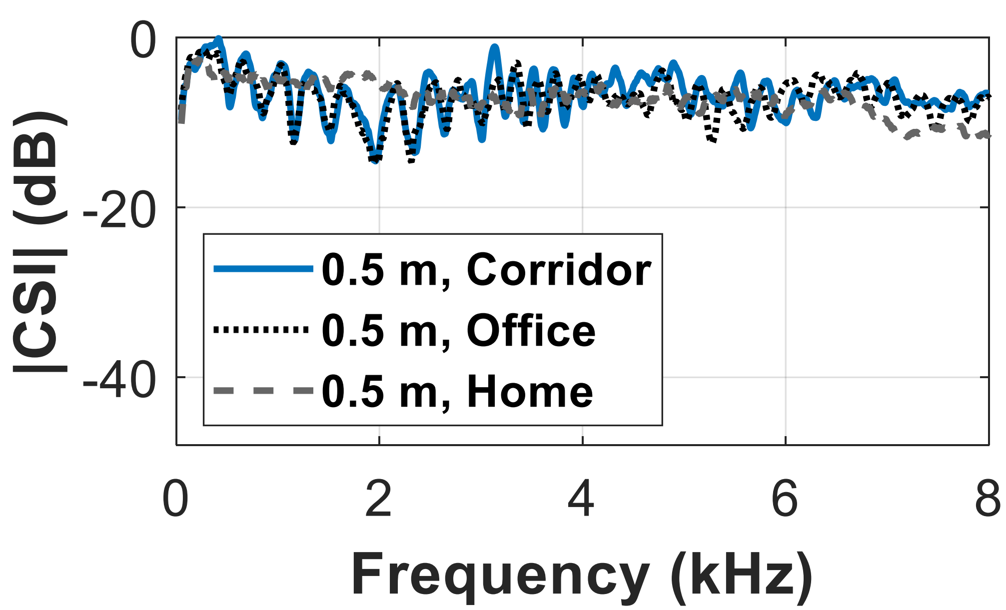
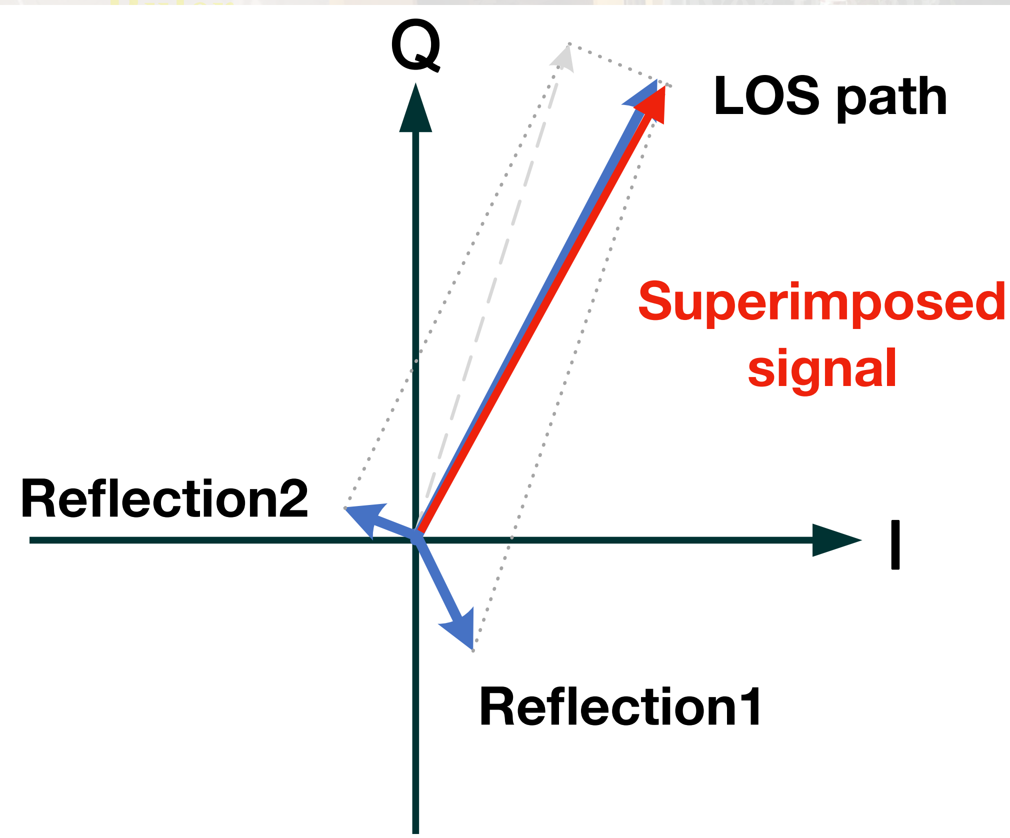
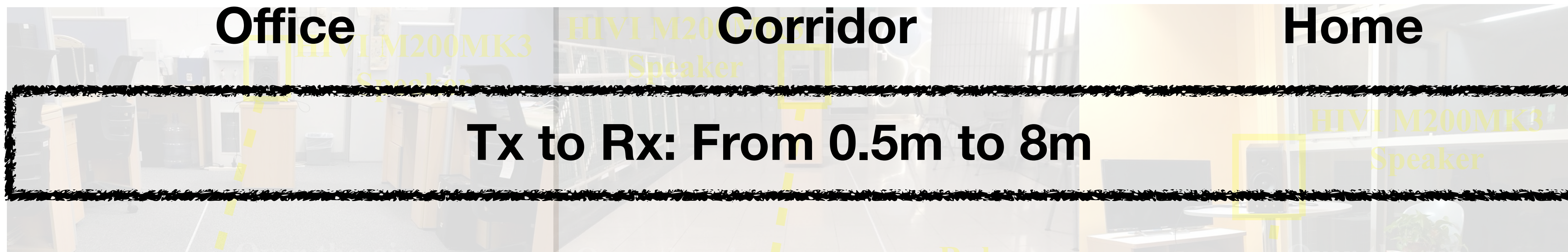


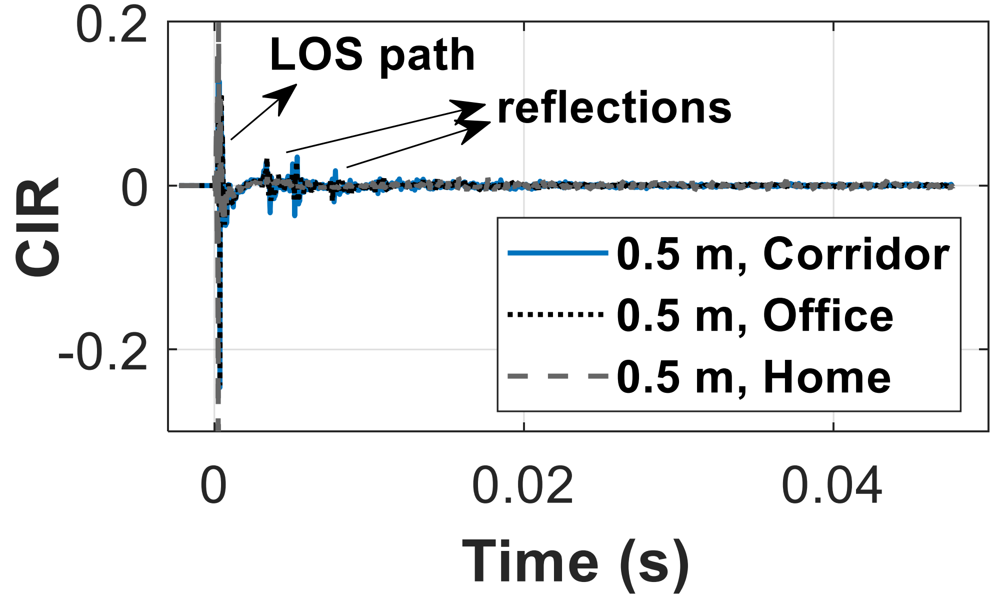


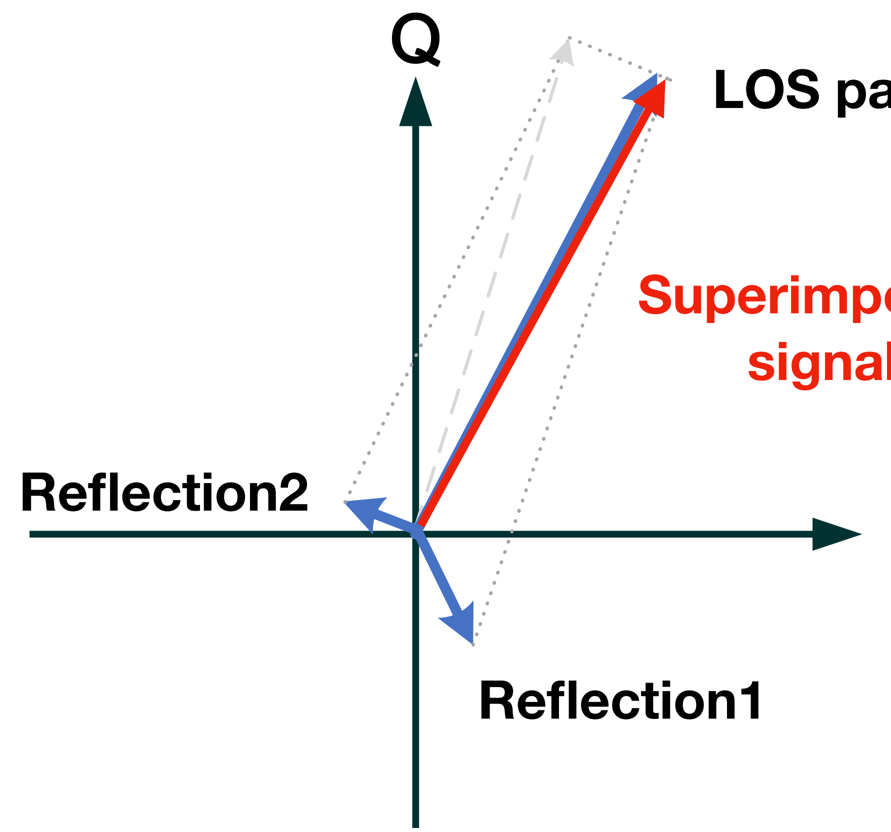


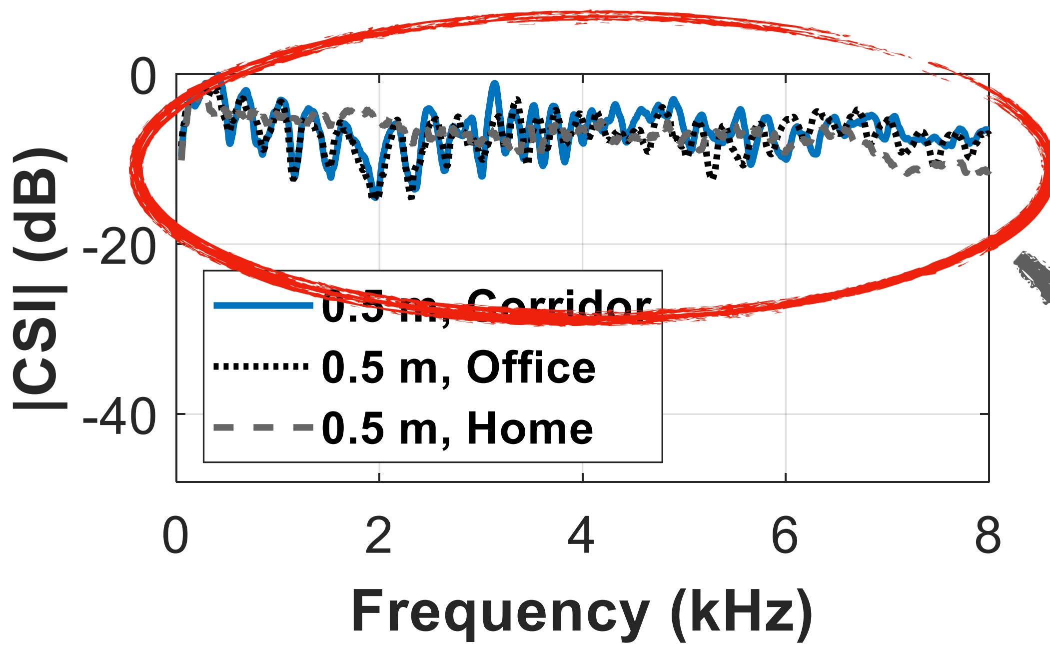


Multi-path: Near range



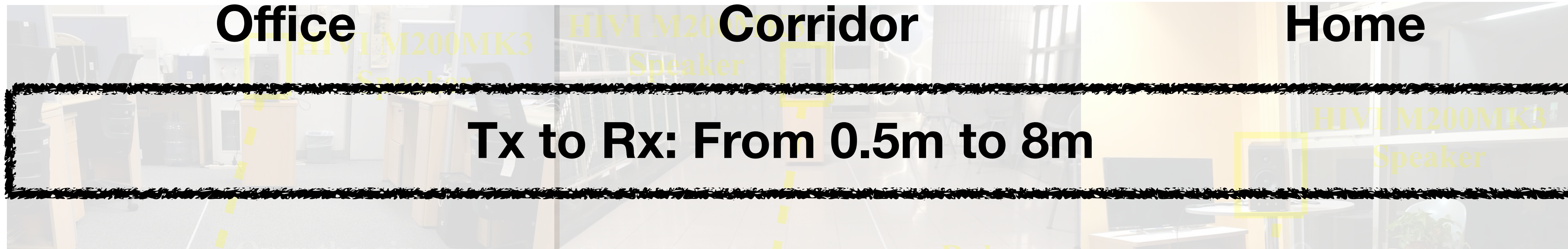






Also not strong and similar!

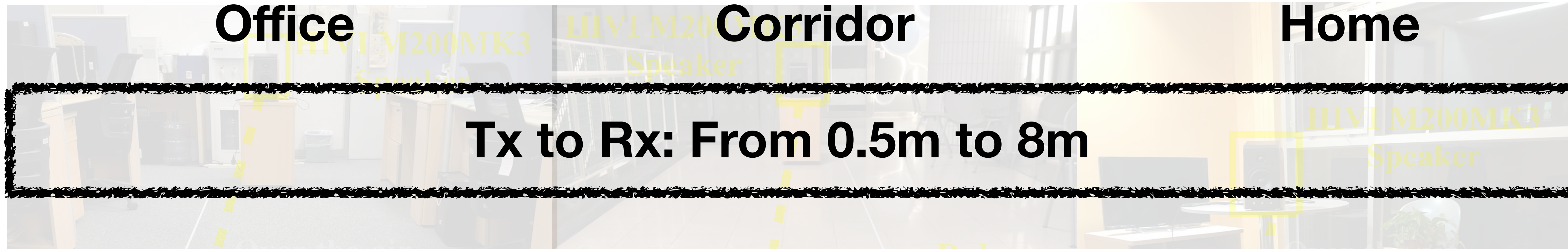
Multi-path: Long range

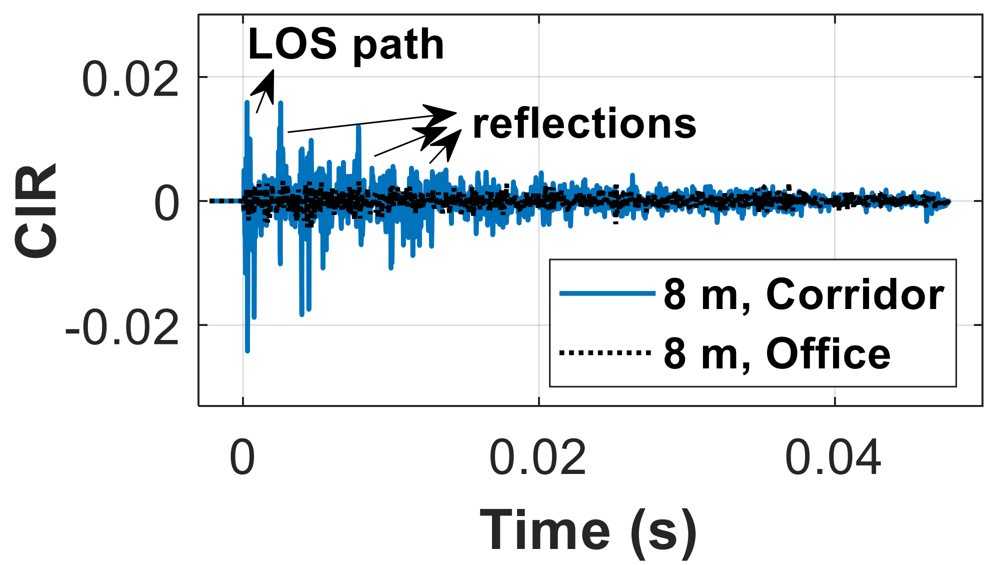


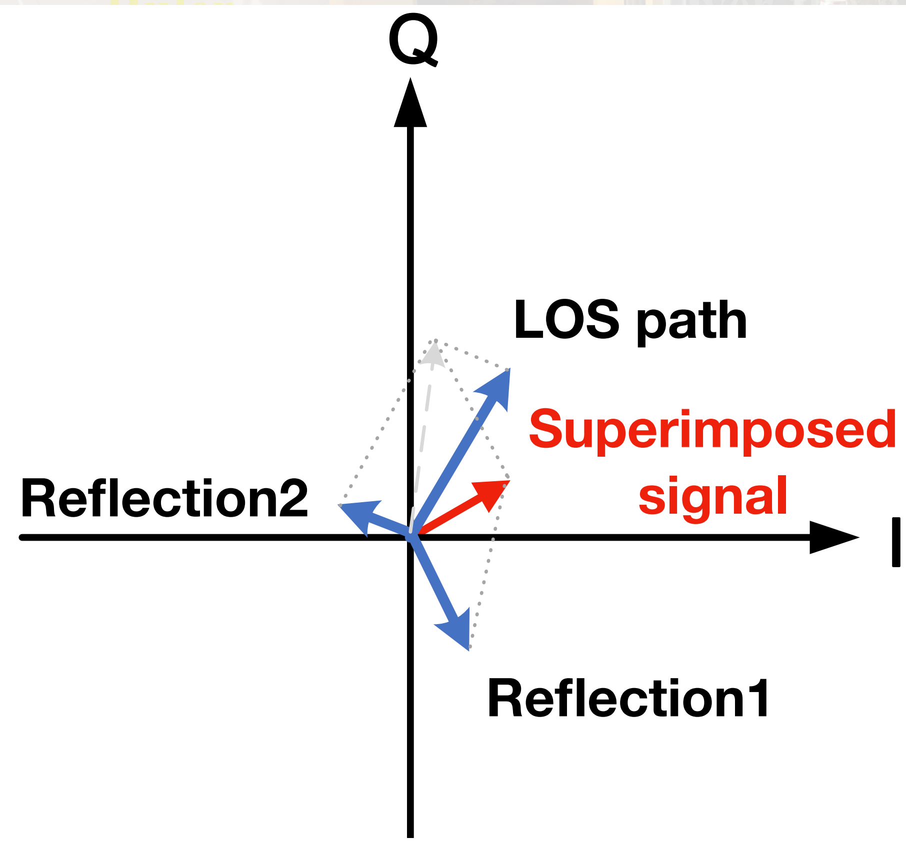
Office **Corridor** **Home**

Tx to Rx: From 0.5m to 8m

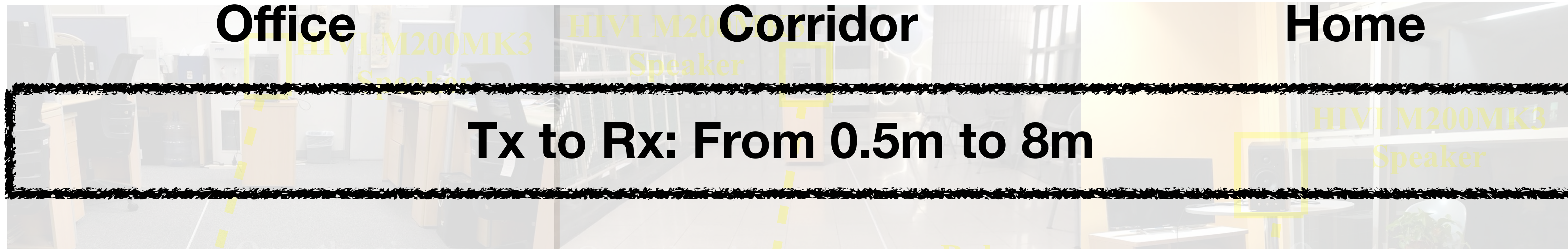
Multi-path: Long range

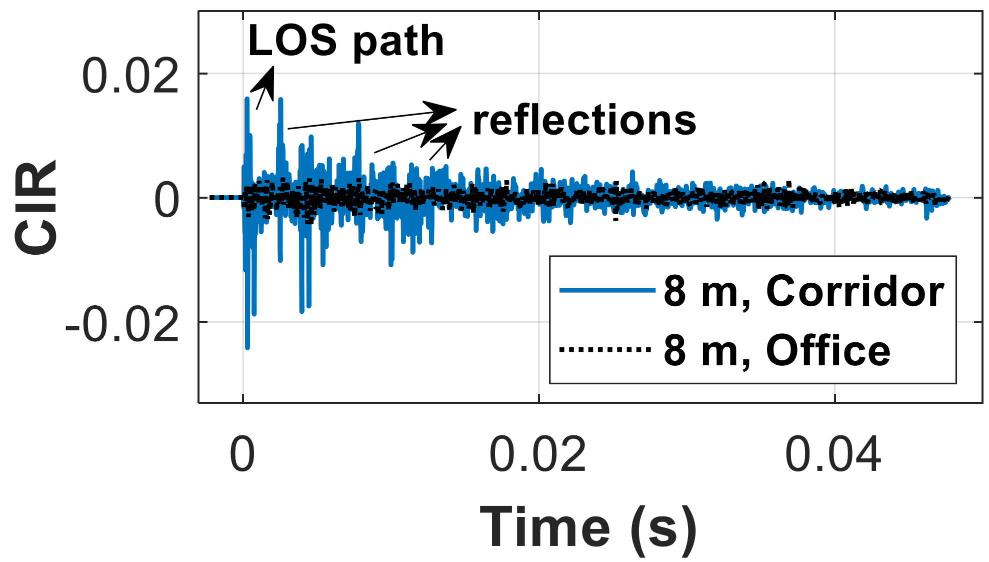


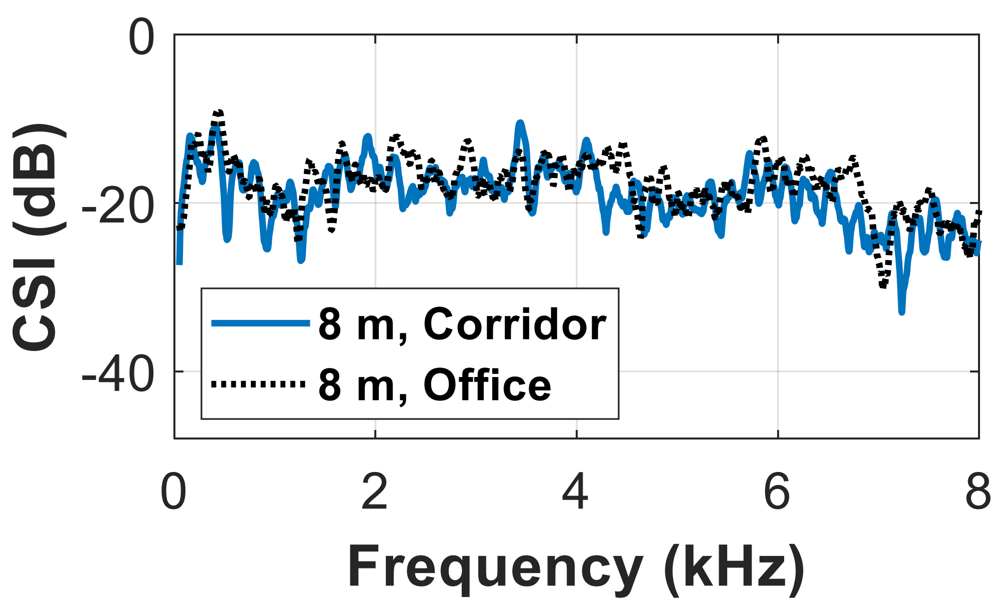


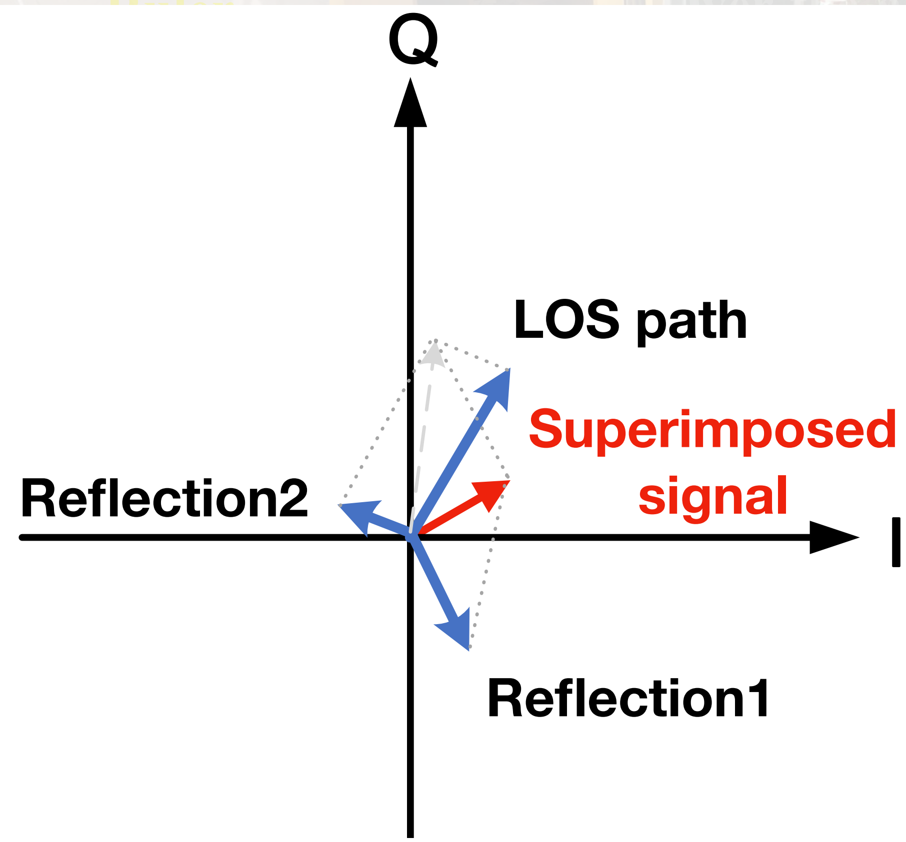


Multi-path: Long range

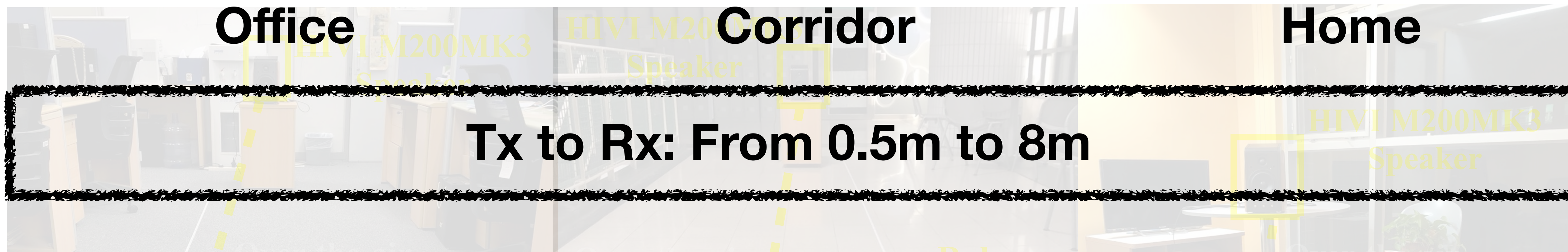


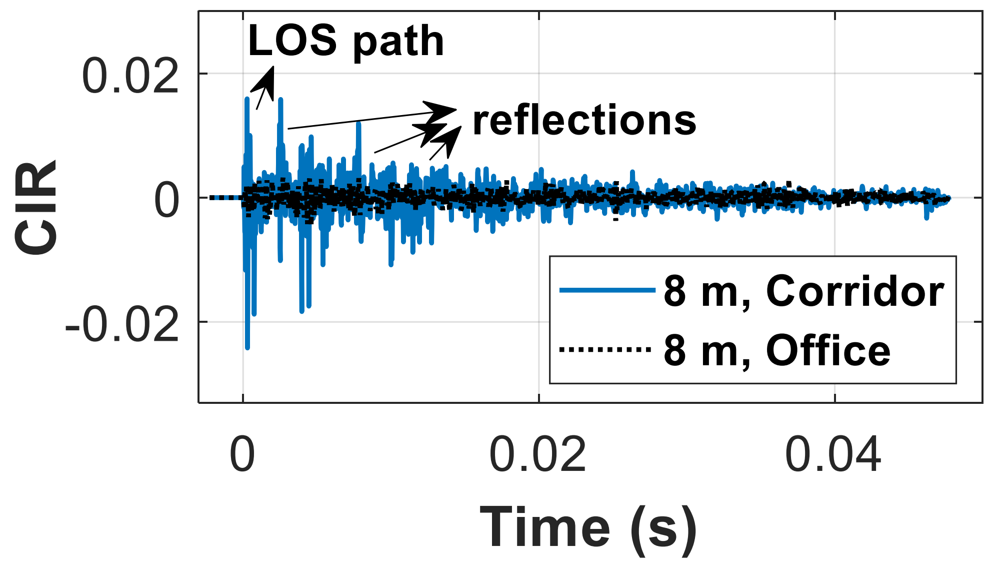


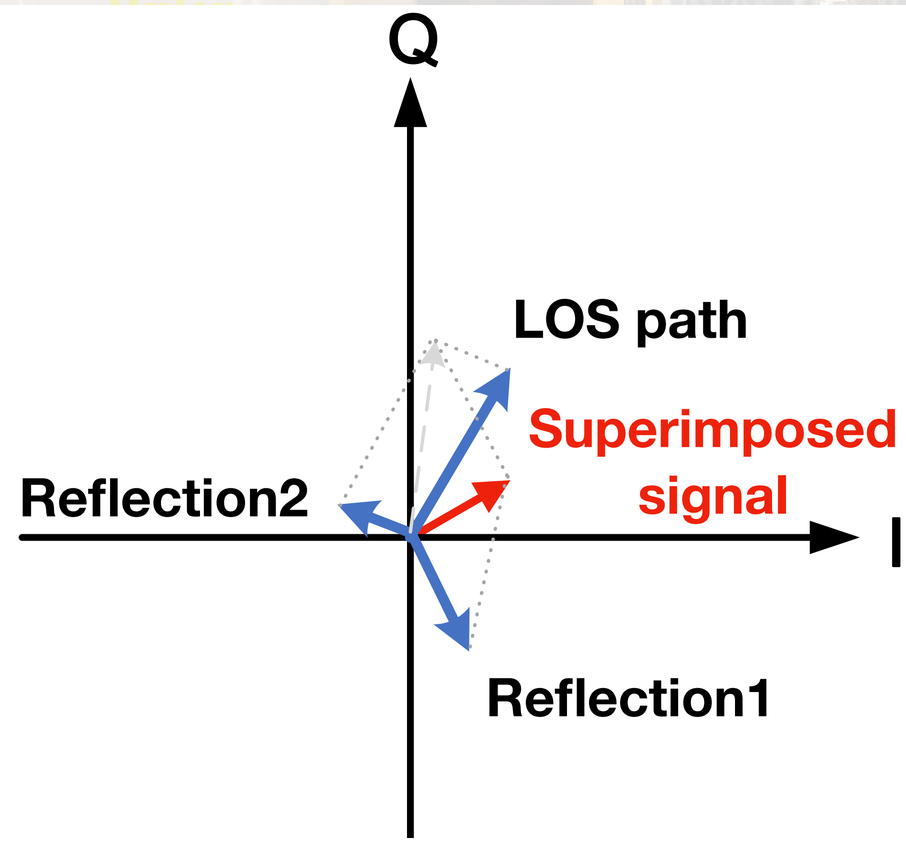


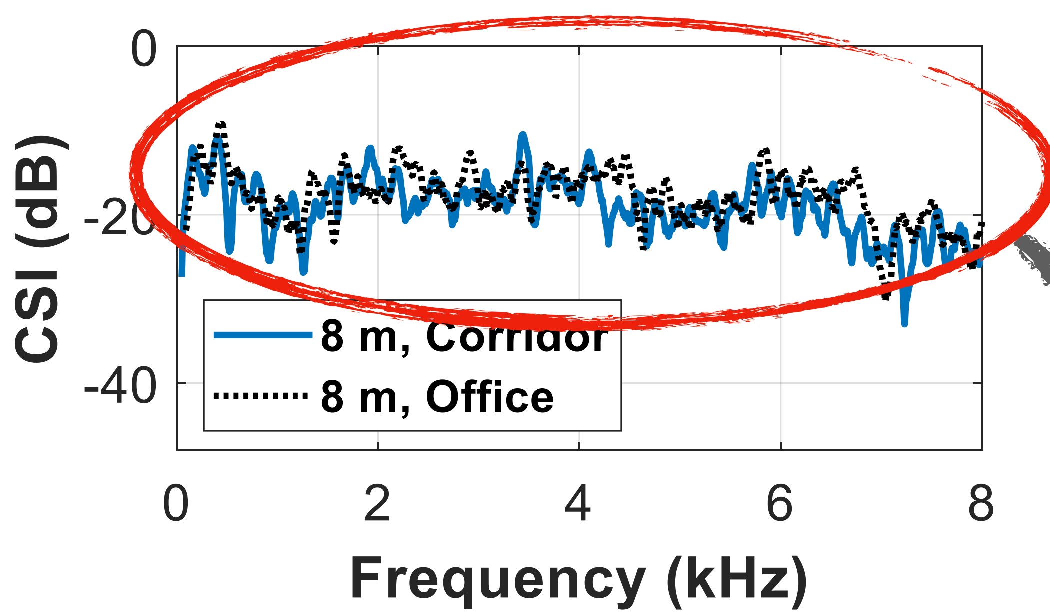


Multi-path: Long range





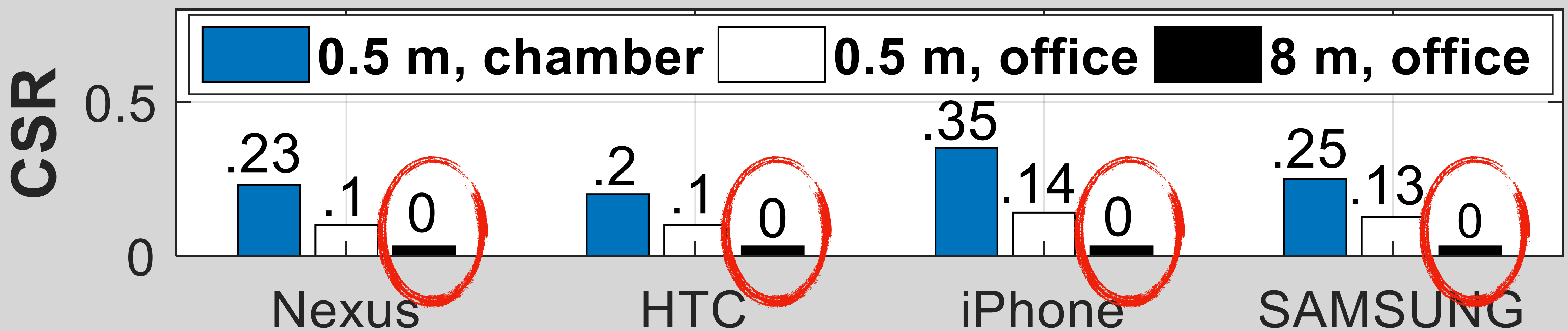




Stronger and unpredictable!

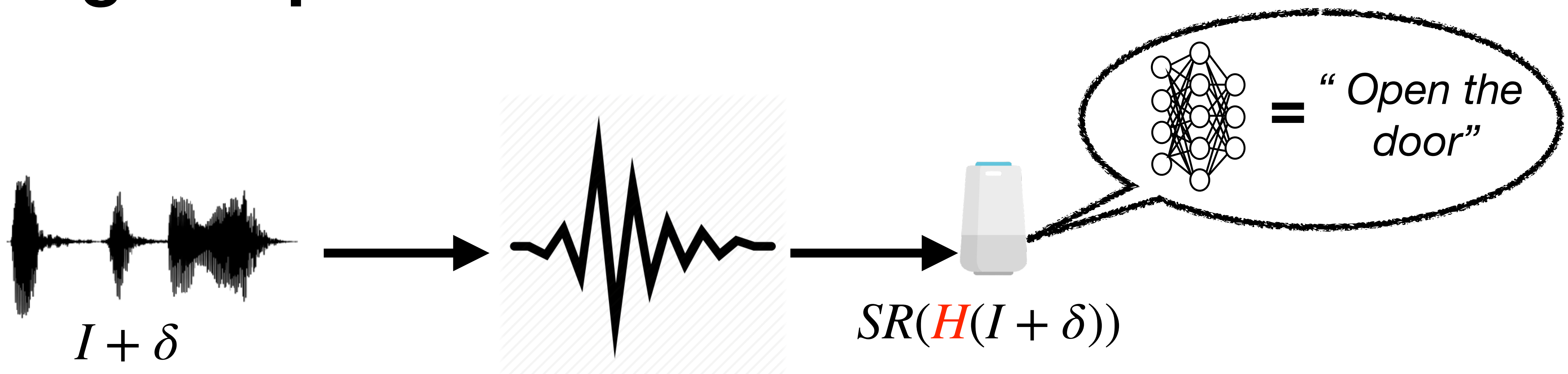
Multi-path: Long range

Character Successful Rate (CSR):



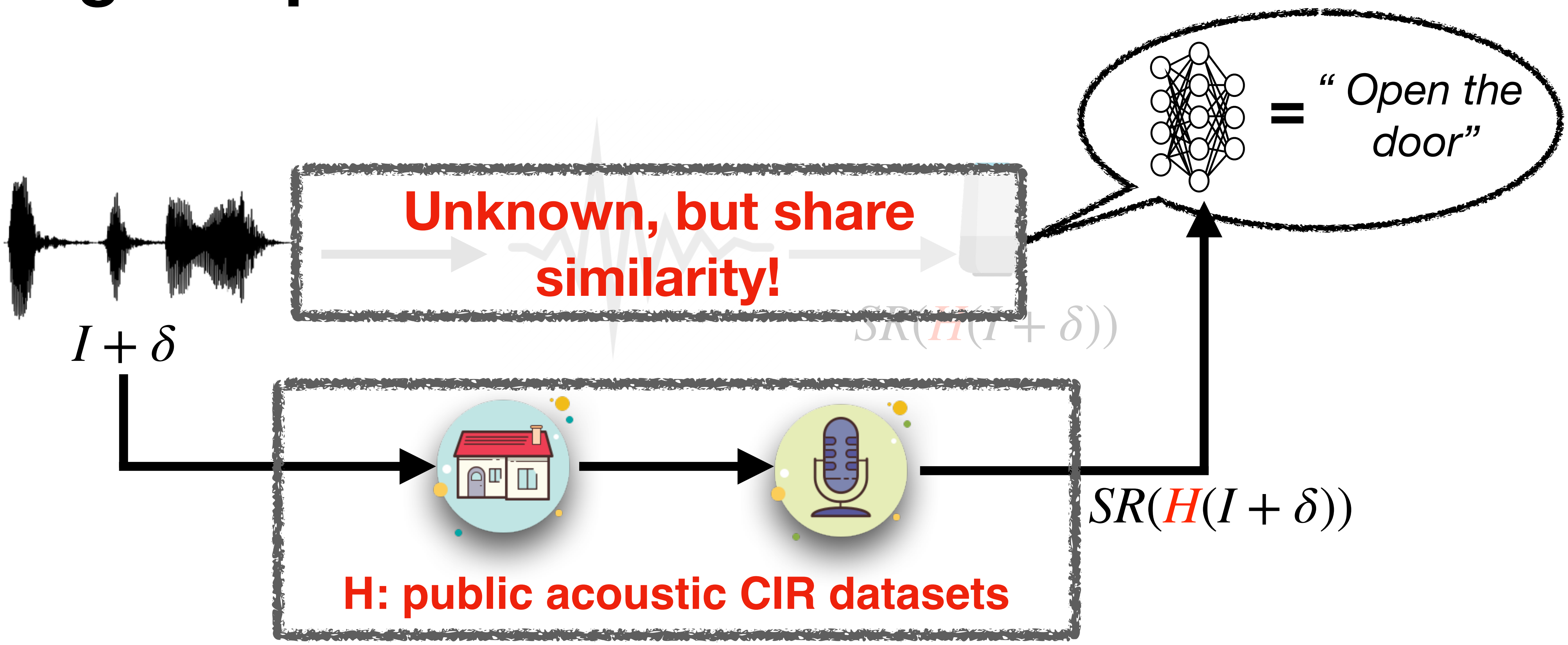
Highly unpredictable!

Design Inspiration

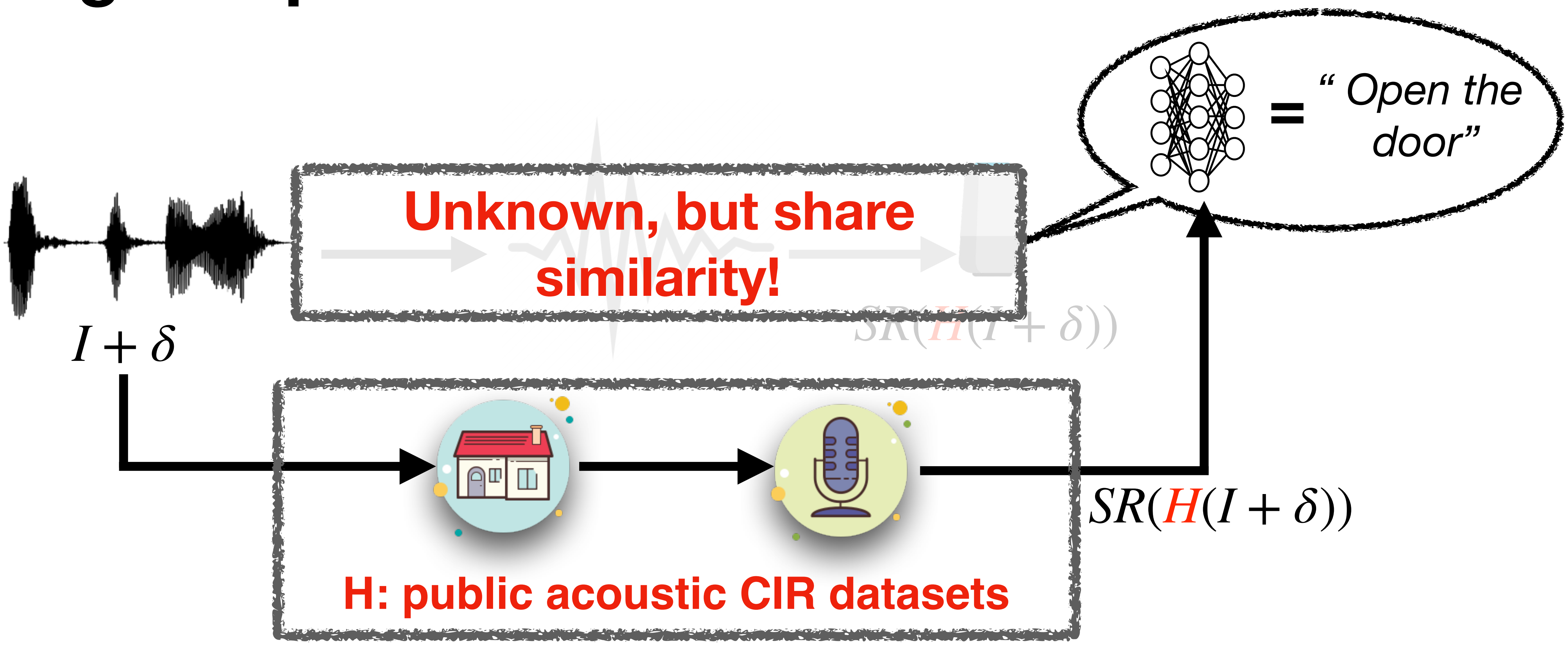


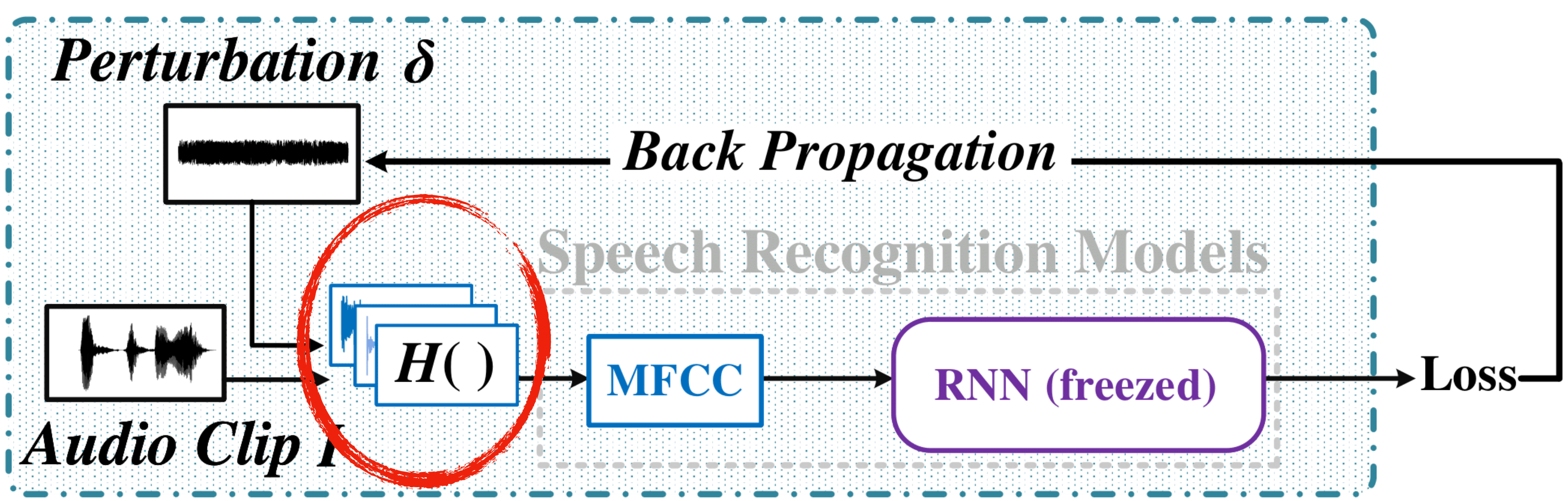
Design Inspiration

Design Inspiration



Design Inspiration

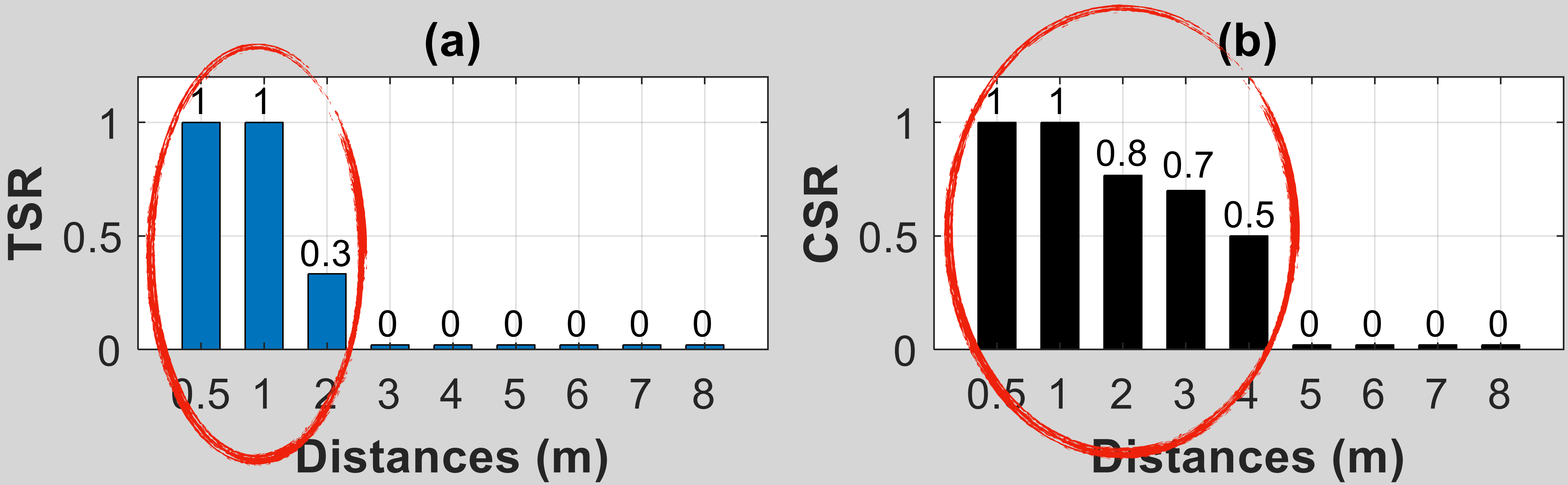




$$\arg\min_{\delta}\ \alpha\cdot dB_I(\delta)+\frac{1}{M}\sum_i Loss(SR(H_i(I+\delta)),T')$$

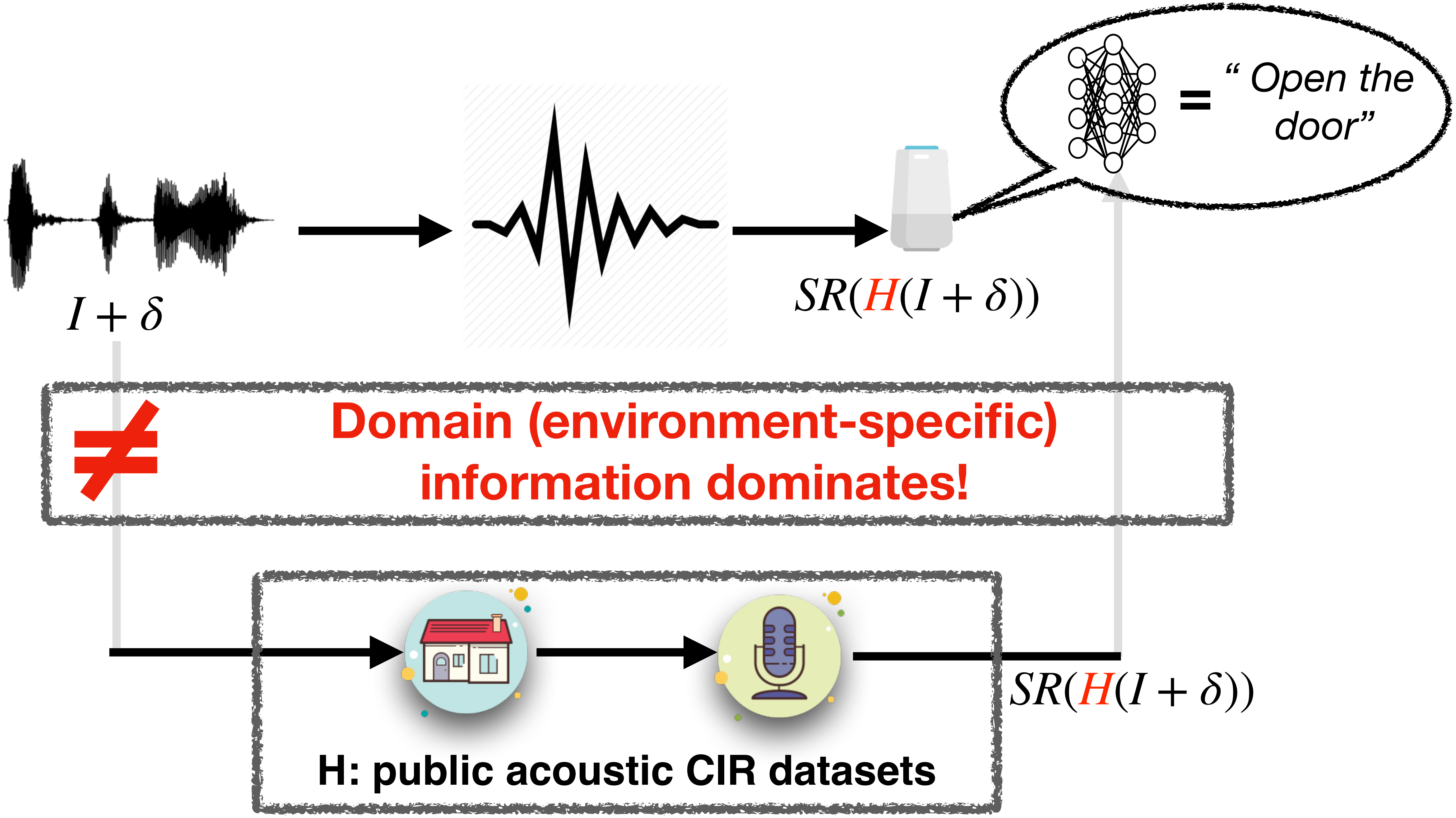
Design Inspiration

Transcript and Character Successful Rate:

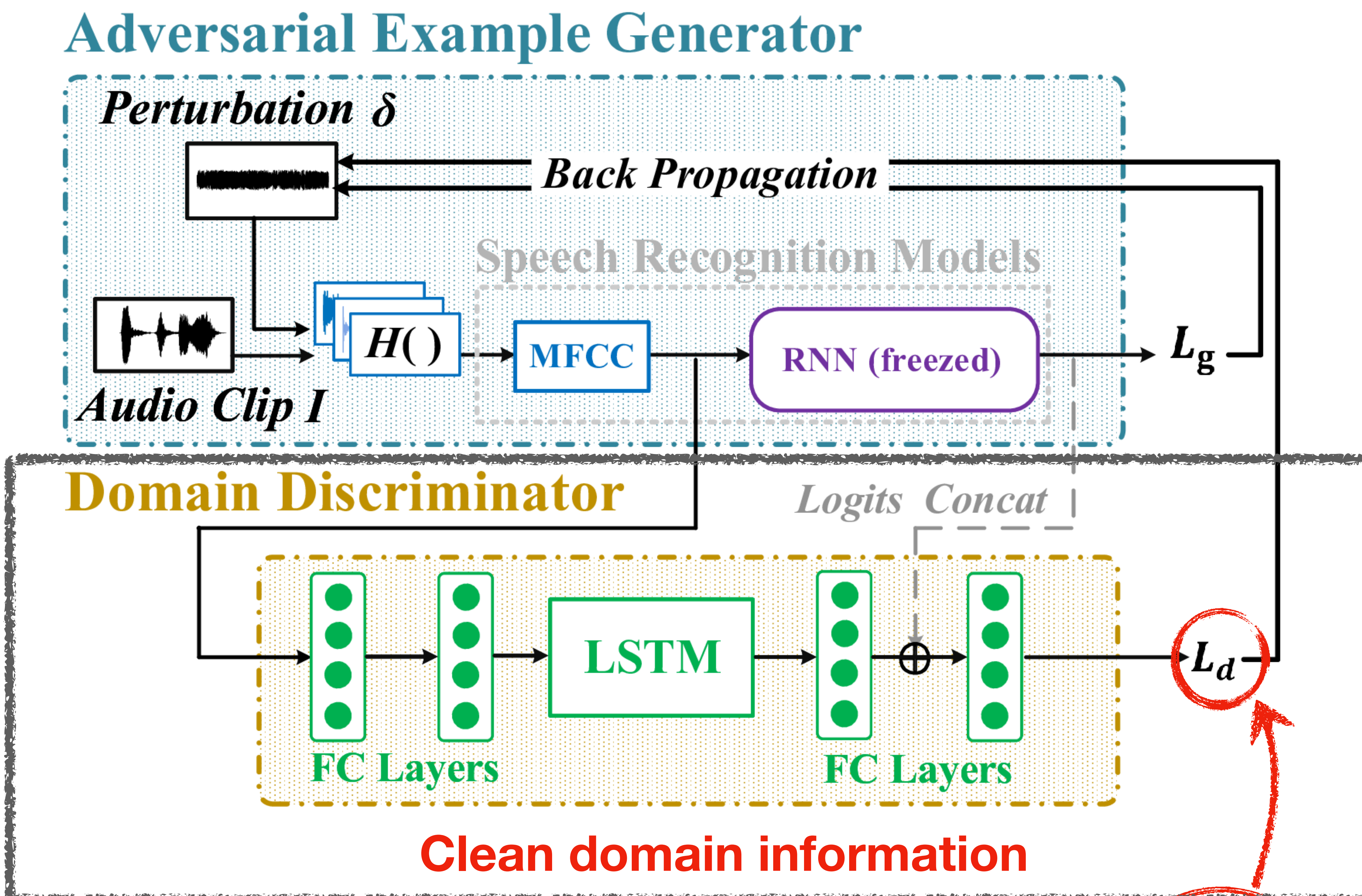


$$\arg\min_{\delta}\ \alpha \cdot dB_I(\delta) + \frac{1}{M}\sum_i Loss(SR(H_i(I+\delta)), T')$$

Design Inspiration



Metamorph: Meta-Enha

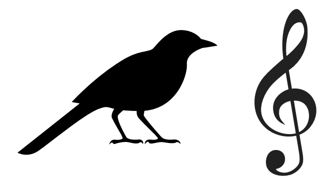


$$\arg\min_{\delta}\ \alpha \cdot dB_I(\delta) + \frac{1}{M}\sum_i Loss(SR(H_i(I+\delta)), T') - \beta \cdot L_d$$

Metamorph: Meta-Qual

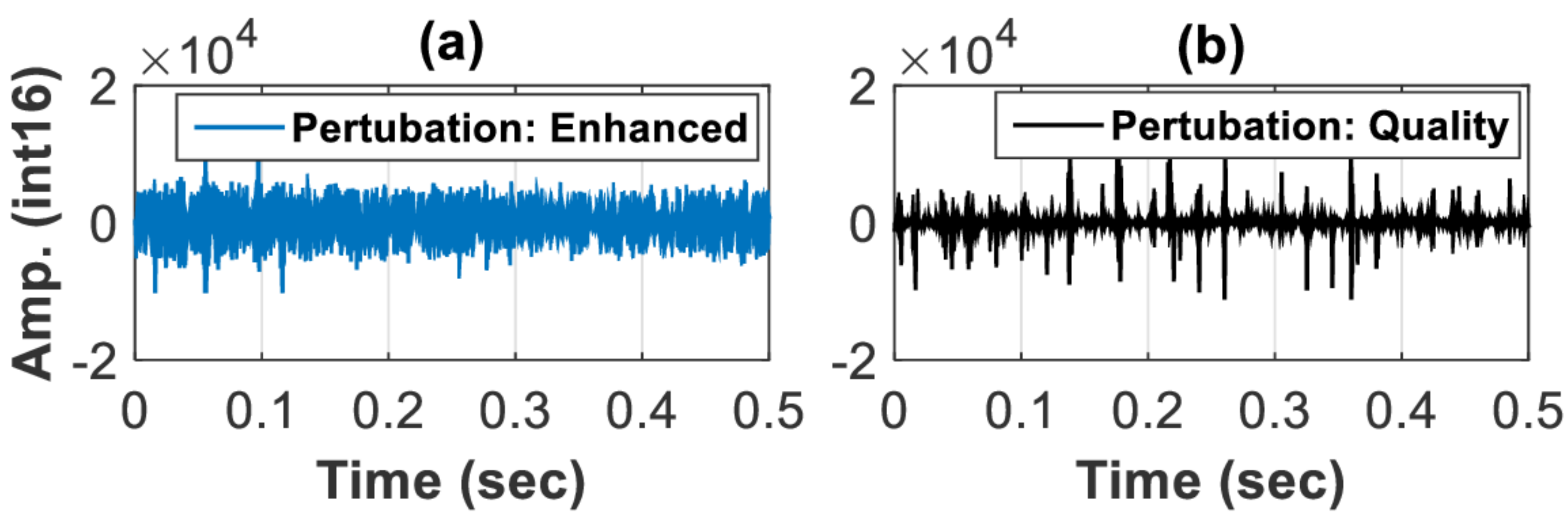
- Acoustic Graffiti:

$$distance(\delta, \hat{N})$$



- Reducing Perturbation's Coverage:

L1/L2 regularization



Evaluation: Audio Quality

- Examples

Classical music

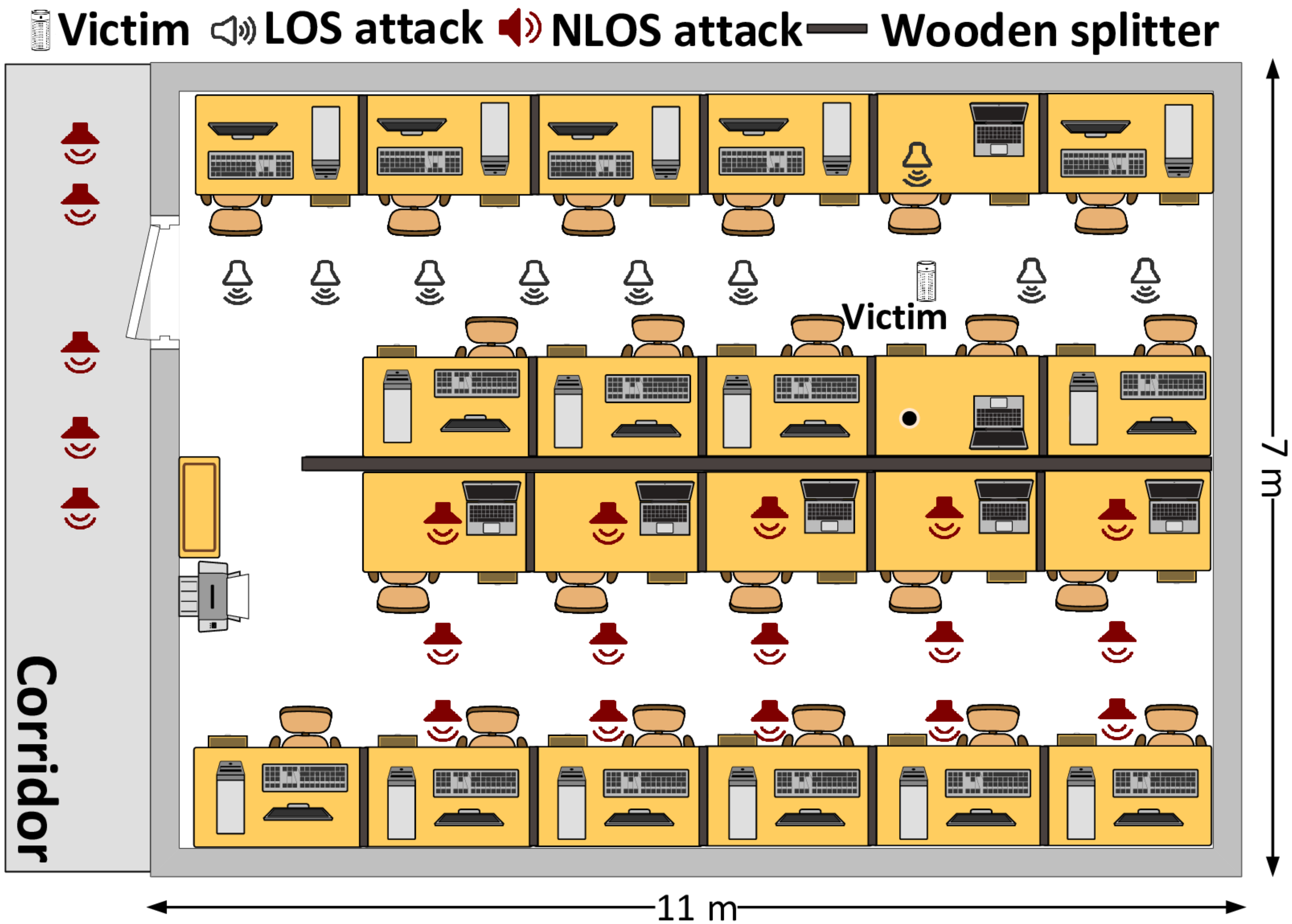
Original:	Meta-Enha:	Meta-Qual:
[no transcription]	"hello world"	"hello world"

Human speech

Original:	Meta-Enha:	Meta-Qual:
"your son went to serve at a distant place and became a centurion"	"open the door"	"open the door"

Evaluation: Attack Successful Rate

- Attack Target: “DeepSpeech” (White-Box)



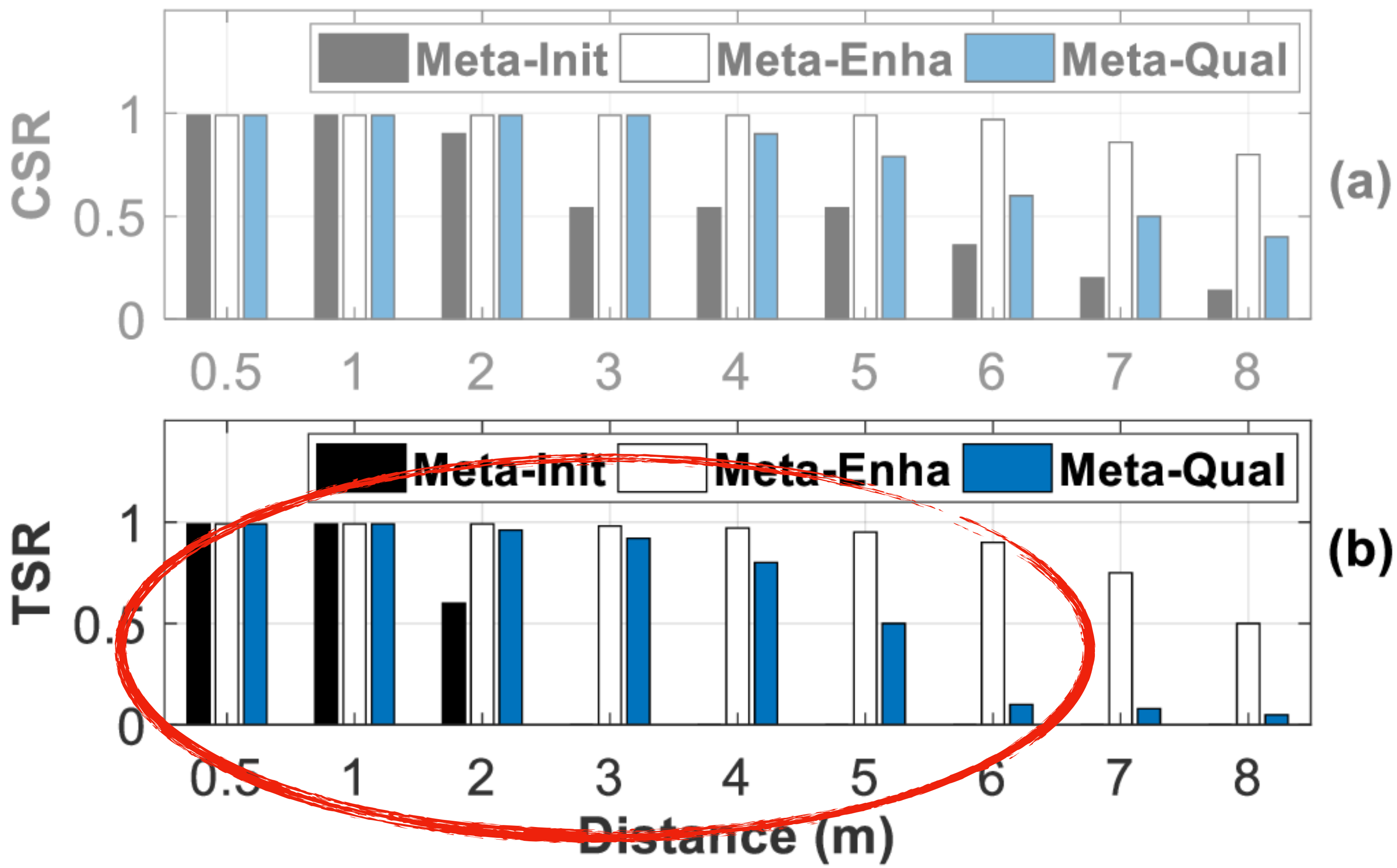
A multi-path prevalent office

Evaluation: Attack Successful Rate

- Line-of-Sight (LOS) Attack

Character Successful Rate

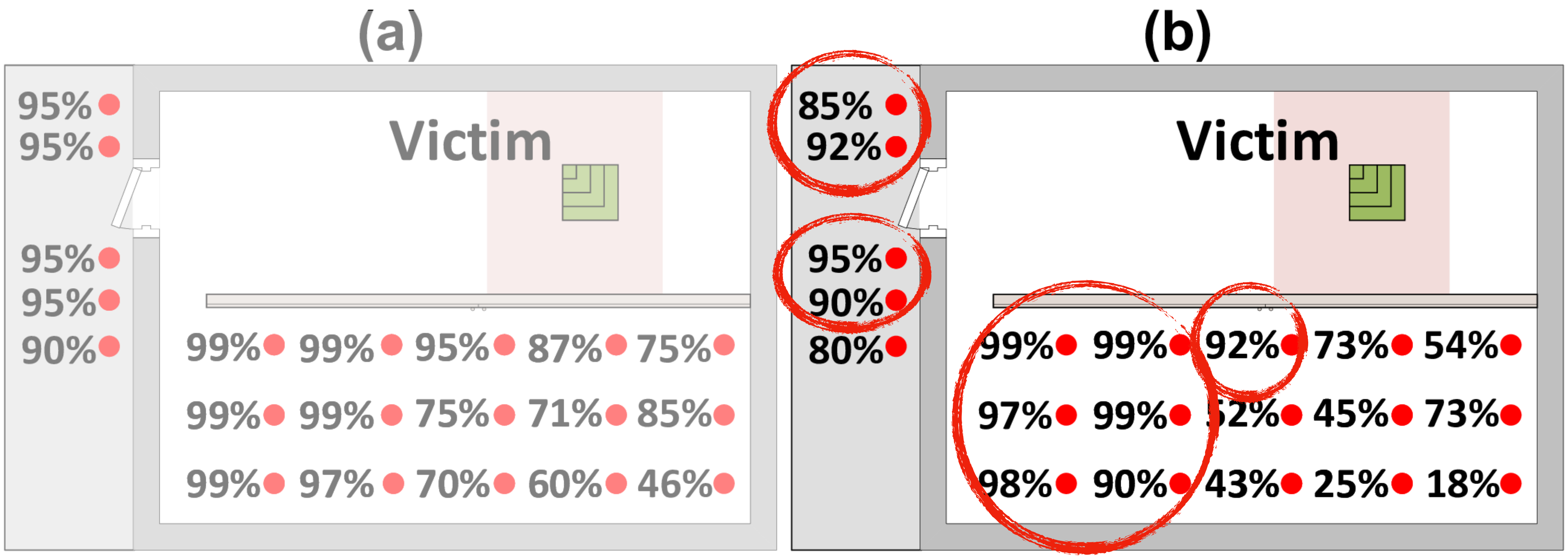
Transcript Successful Rate



Meta-Enha: > 90% attack successful rate

Evaluation: Attack Successful Rate

- No-Line-of-Sight (NLOS) Attack



Character Successful Rate　　　　Transcript Successful Rate

Meta-Enha: over 85% attack successful rate across 11/20 NLOS location!

Conclusion

1. Investigate over-the-air audio adversarial attacks systematically.
2. Propose a "generate-and-clean" two-phase design and improve the audio quality.
3. Develop a prototype and conduct extensive evaluations.

Visit acoustic-metamorph-system.github.io for more information!