MUTE: Bringing IoT to Noise Cancellation

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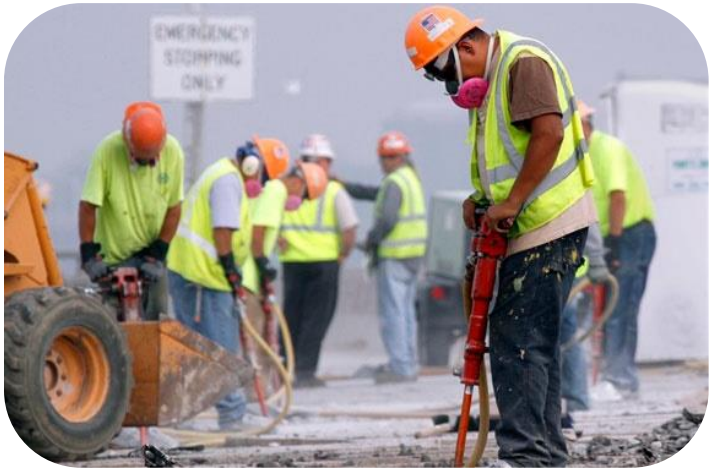
Haitham Hassanieh, Romit Roy Choudhury

Noise is everywhere …

Coworker Chatting over Phone

Construction Site



Lawn Mower in Early Morning

Busy Streets in Cities

Existing Solutions

Existing Solutions

This Paper

Better Noise Cancellation

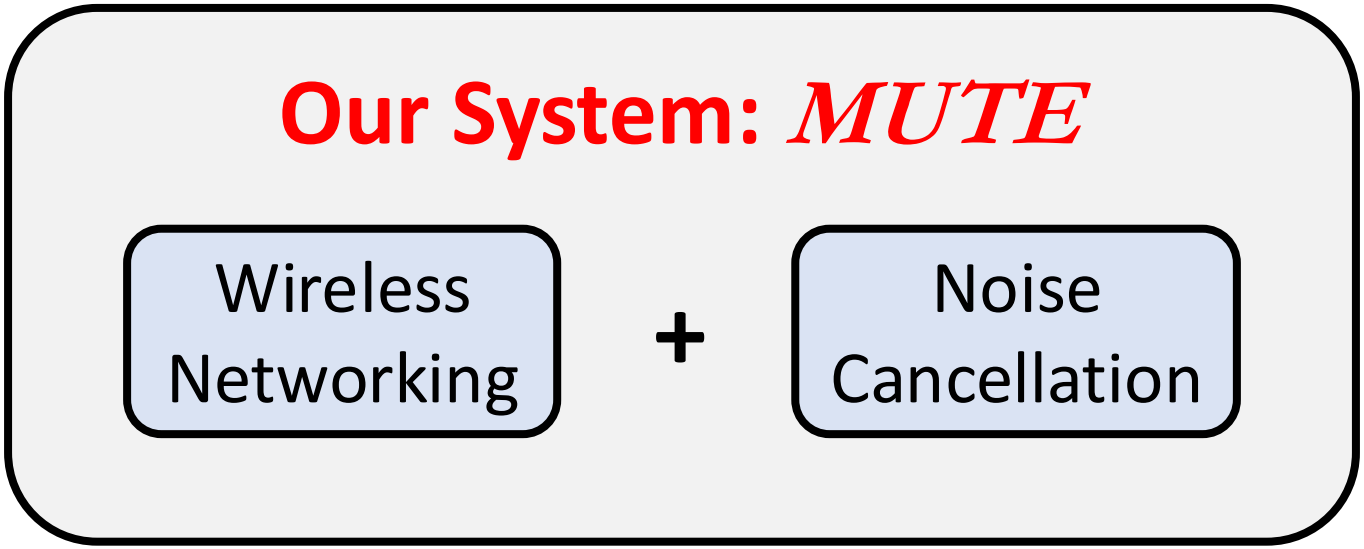
Existing Solutions

This Paper

Better Noise Cancellation

Better Form Factor (Hollow)

Comparable Performance


Our System: MUTE
Wireless Networking
+
Noise Cancellation

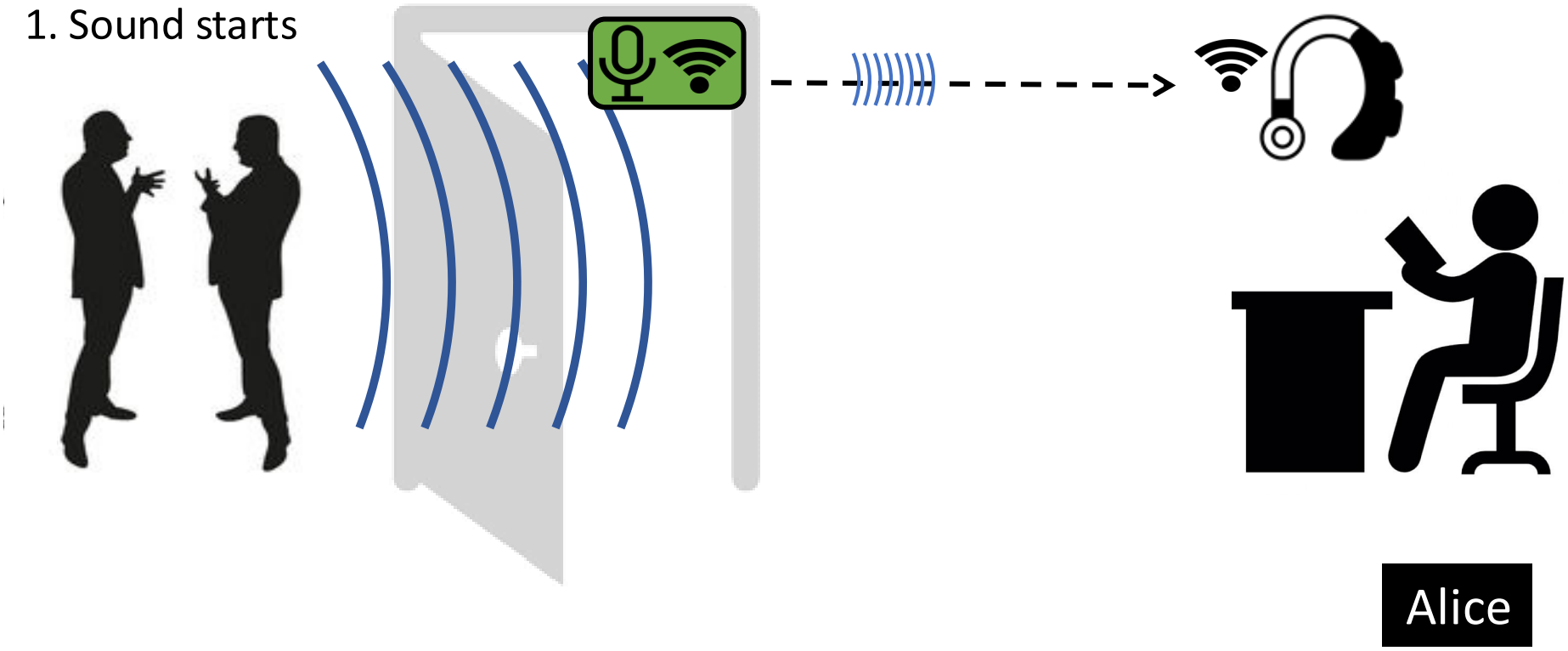
Alice

1. Sound starts

Alice

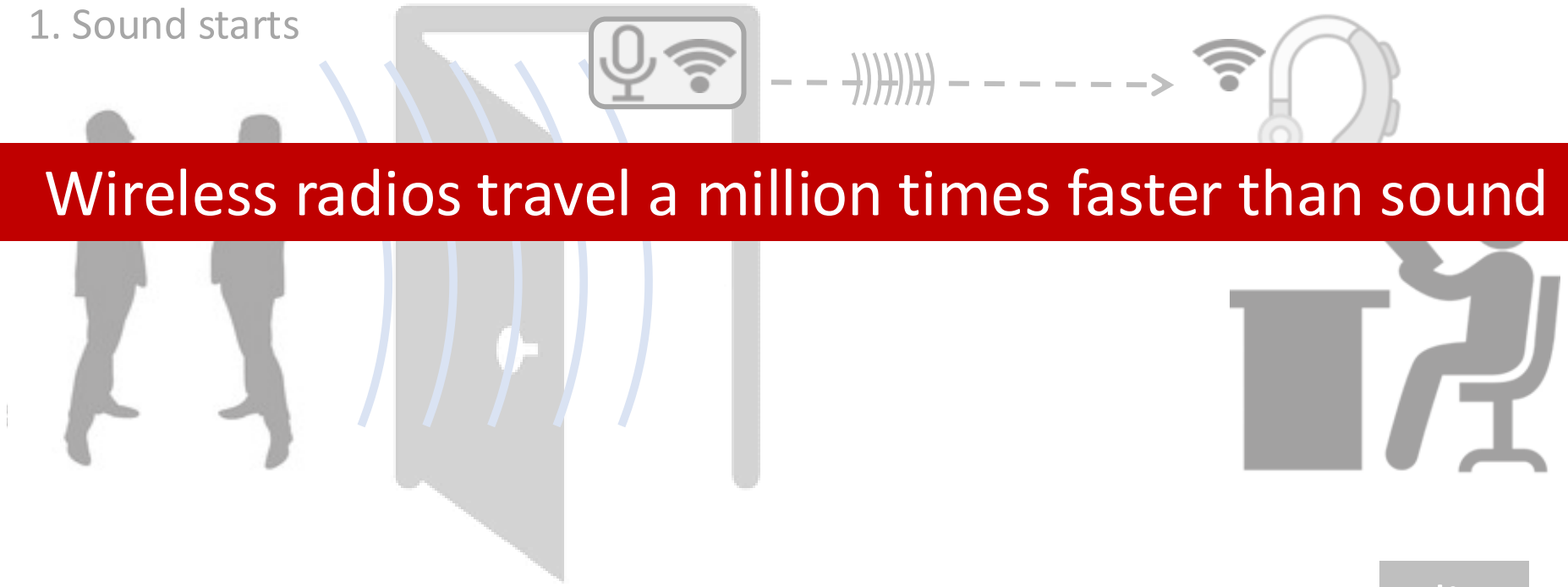
2. IoT relay forwards sound over wireless

1. Sound starts



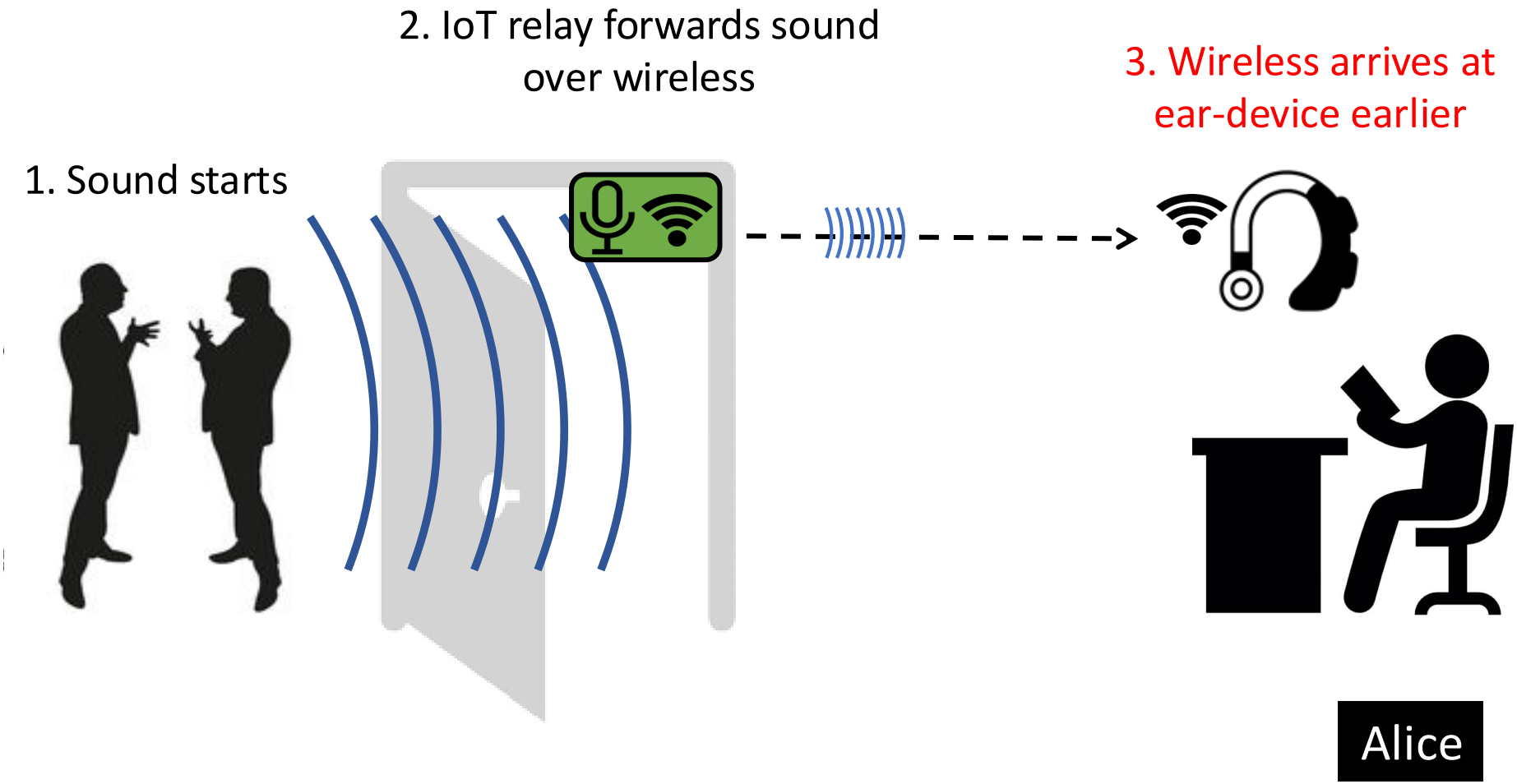
2. IoT relay forwards sound over wireless

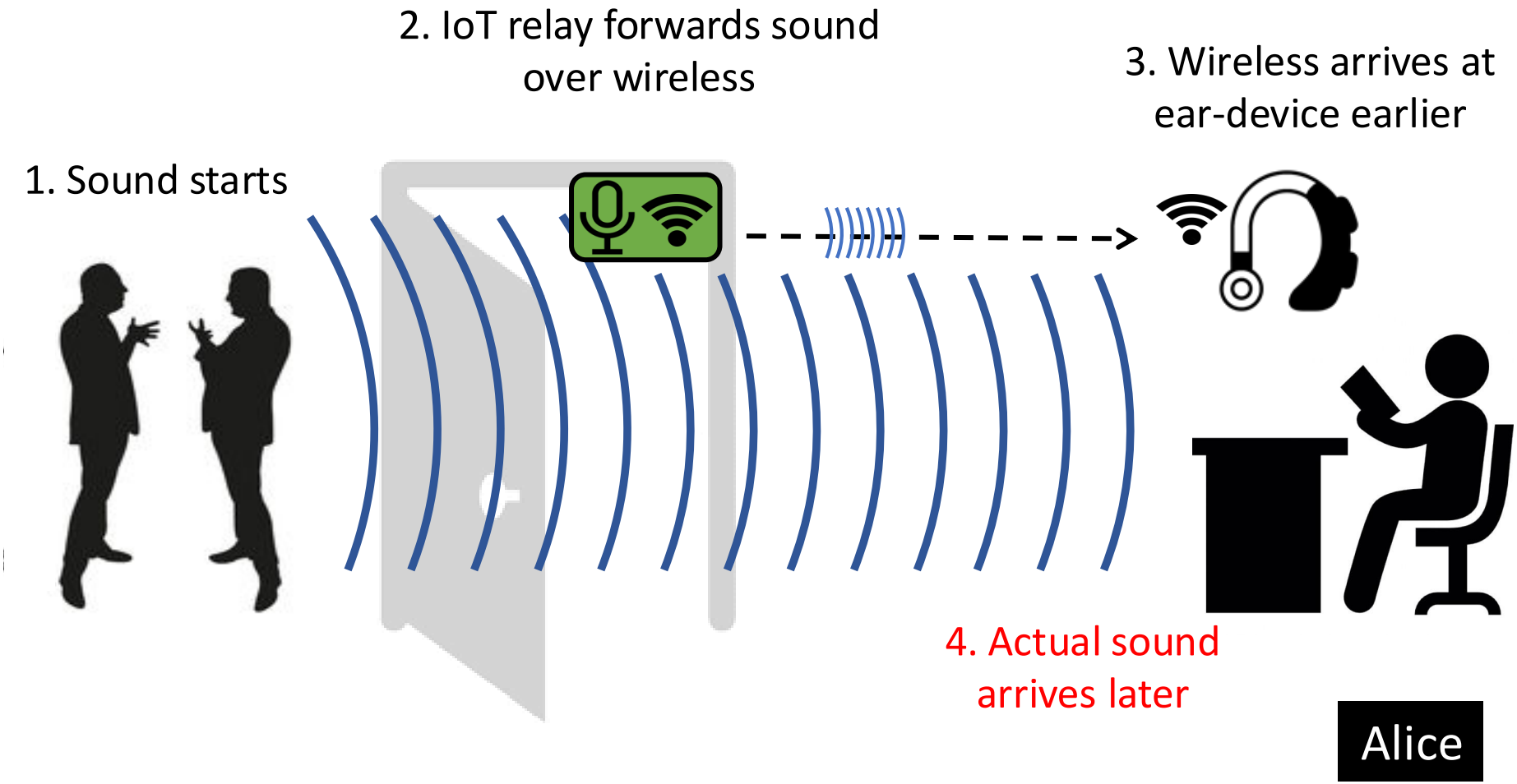
1. Sound starts



Wireless radios travel a million times faster than sound

Alice


2. IoT relay forwards sound over wireless
3. Wireless arrives at ear-device earlier
1. Sound starts
Alice


2. IoT relay forwards sound over wireless
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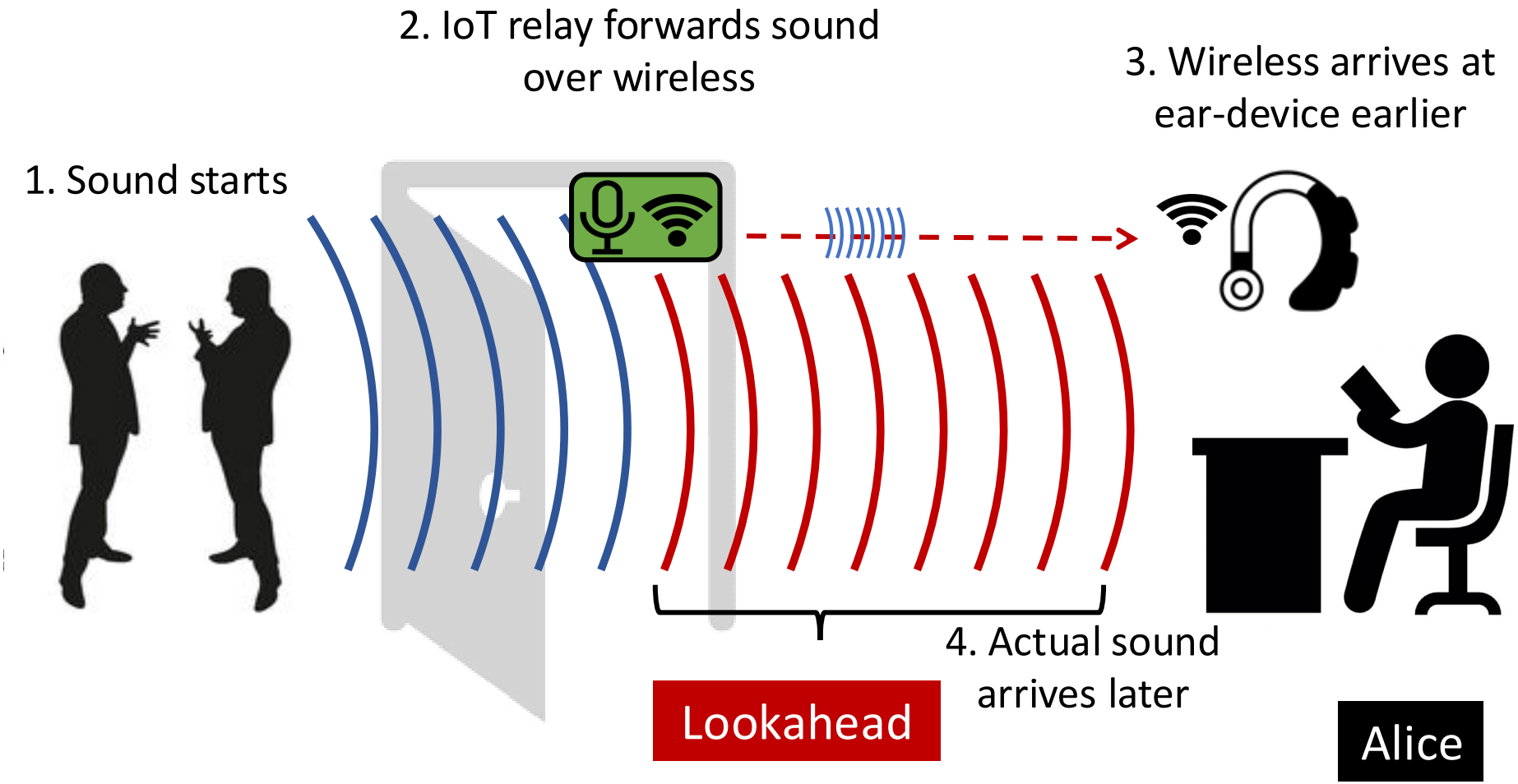
1. Sound starts
4. Actual sound arrives later
Alice


2. IoT relay forwards sound over wireless
3. Wireless arrives at ear-device earlier
1. Sound starts
4. Actual sound arrives later
Lookahead
Alice

Analogy: Light travels much faster than sound

Lookahead allows us to cover ears in time

MUTE: Leverage **lookahead** for noise cancellation

Talk Outline

How can *MUTE* leverage lookahead?

Timing Gain → Wideband Cancellation

Signal Processing Gain → Non-Causal Filtering

Application-Specific Gain → Sound Source Profiling

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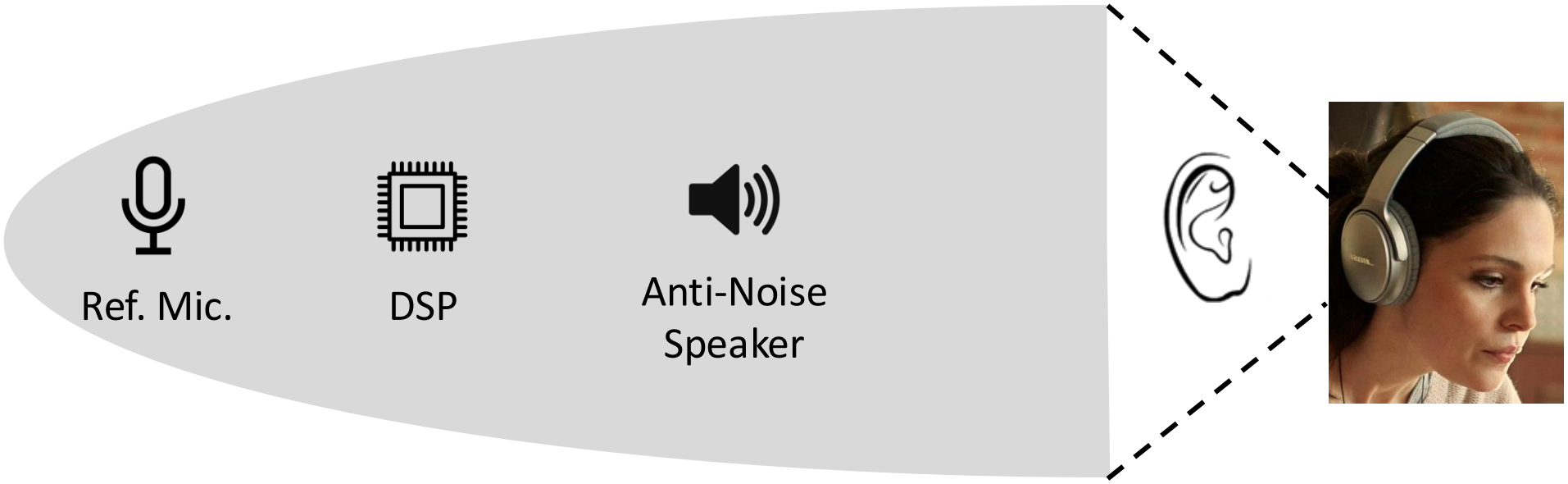
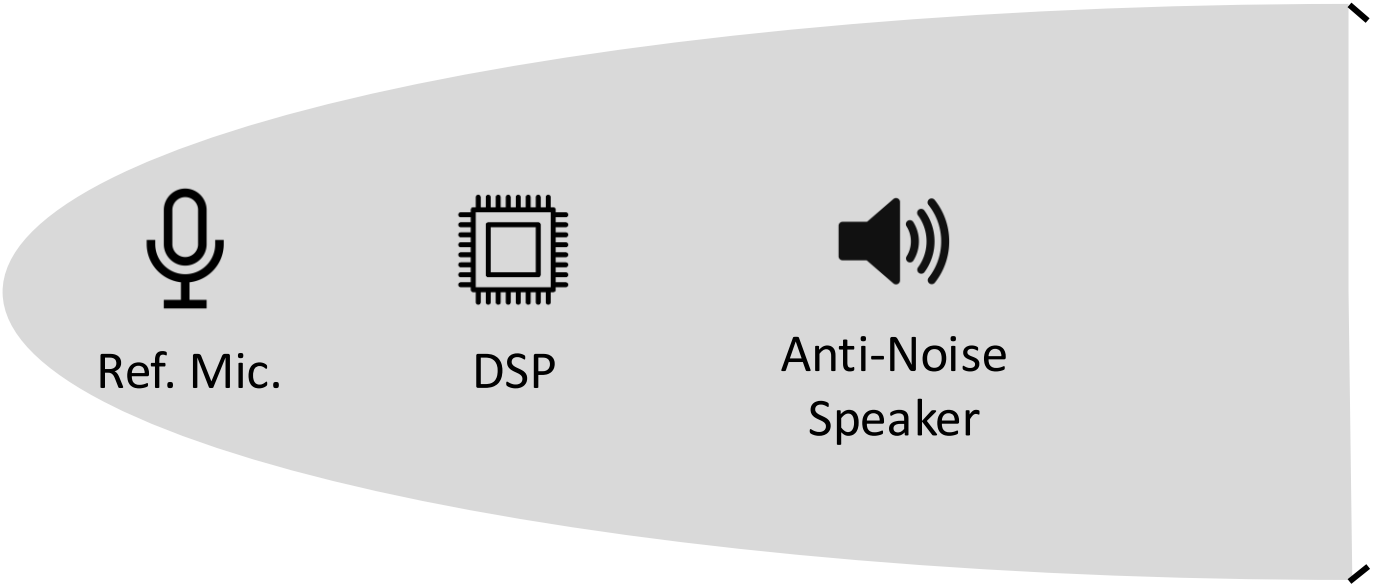
Noise Cancelling Headphones
-- What is inside?

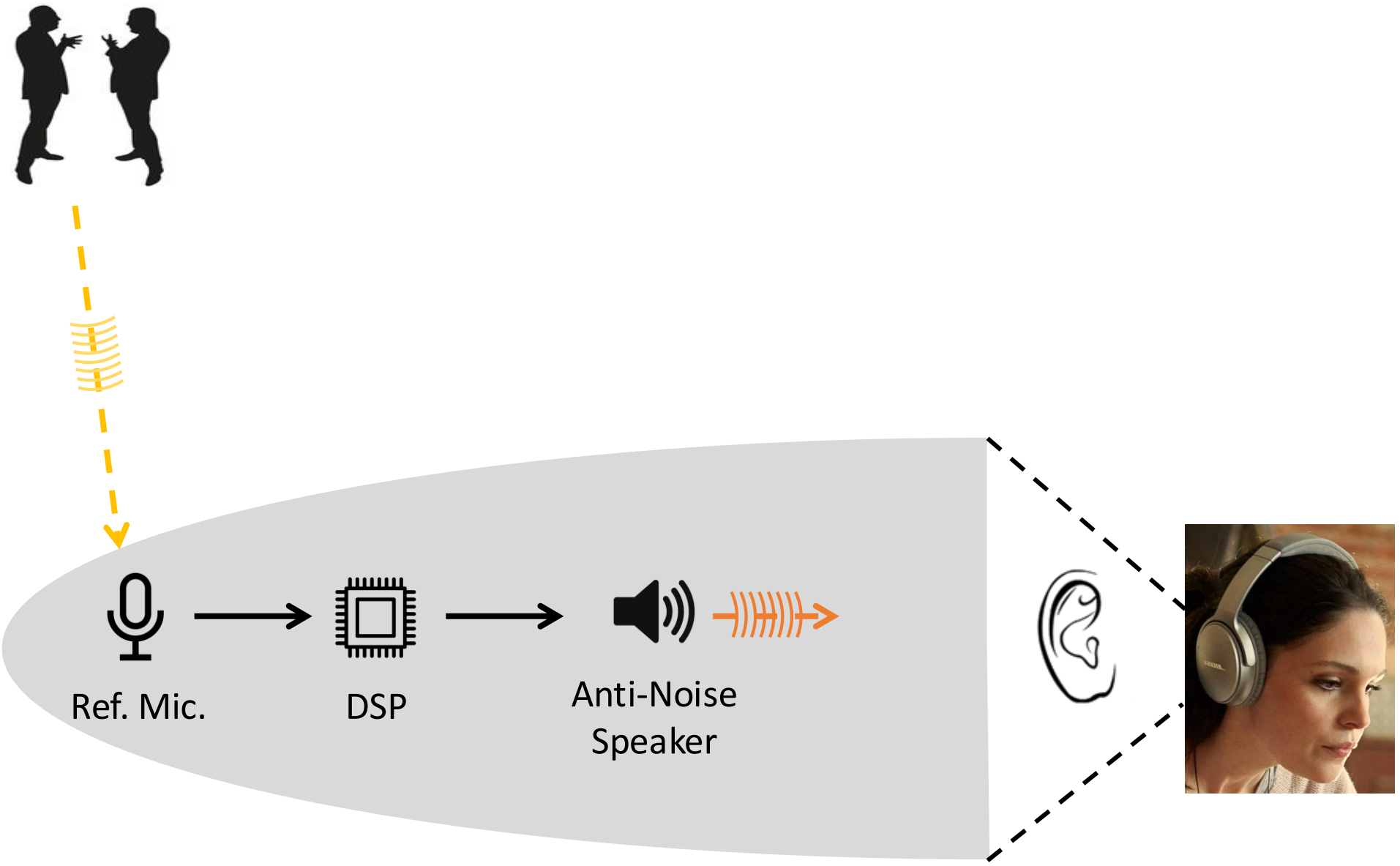
Noise Cancellation Primer



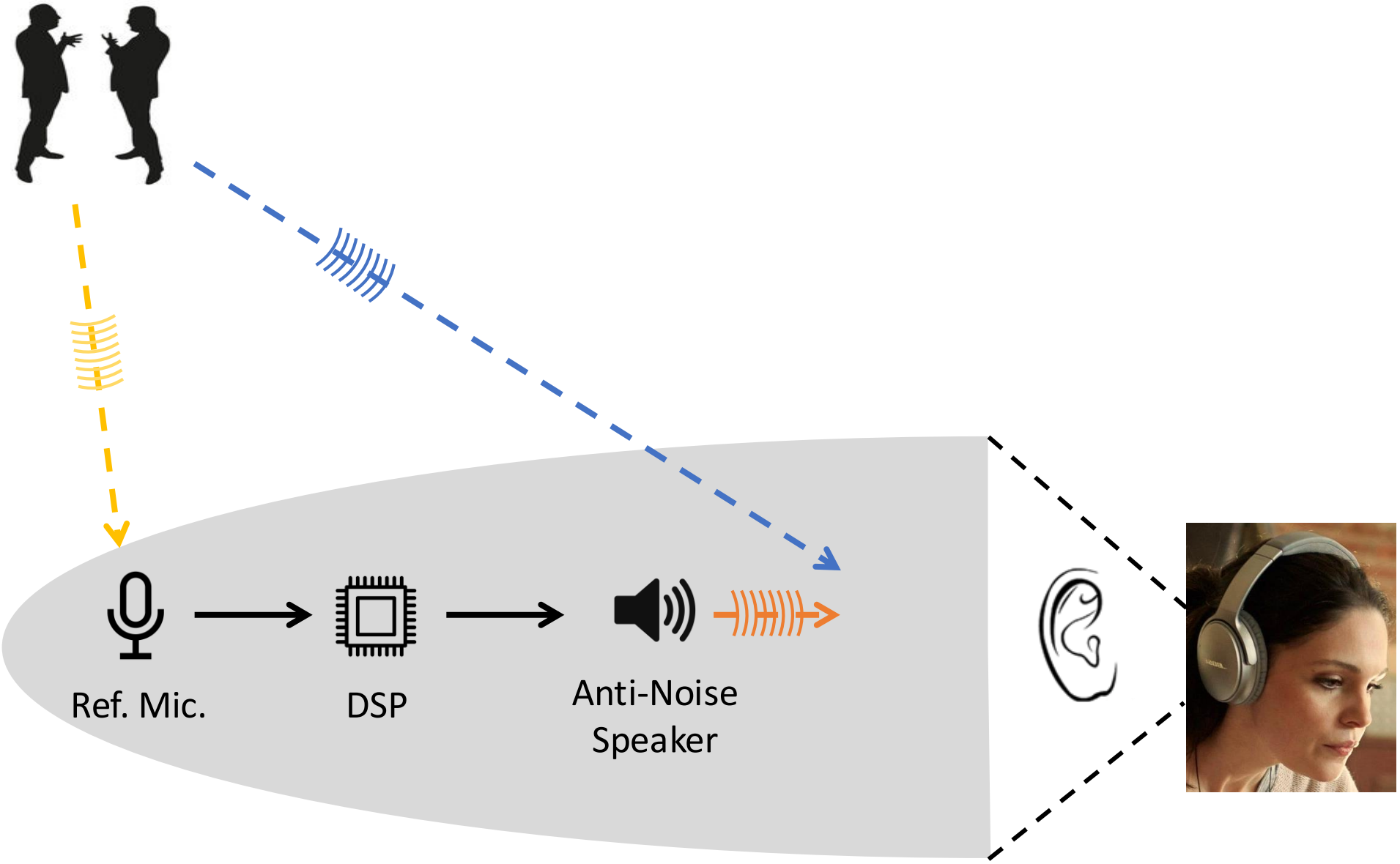
Noise Cancellation Primer



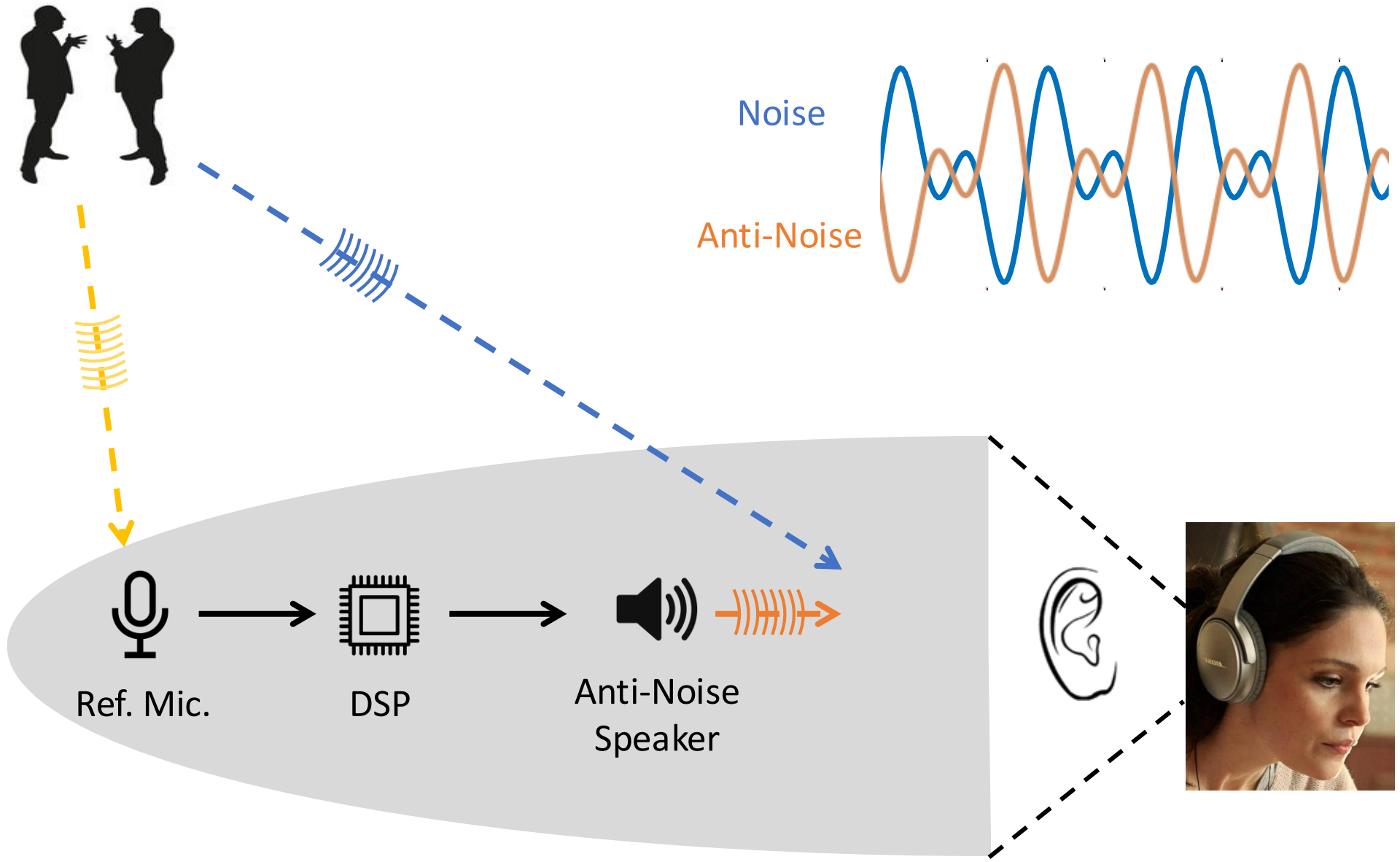
Noise Cancellation Primer



Noise Cancellation Primer



Noise Cancellation Primer



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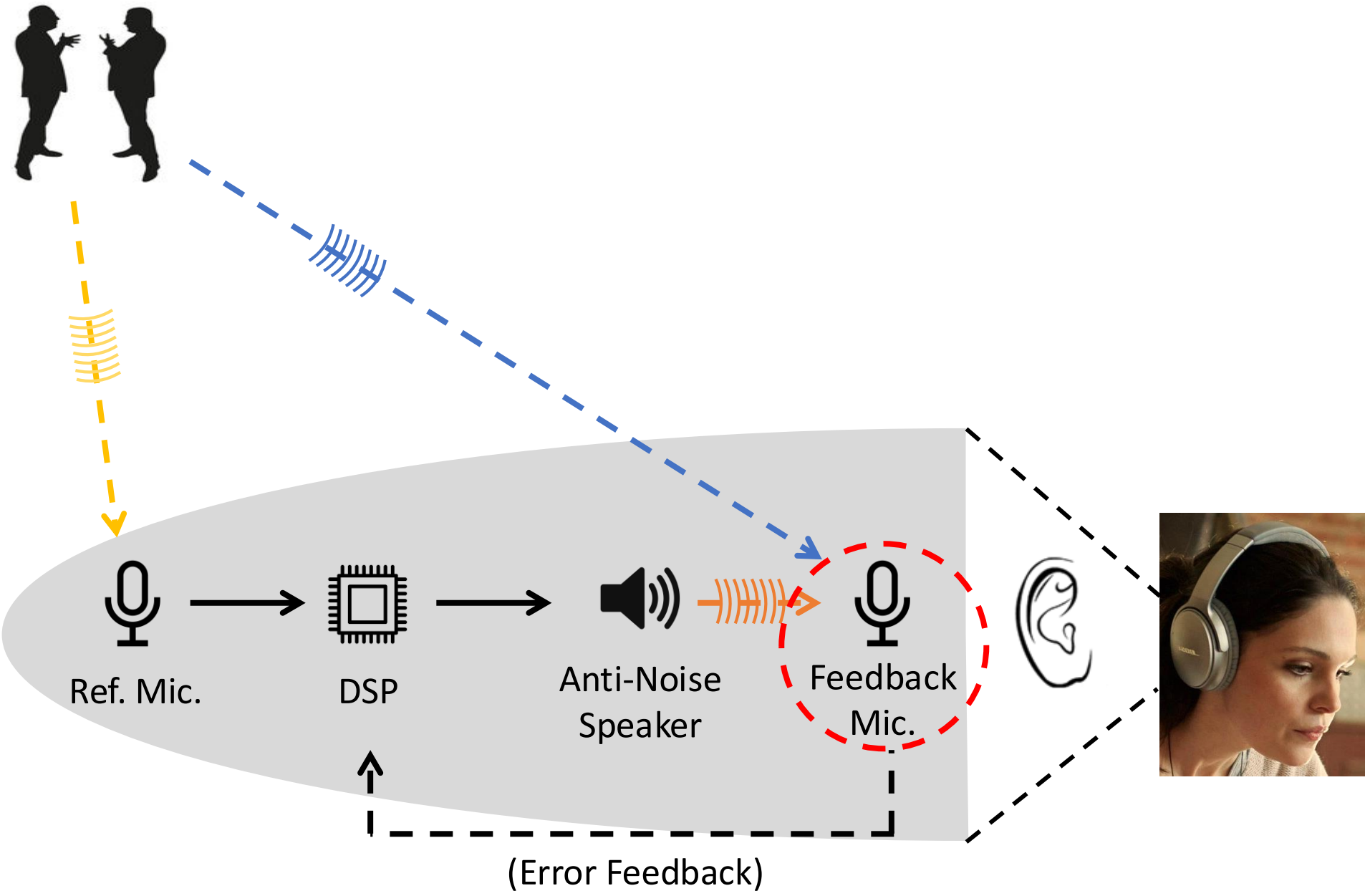


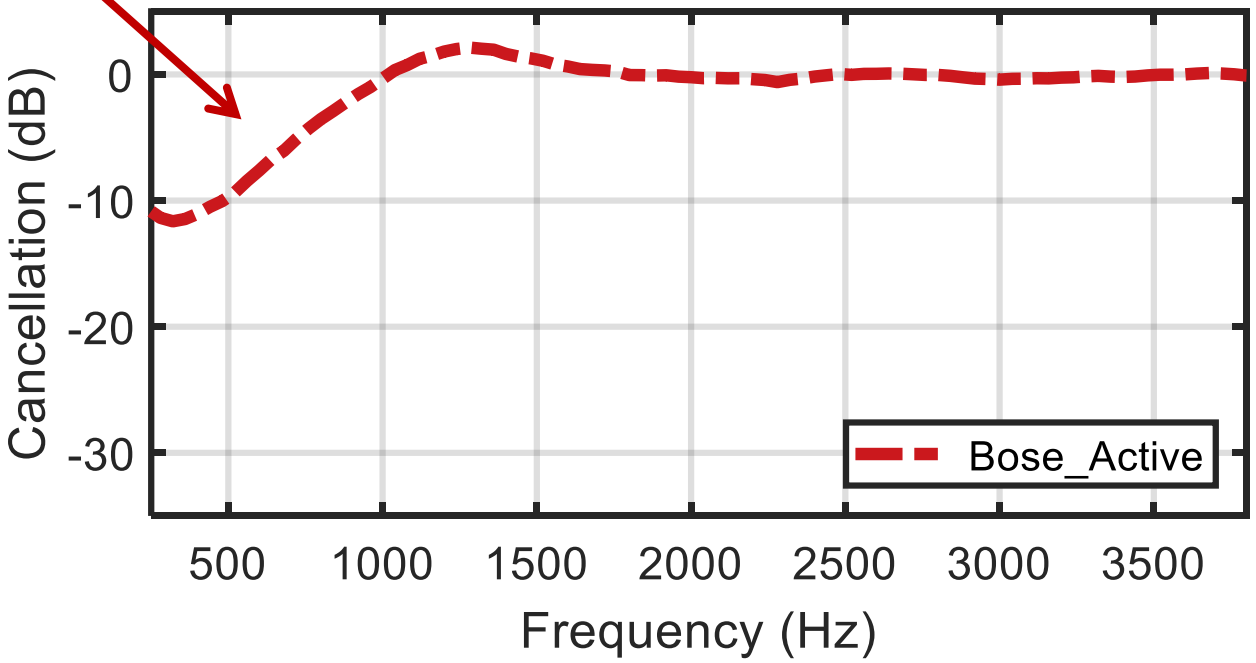
How do they perform today?

Bose QC35

Active noise cancellation
only at low frequencies

Bad

Good



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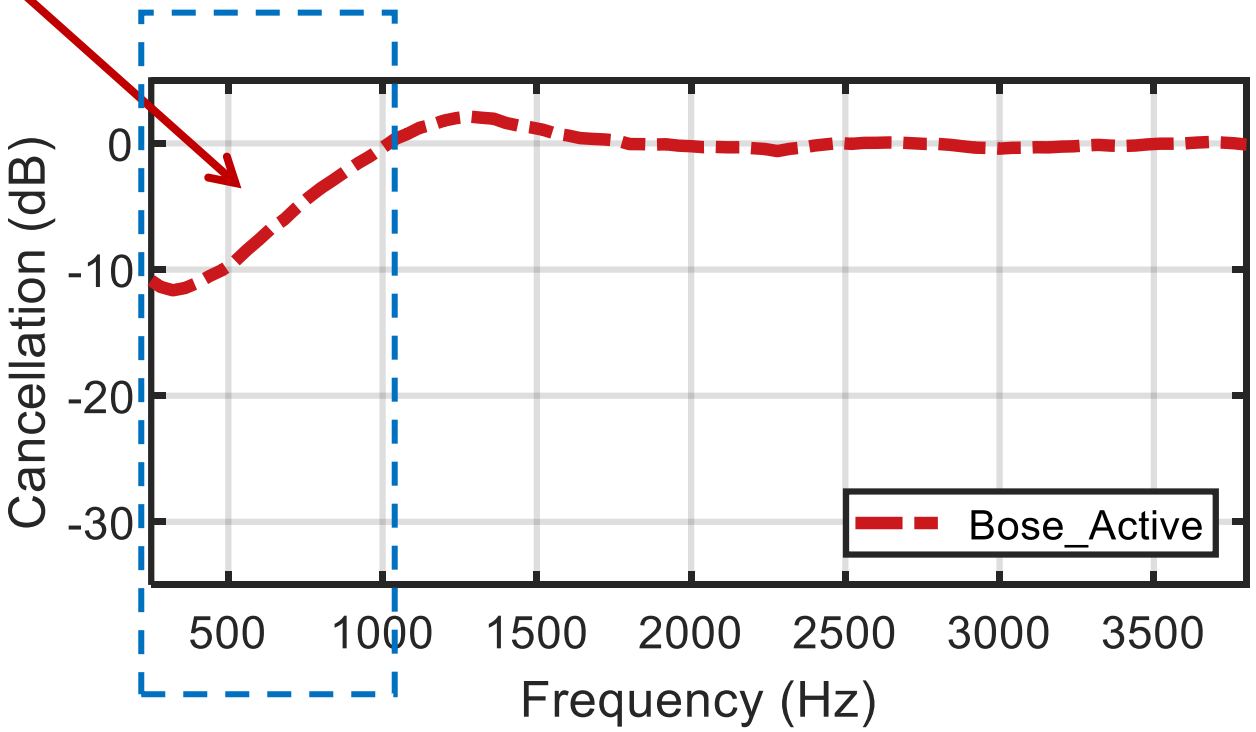

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Active noise cancellation
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Sound absorbing material
blocks high frequencies

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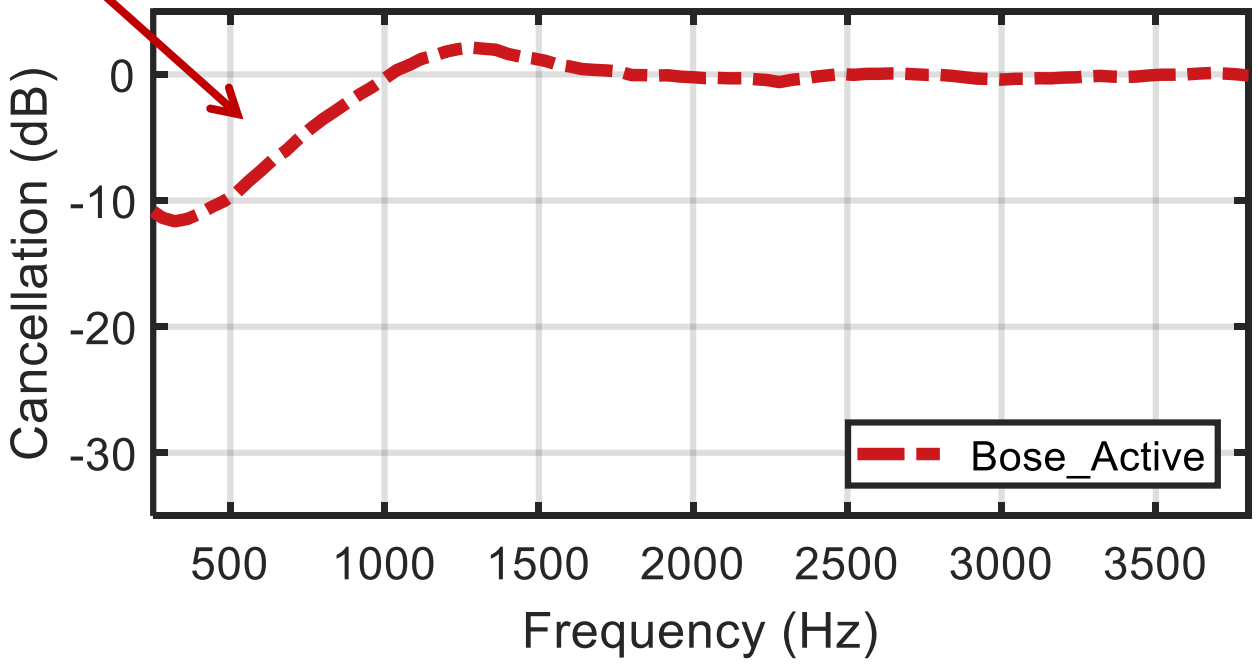
Good



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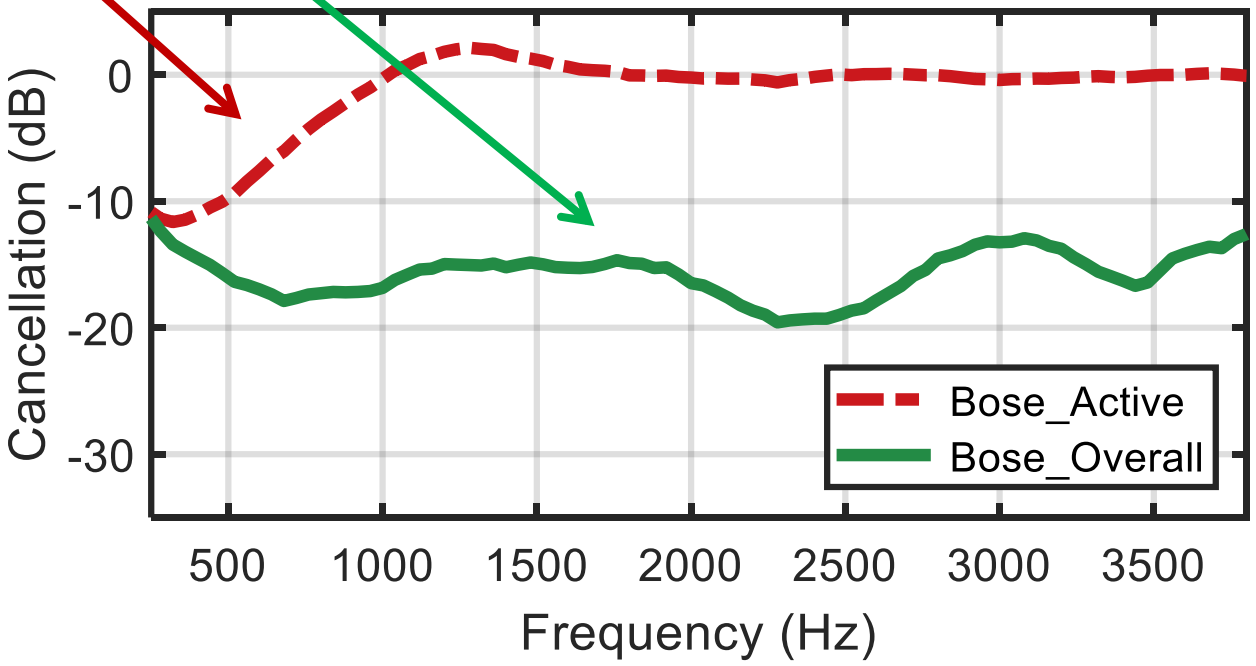
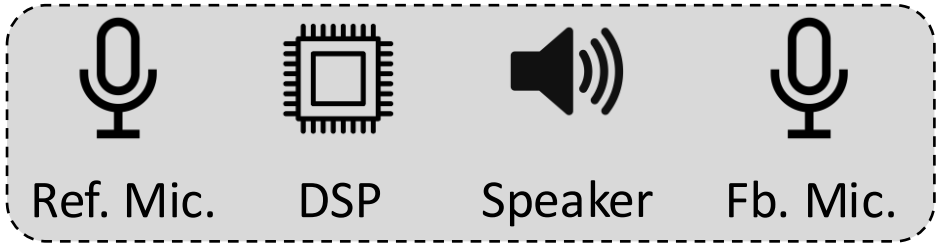
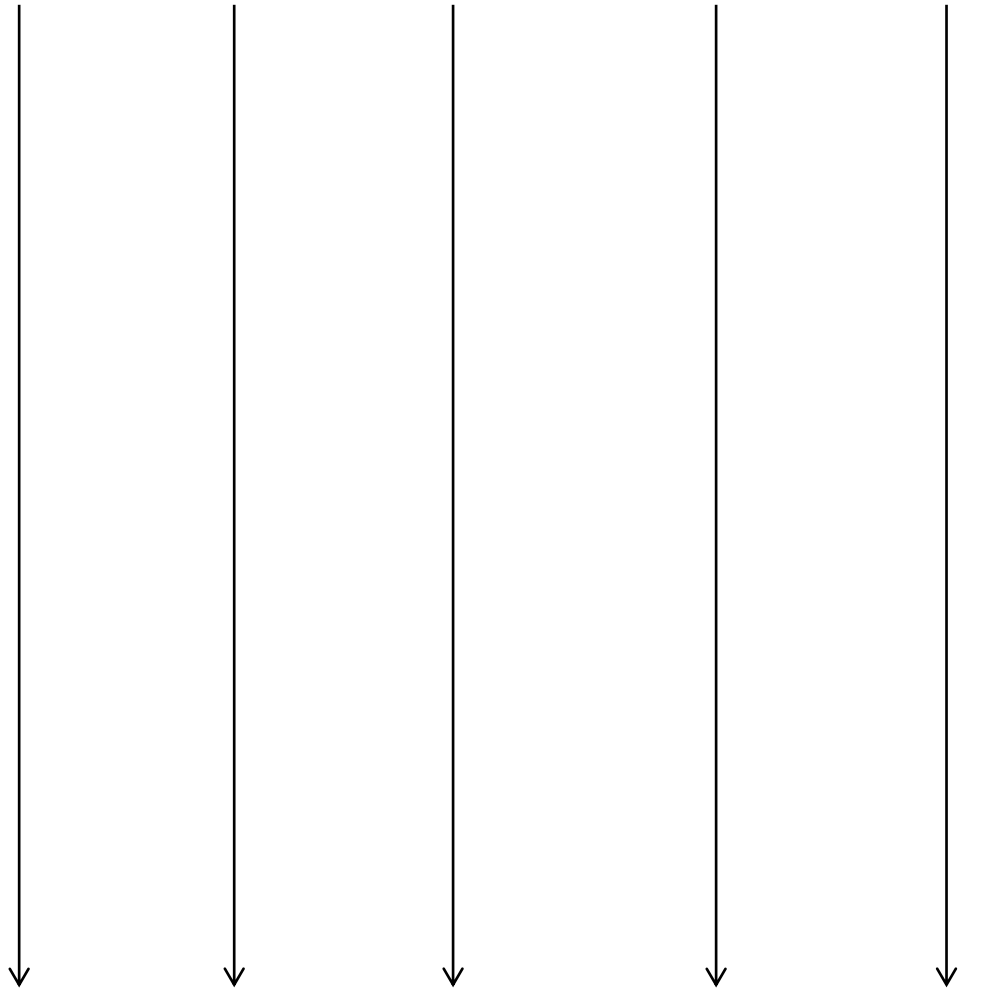


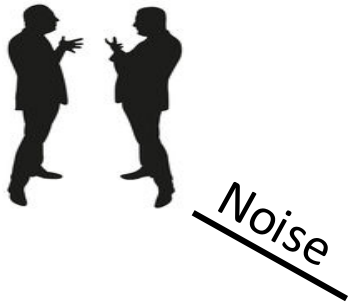
Why does noise cancellation not work at higher frequencies?

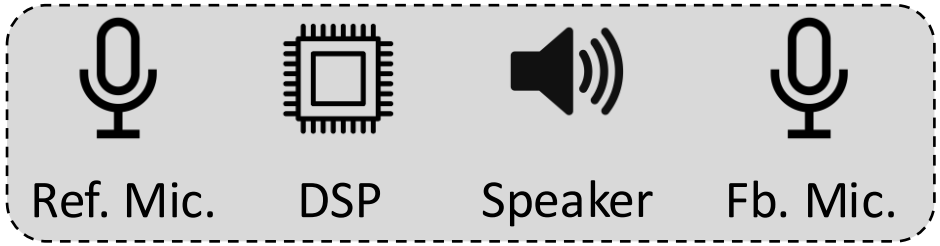
Let’s look into the headphone again.

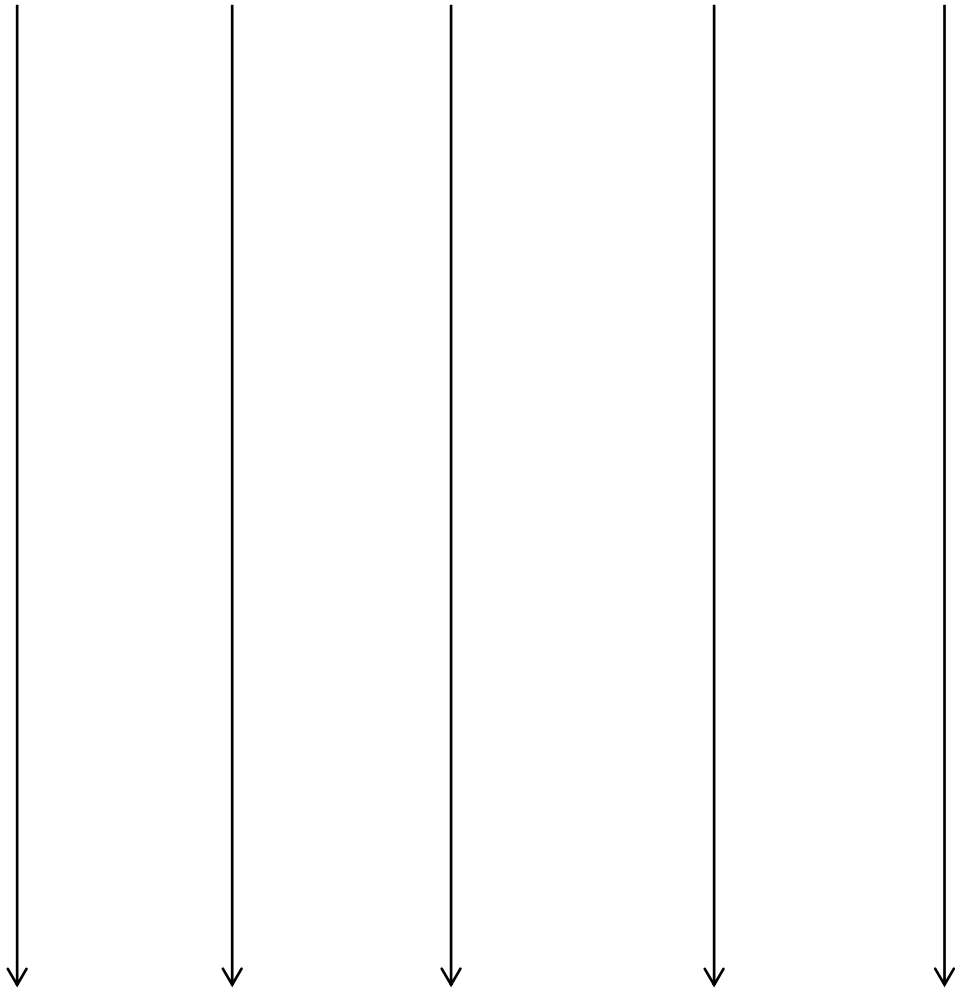

Ref. Mic.
DSP
Speaker
Fb. Mic.



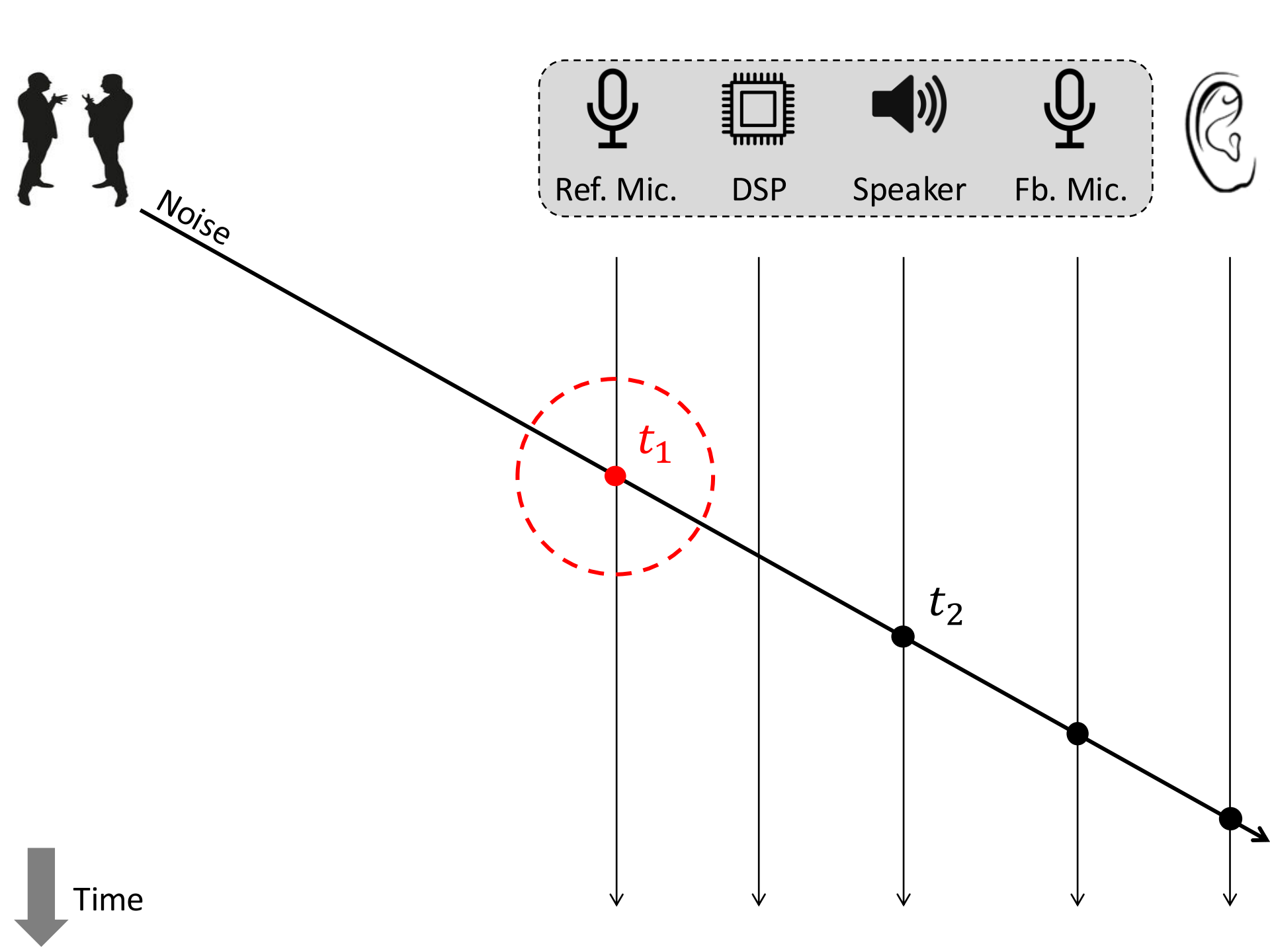

Time

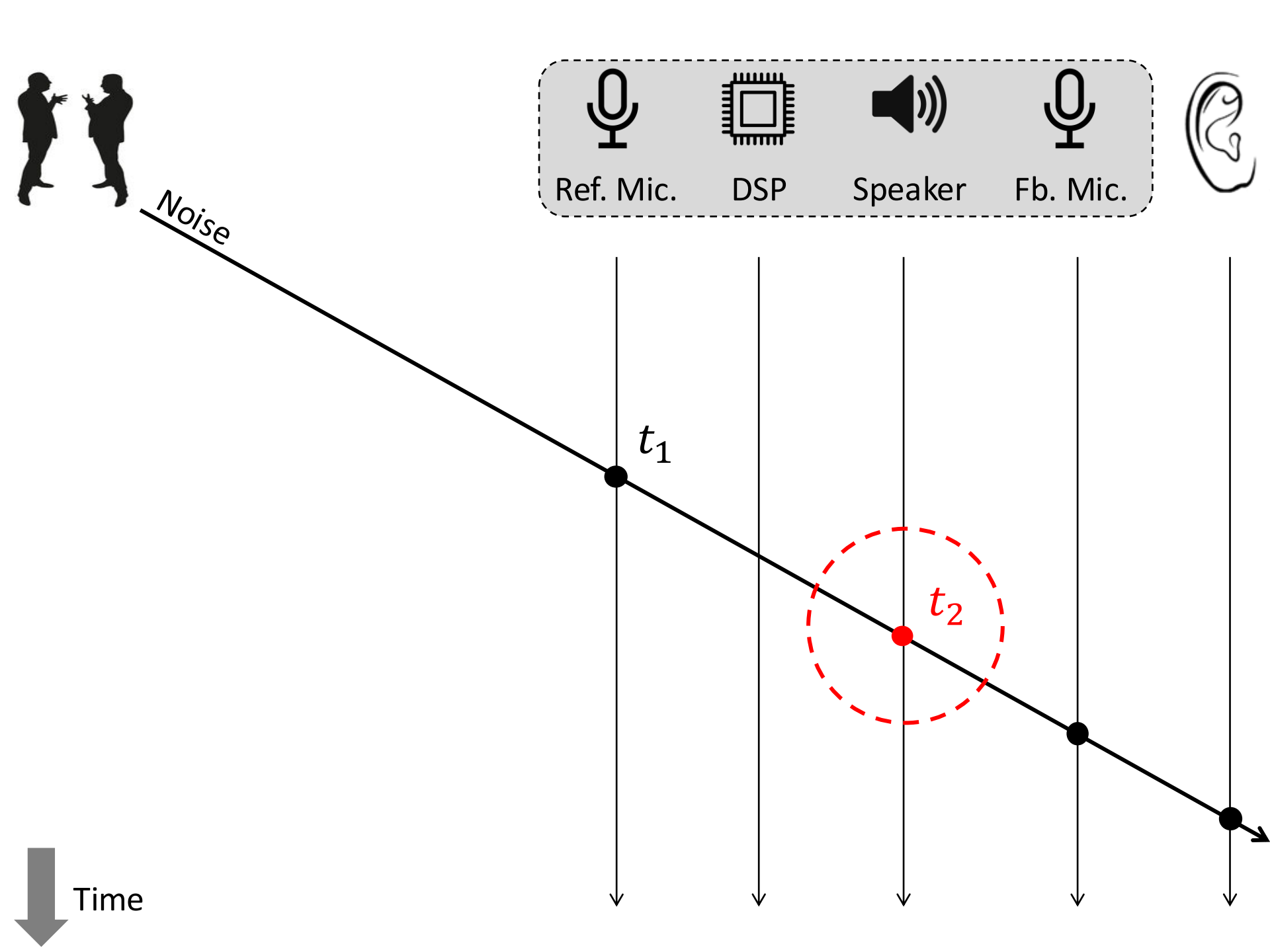

Noise

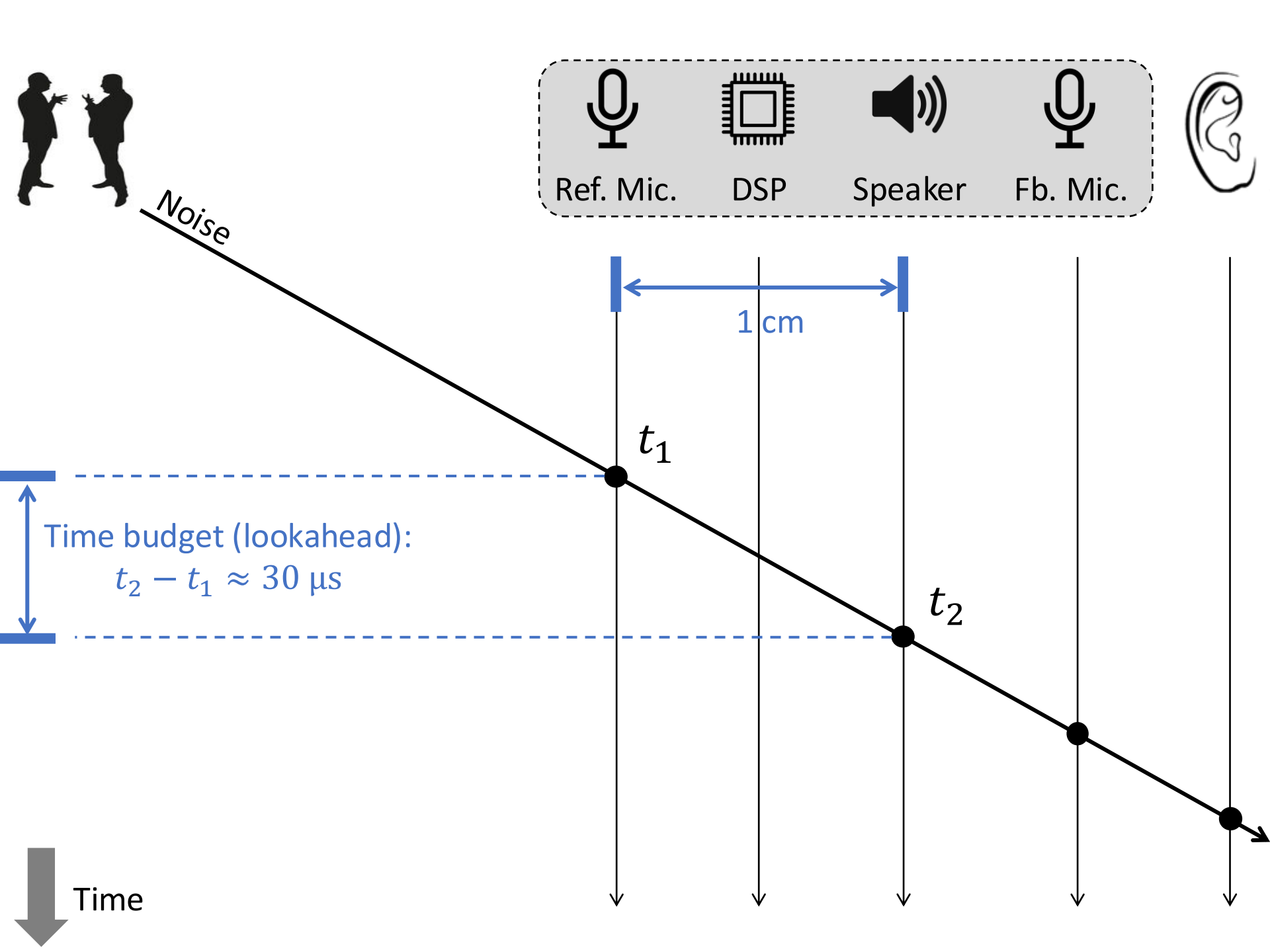

Ref. Mic.
DSP
Speaker
Fb. Mic.

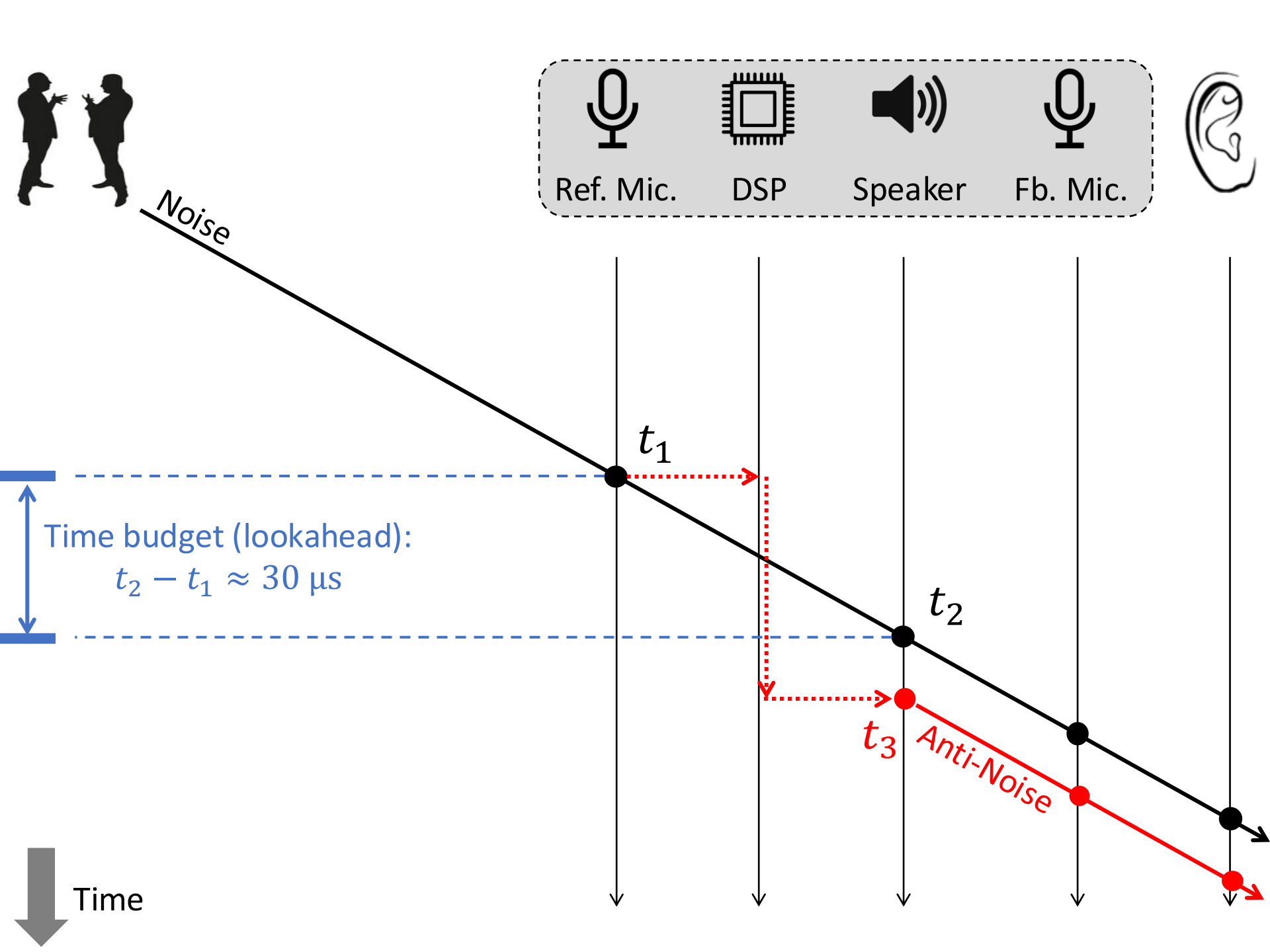


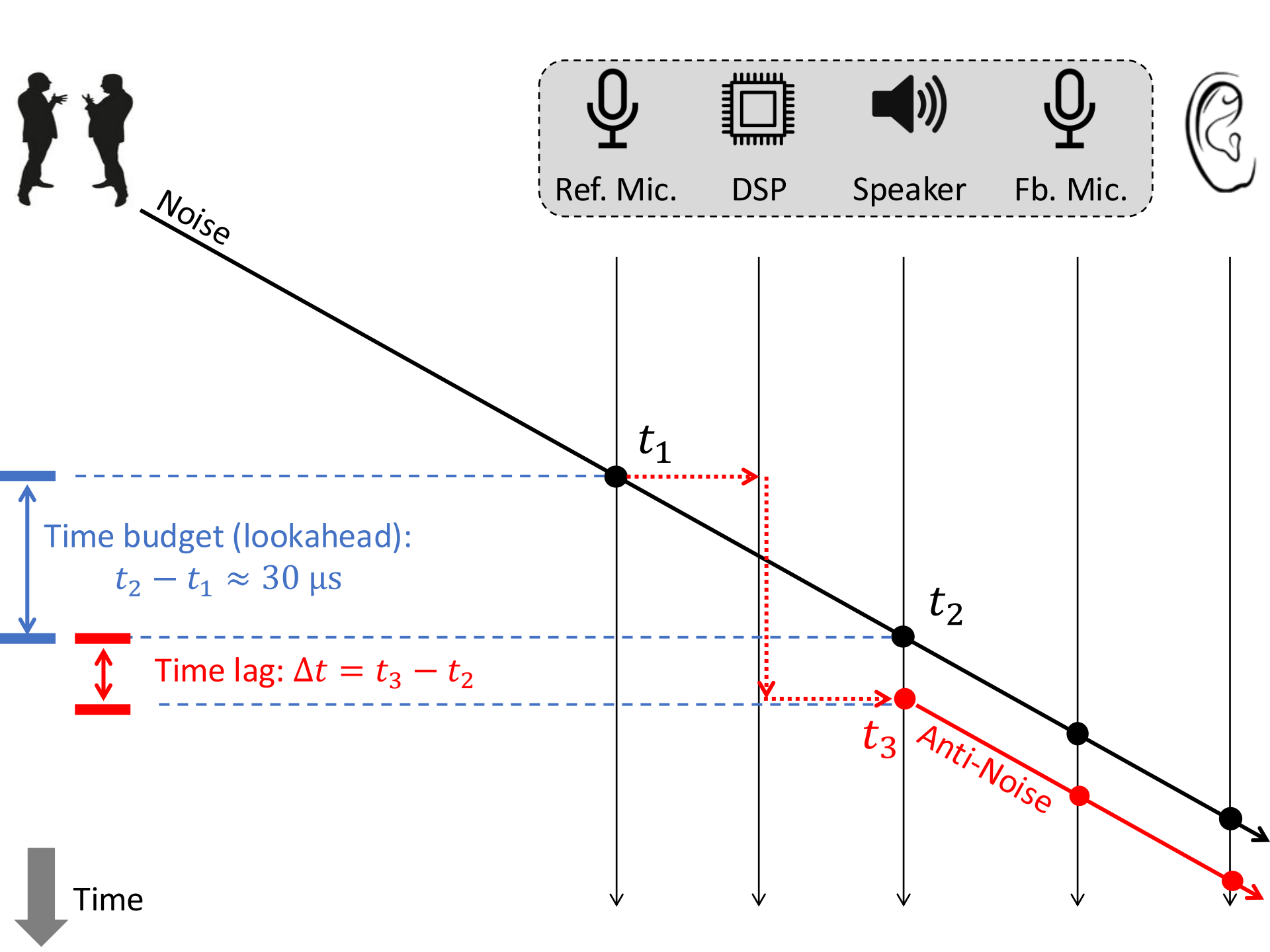

Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
t_2
Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
t_2
Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
1 cm
t_1
t_2
Time budget (lookahead):
$t_2 - t_1 \approx 30\ \mu s$
Time

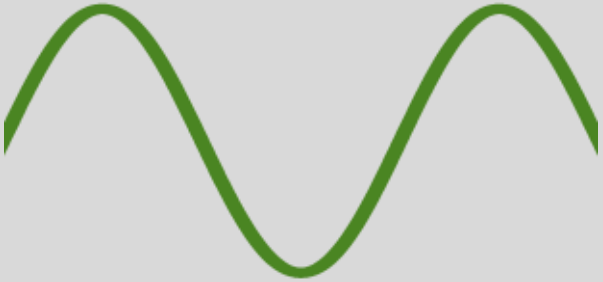

Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
t_2
t_3
Anti-Noise
Time budget (lookahead):
$t_2 - t_1 \approx 30\ \mu s$
Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
t_2
t_3
Time budget (lookahead):
$t_2 - t_1 \approx 30\ \mu s$
Time lag: $\Delta t = t_3 - t_2$
Anti-Noise
Time

Low Frequency:

Noise

Anti-Noise

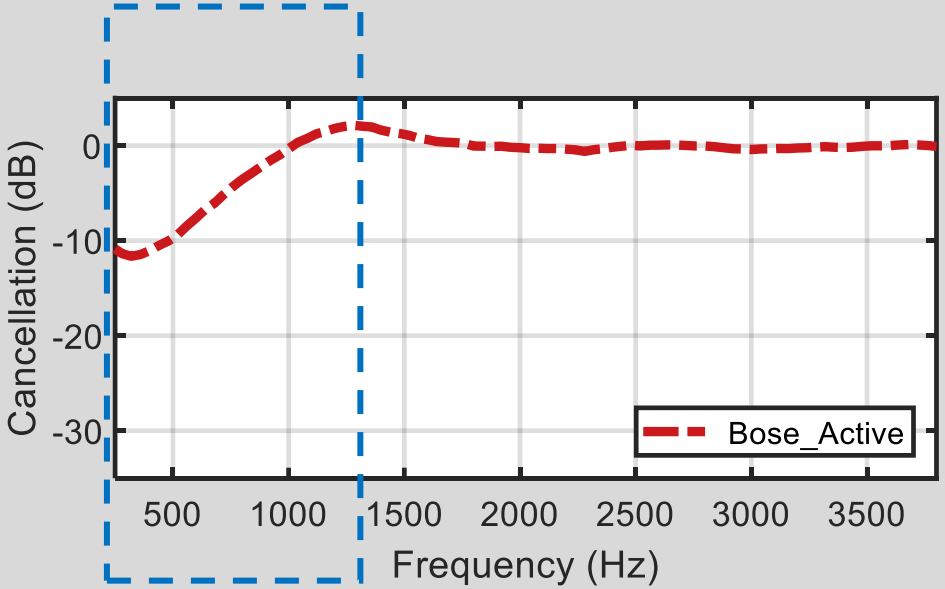


Residual Error

Time

Noise

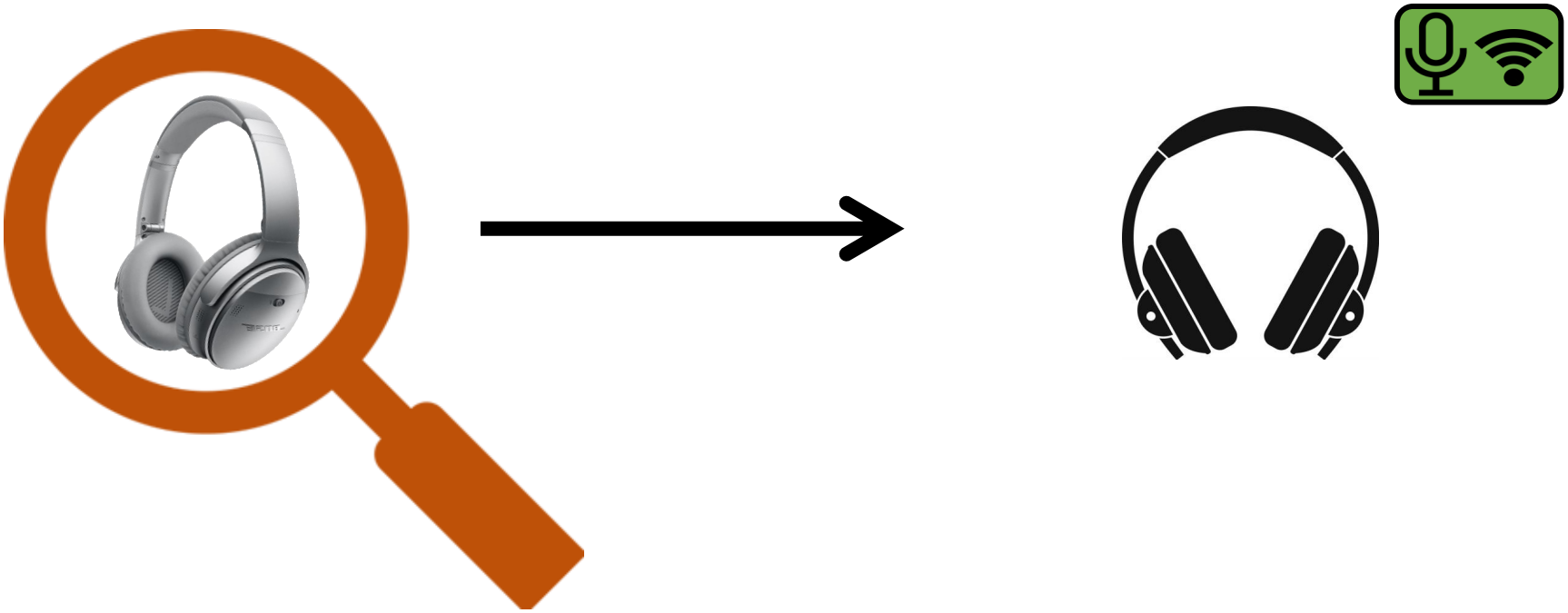
Ref. Mic. DSP Speaker Fb. Mic.

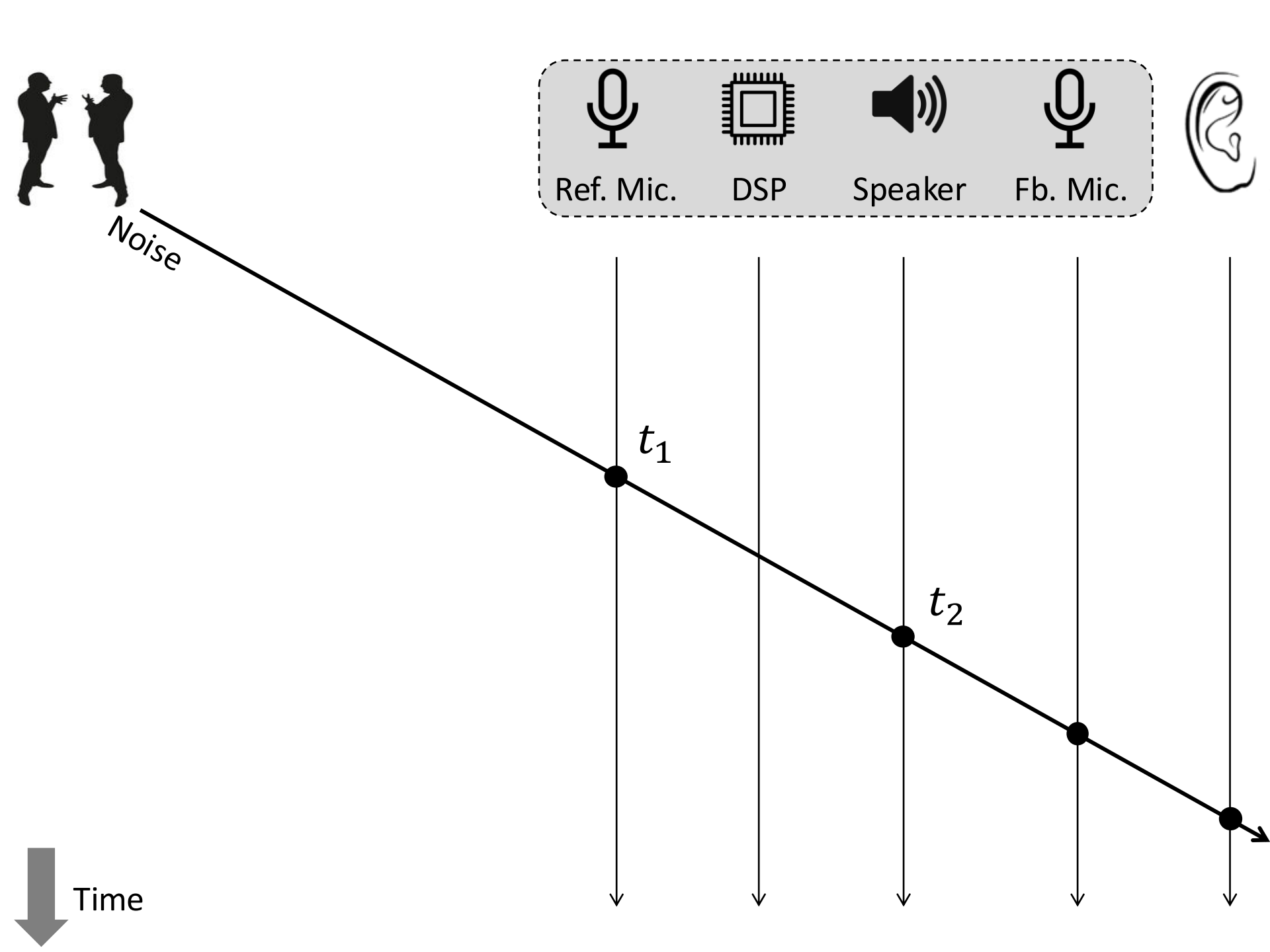


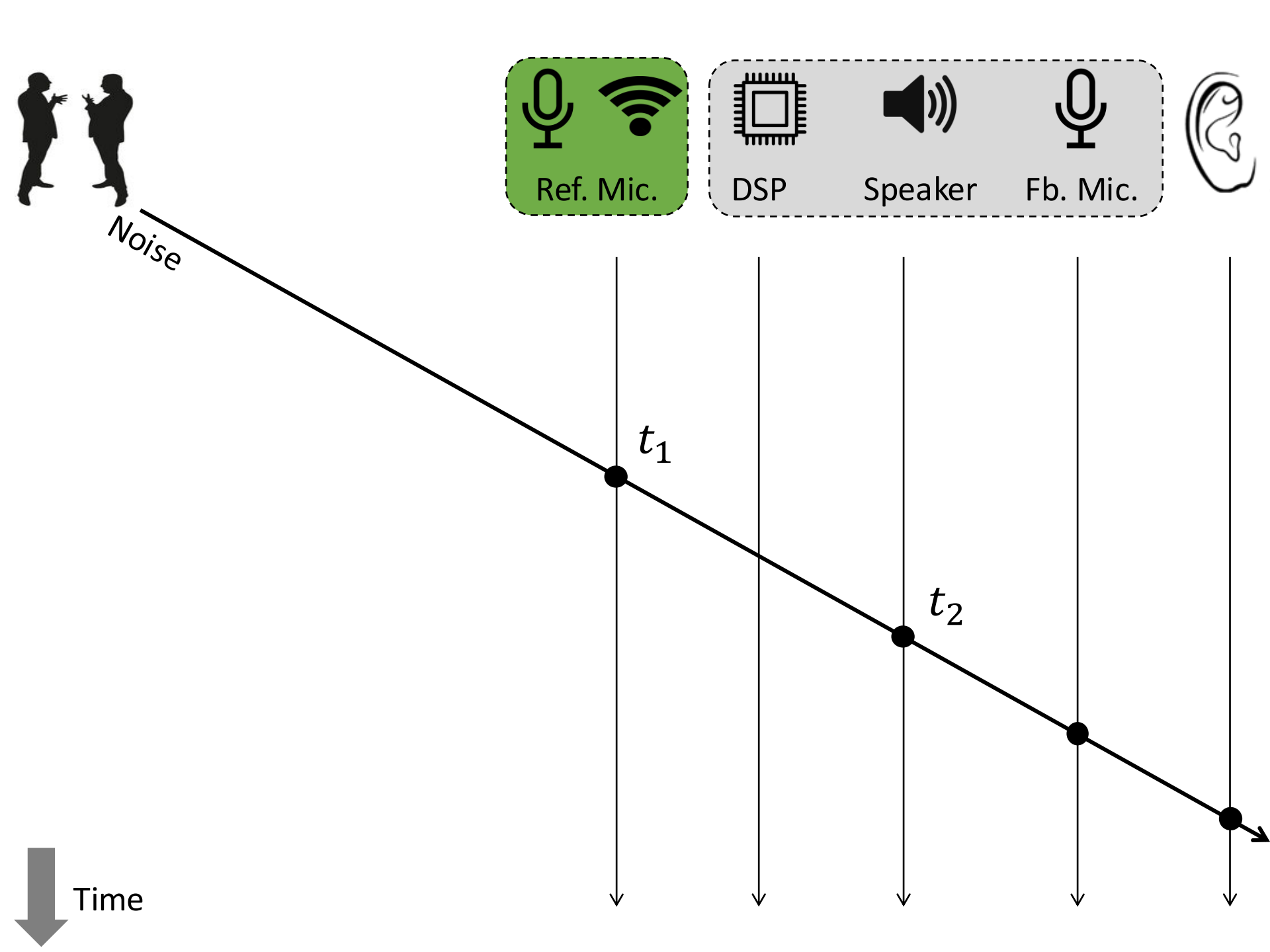
-Noise

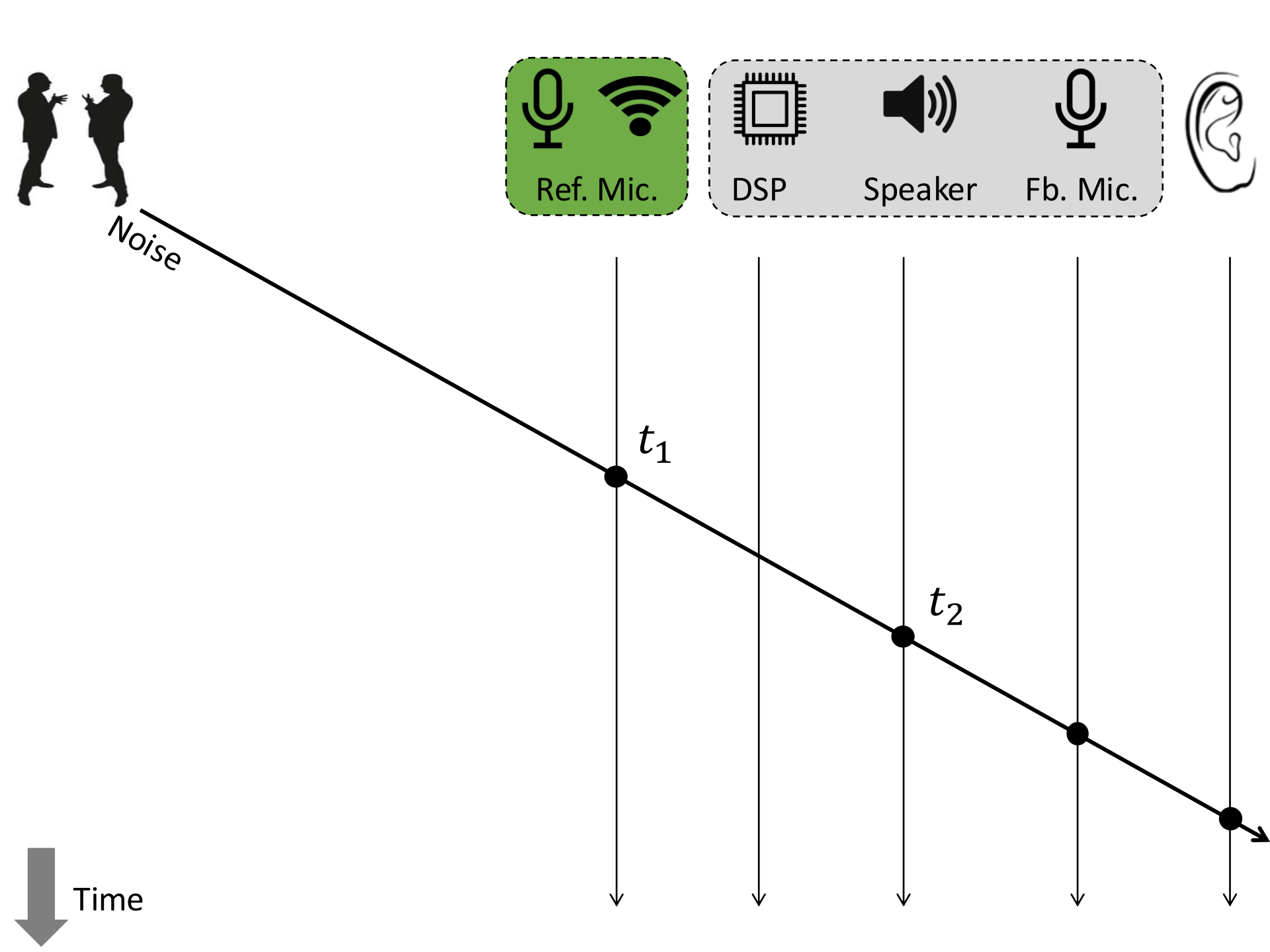
Time

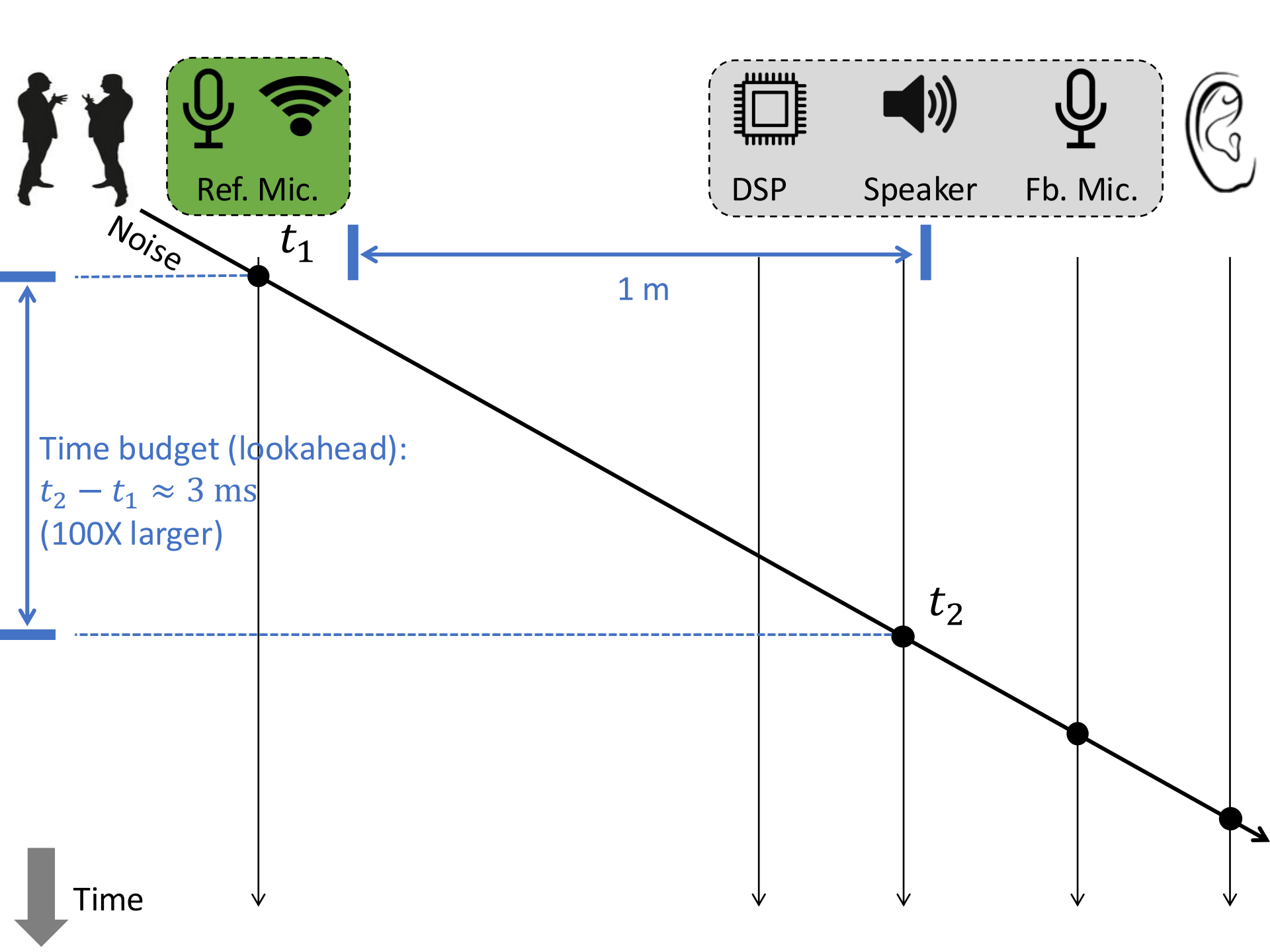
Let’s now look at noise cancellation in MUTE …

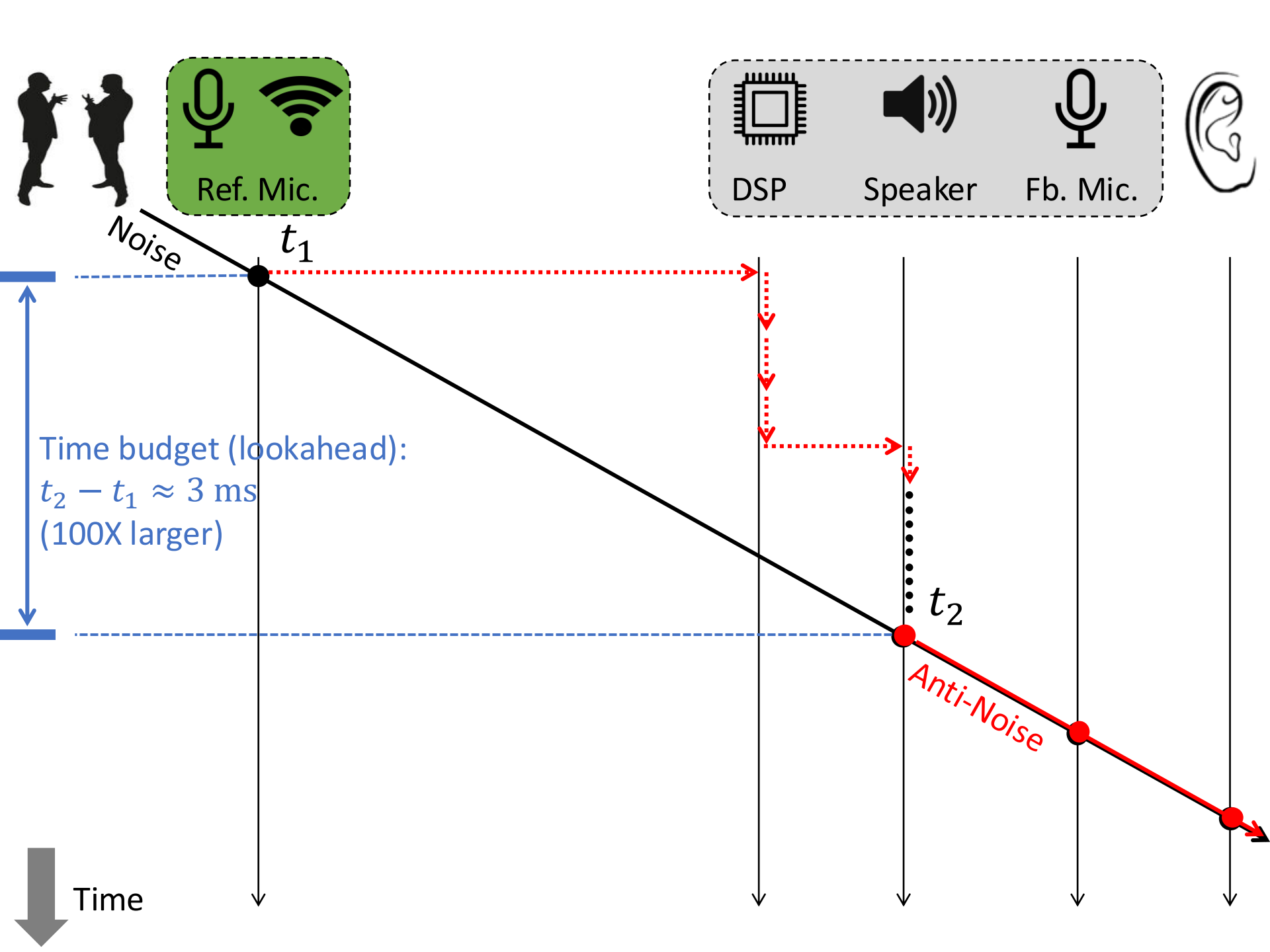


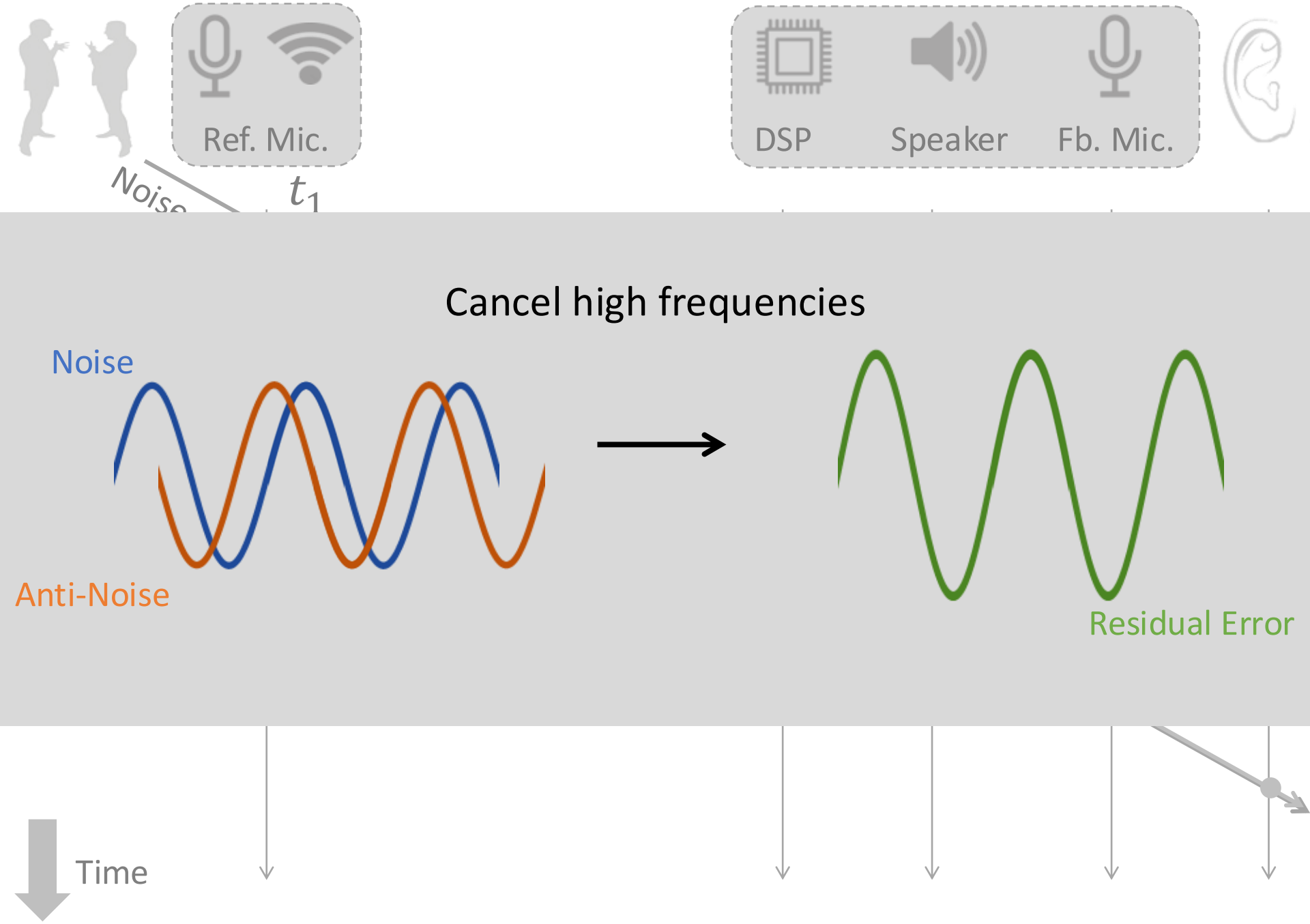

Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
t_2
Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
t_2
Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
t_2
Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
1 m
Time budget (lookahead):
$t_2 - t_1 \approx 3$ ms
(100X larger)
t_2
Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
Time budget (lookahead):
$t_2 - t_1 \approx 3$ ms
(100X larger)
t_2
Anti-Noise
Time


Ref. Mic.
DSP
Speaker
Fb. Mic.
Noise
t_1
Cancel high frequencies
Noise
Anti-Noise
Residual Error
Time

Talk Outline

How can *MUTE* leverage lookahead?

Timing Gain → Wideband Cancellation

Signal Processing Gain → Non-Causal Filtering

Application-Specific Gain → Sound Source Profiling

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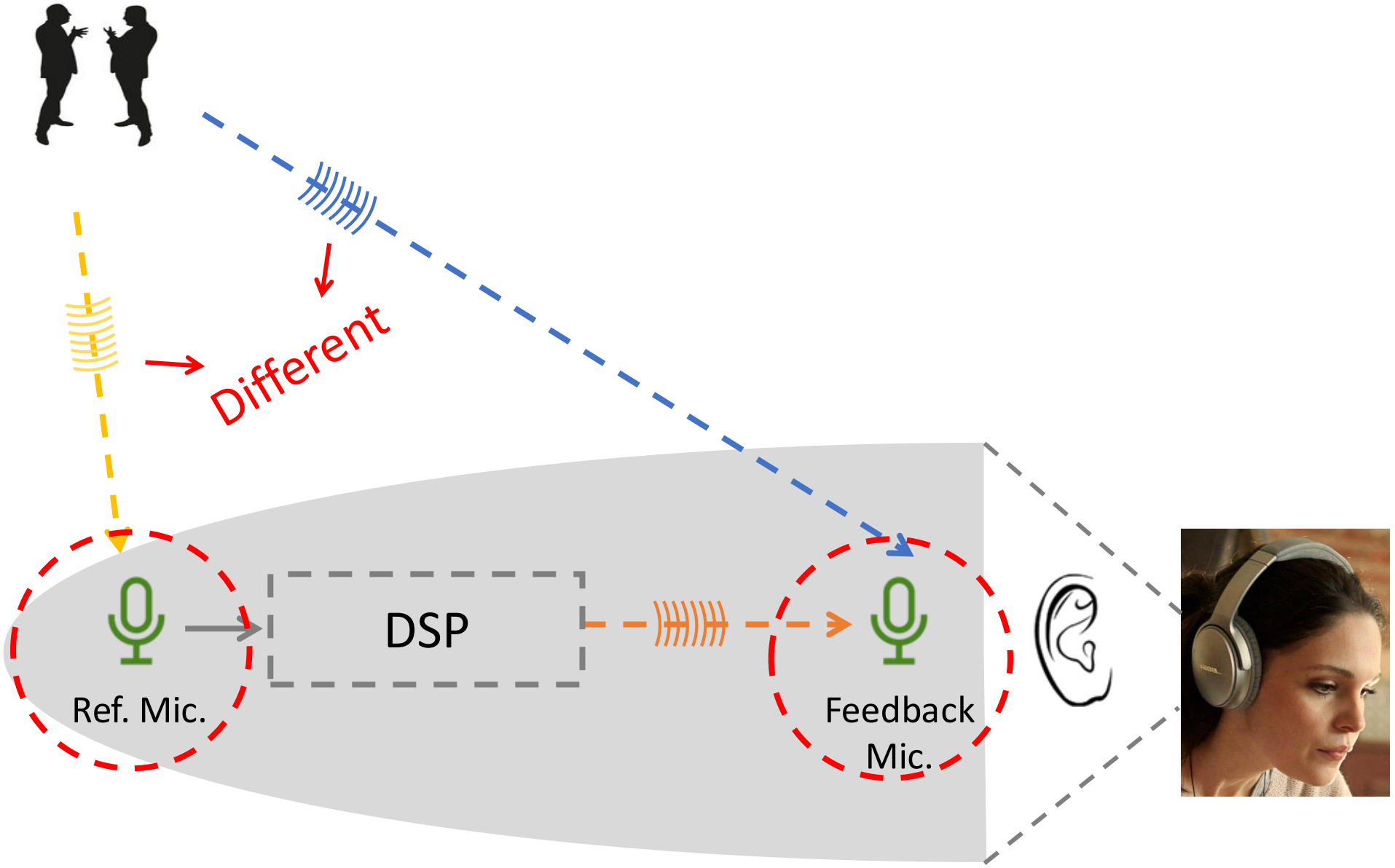
Noise Cancellation Primer



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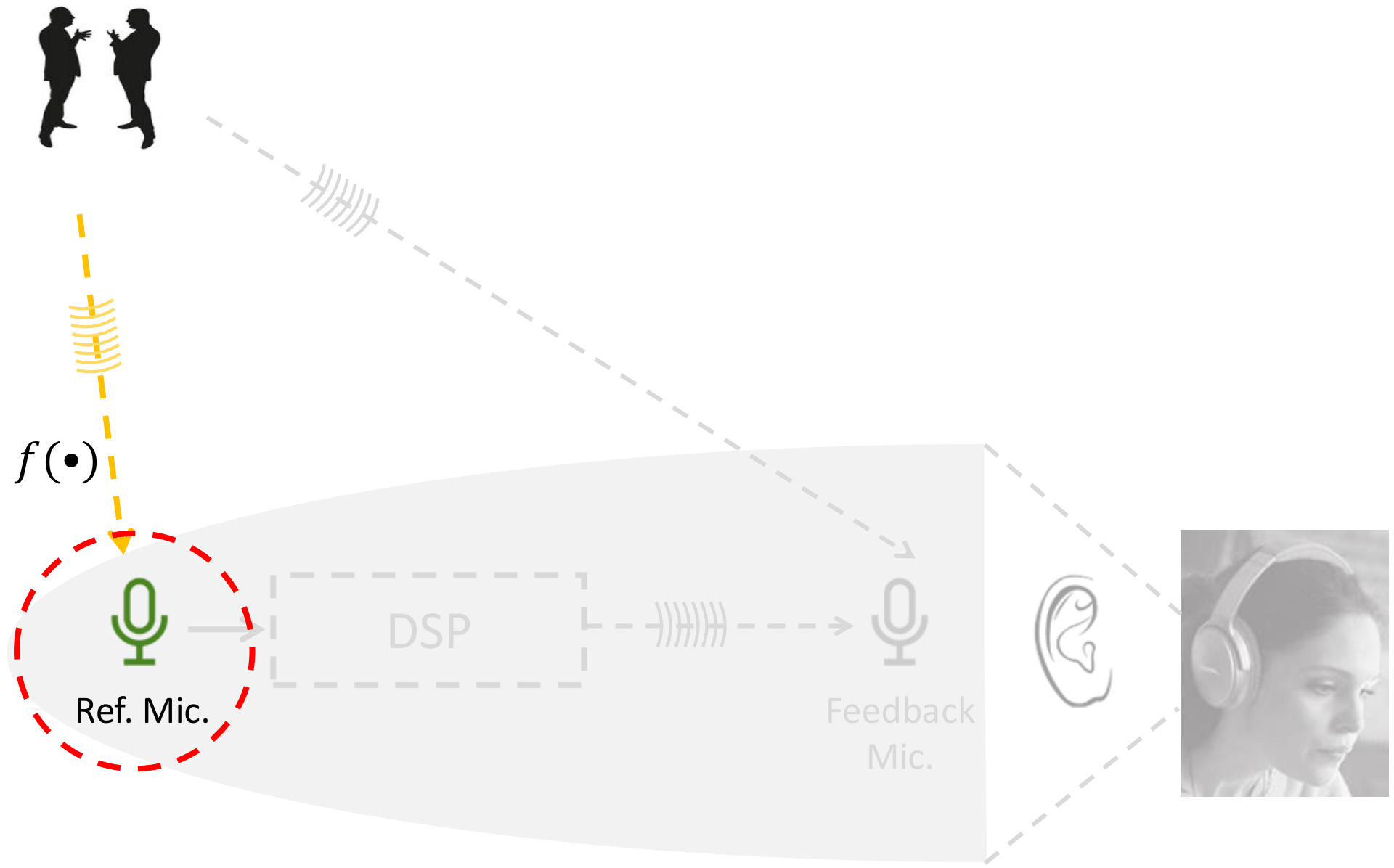
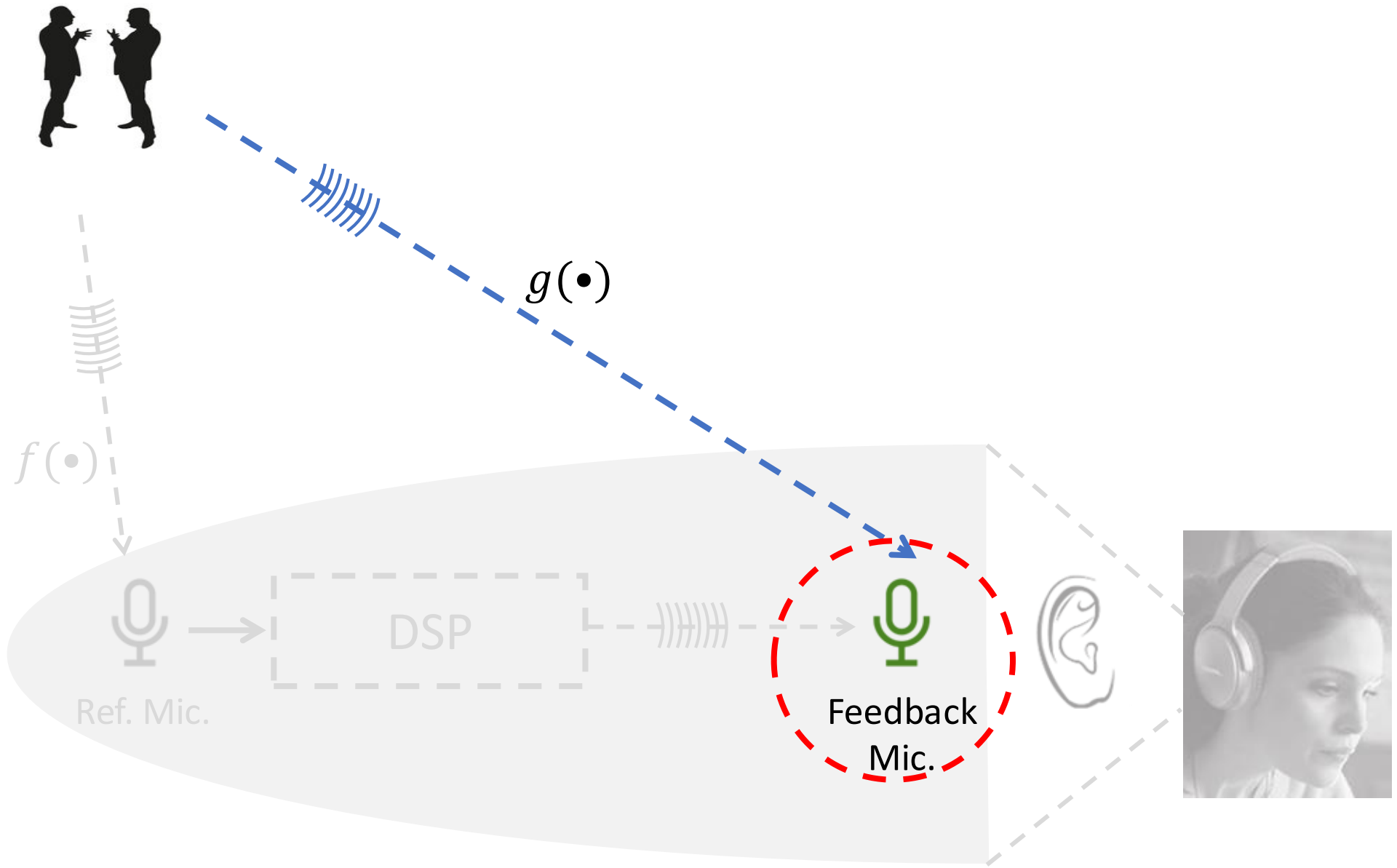
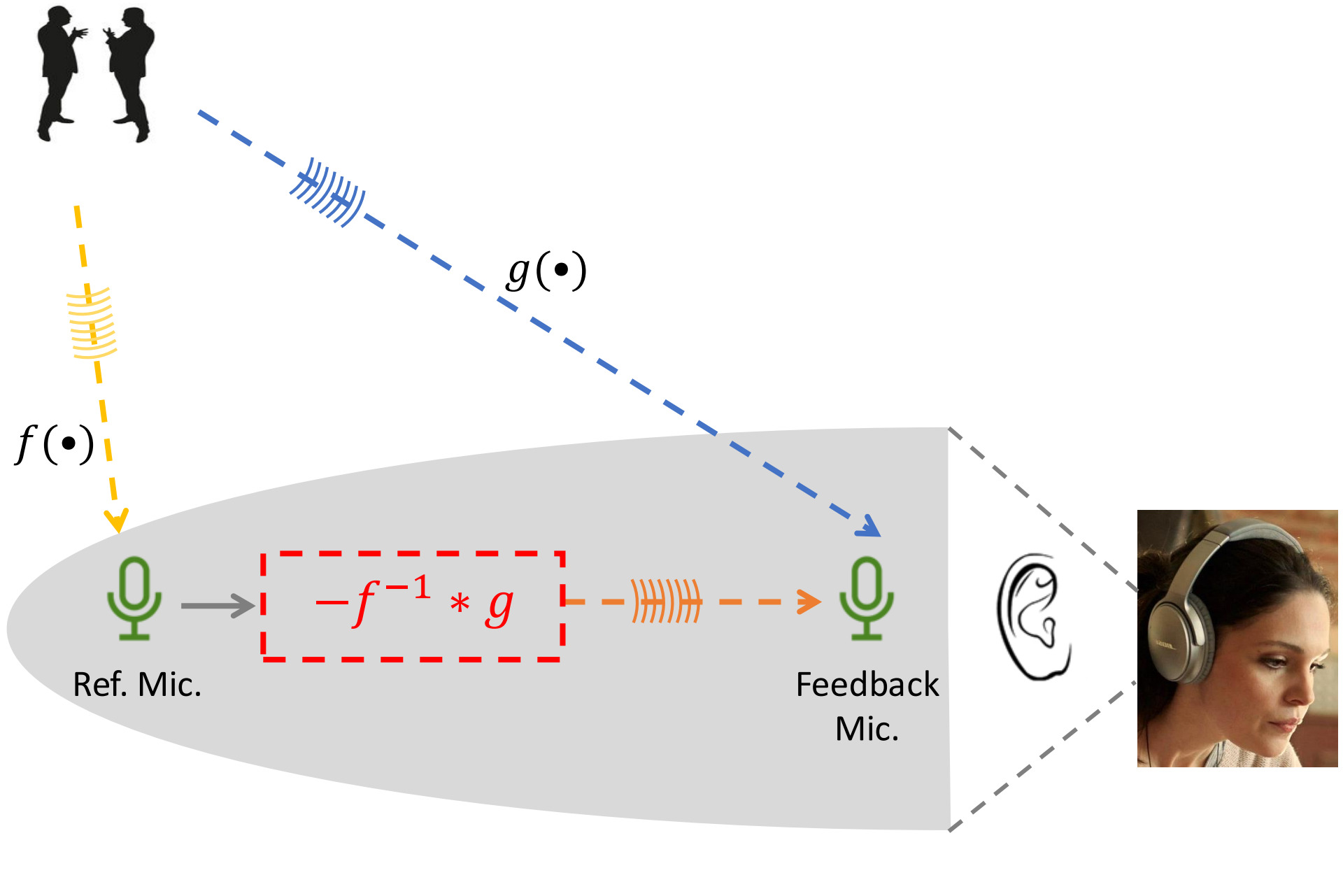


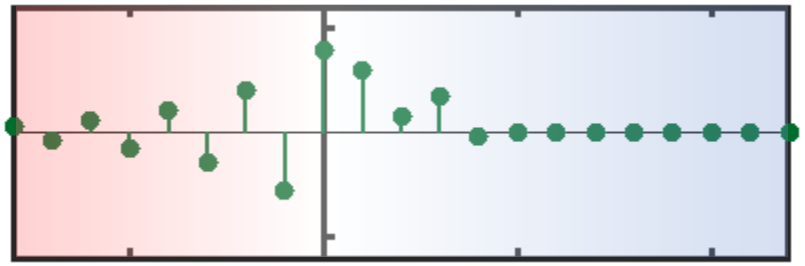
Noise Cancellation Primer



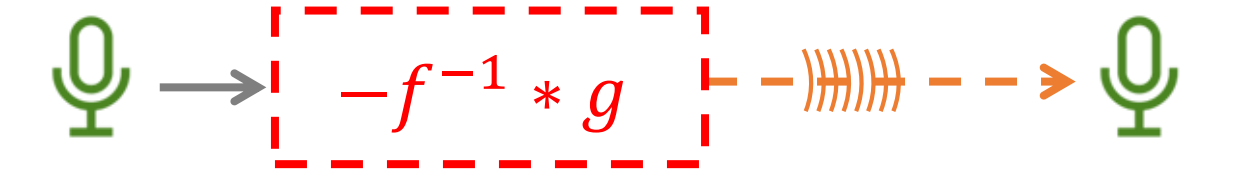
Noise Cancellation Primer



Channel Impulse Response



Future Current Past



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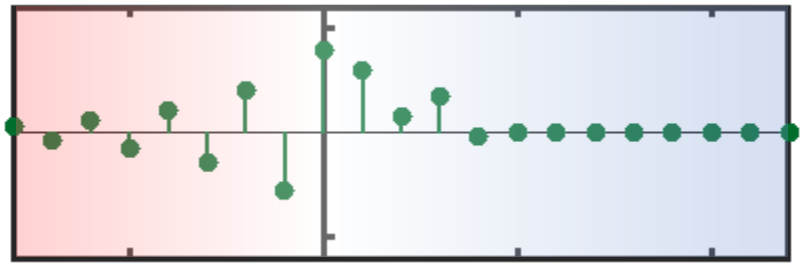
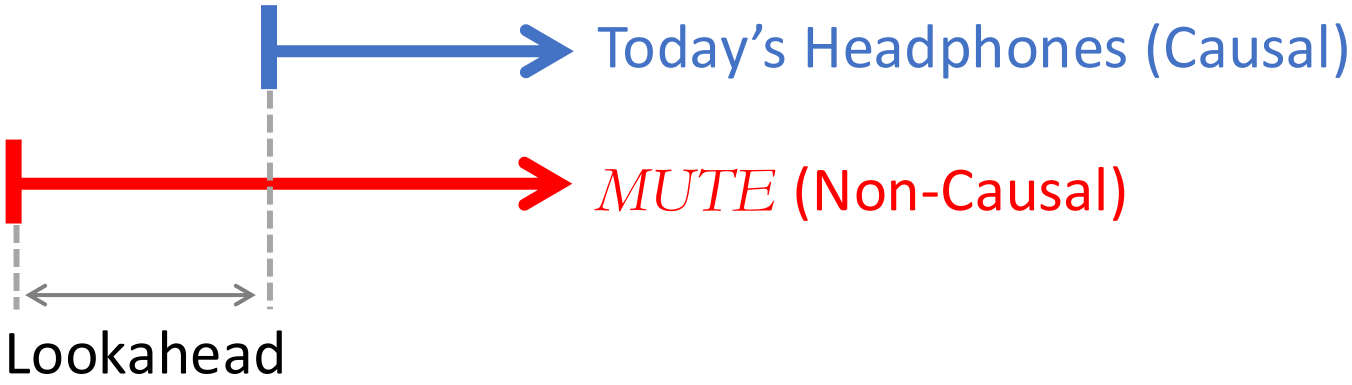


Future Current Past



"Lookahead" → Non-Causal Filtering → Better Cancellation

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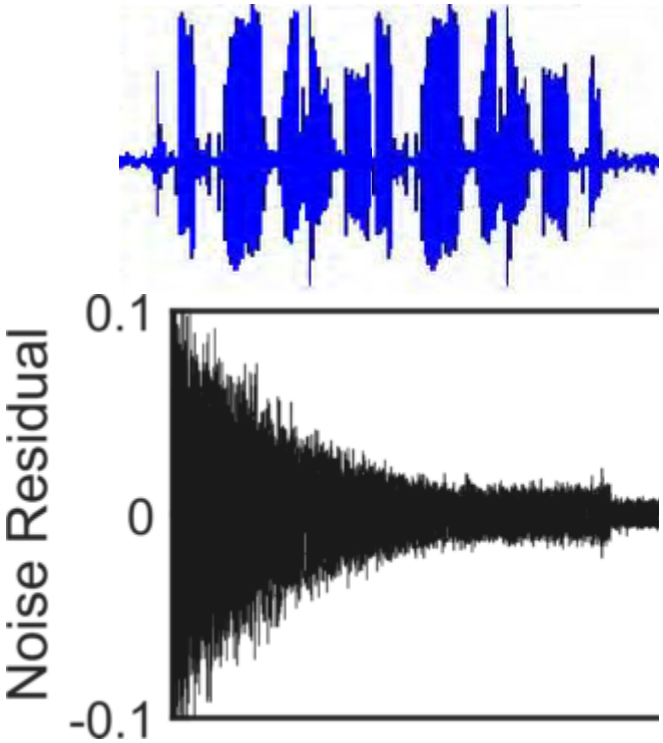
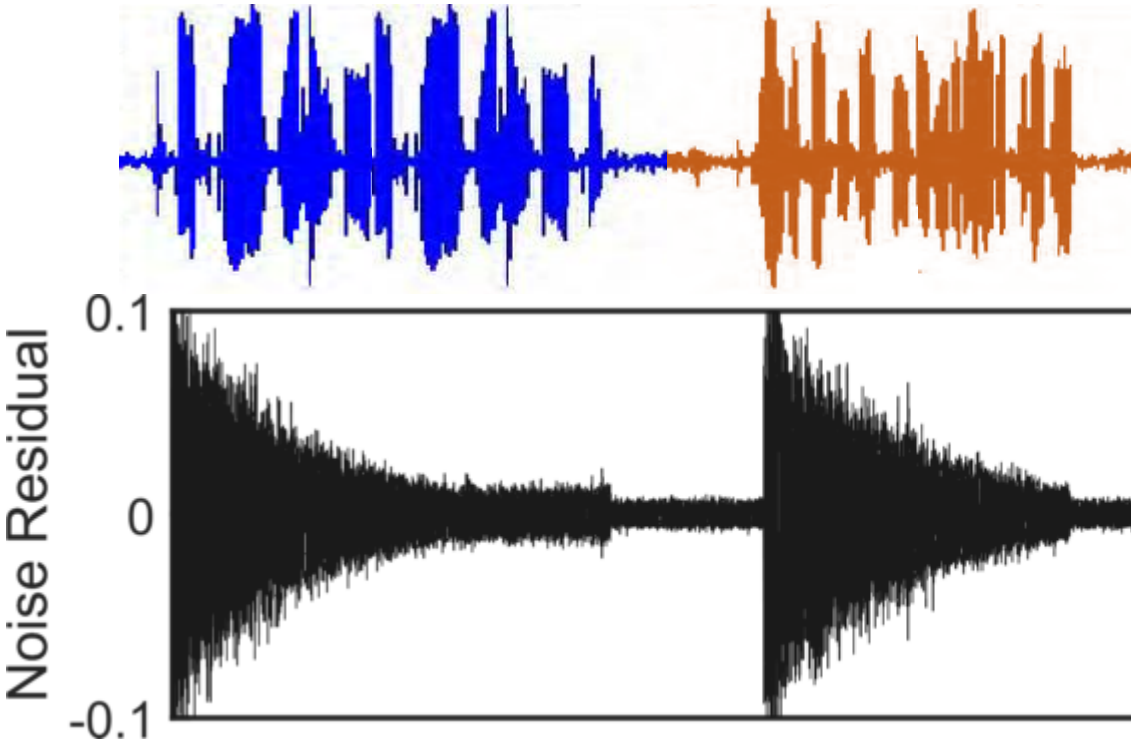
Alice

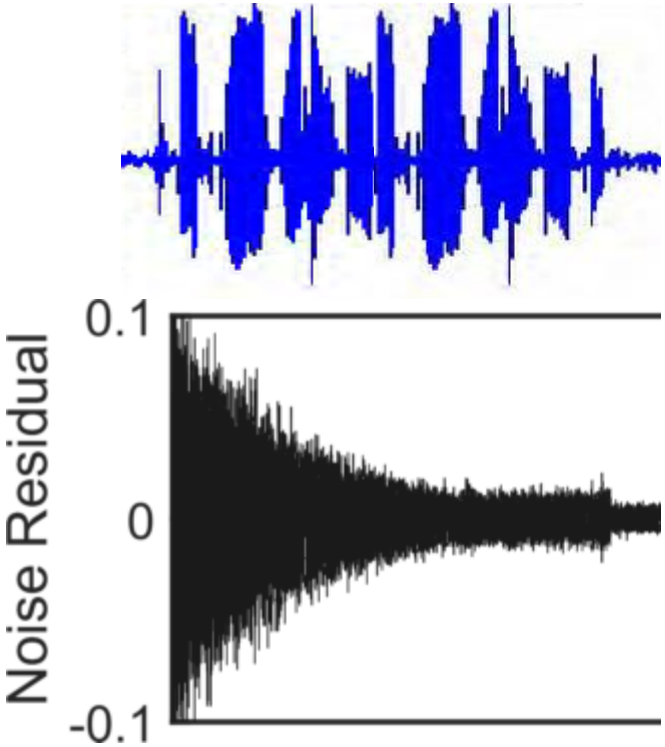


Alice Bob

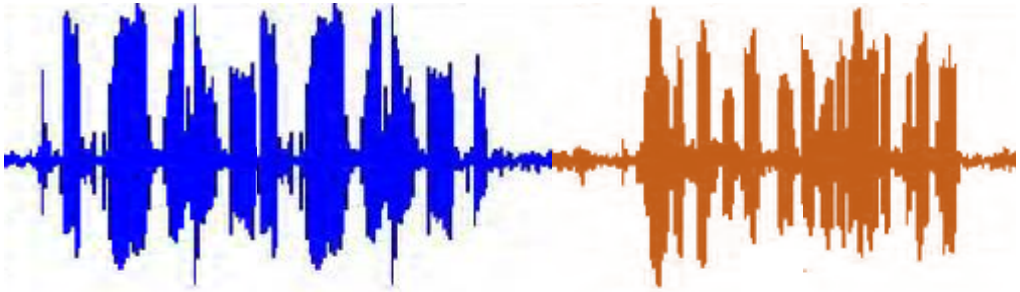


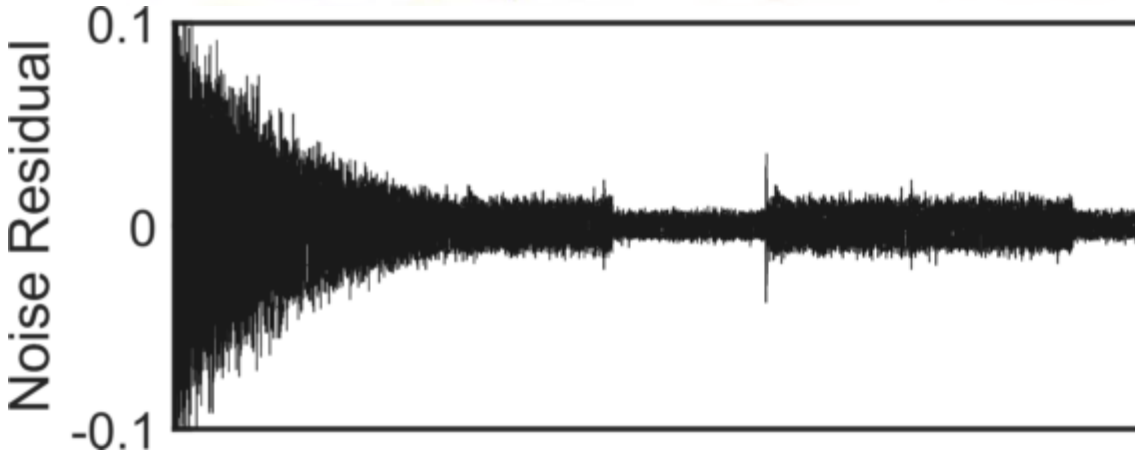
With lookahead …

Alice



Alice Bob





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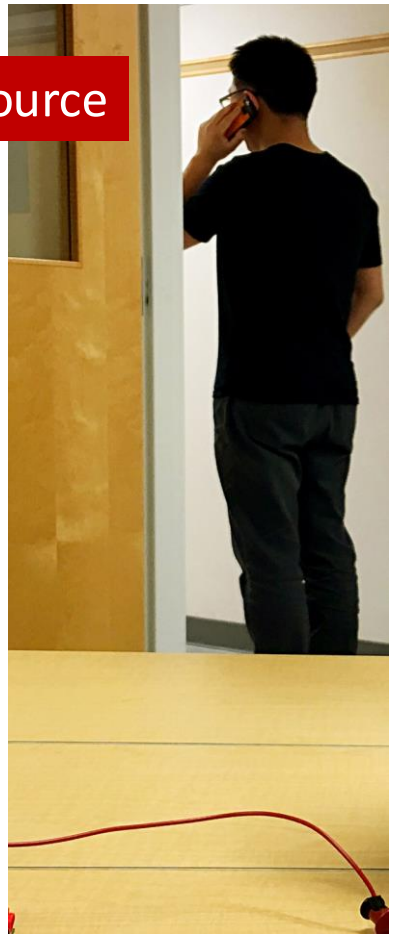
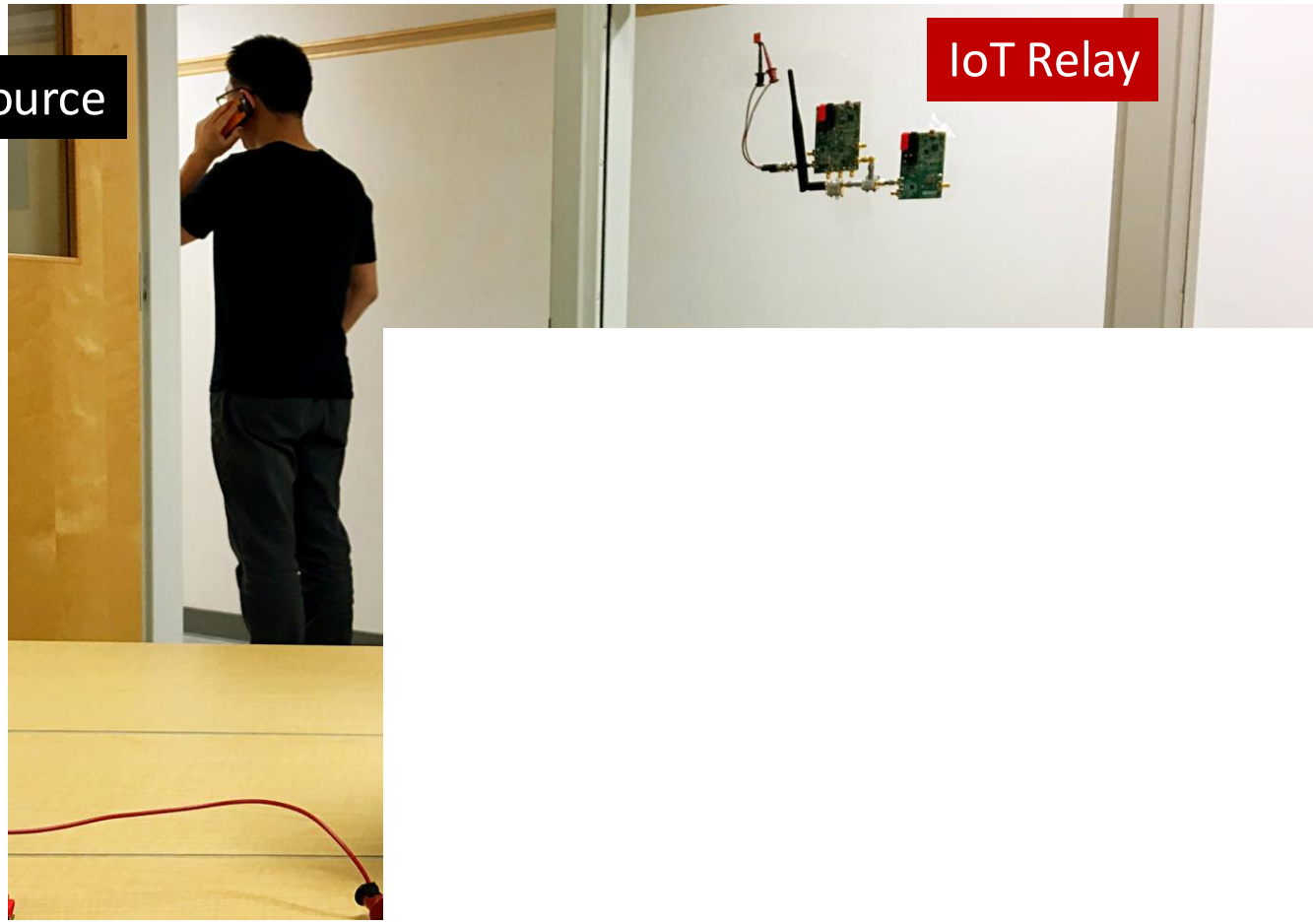
Implementation & Evaluation

MUTE Platform

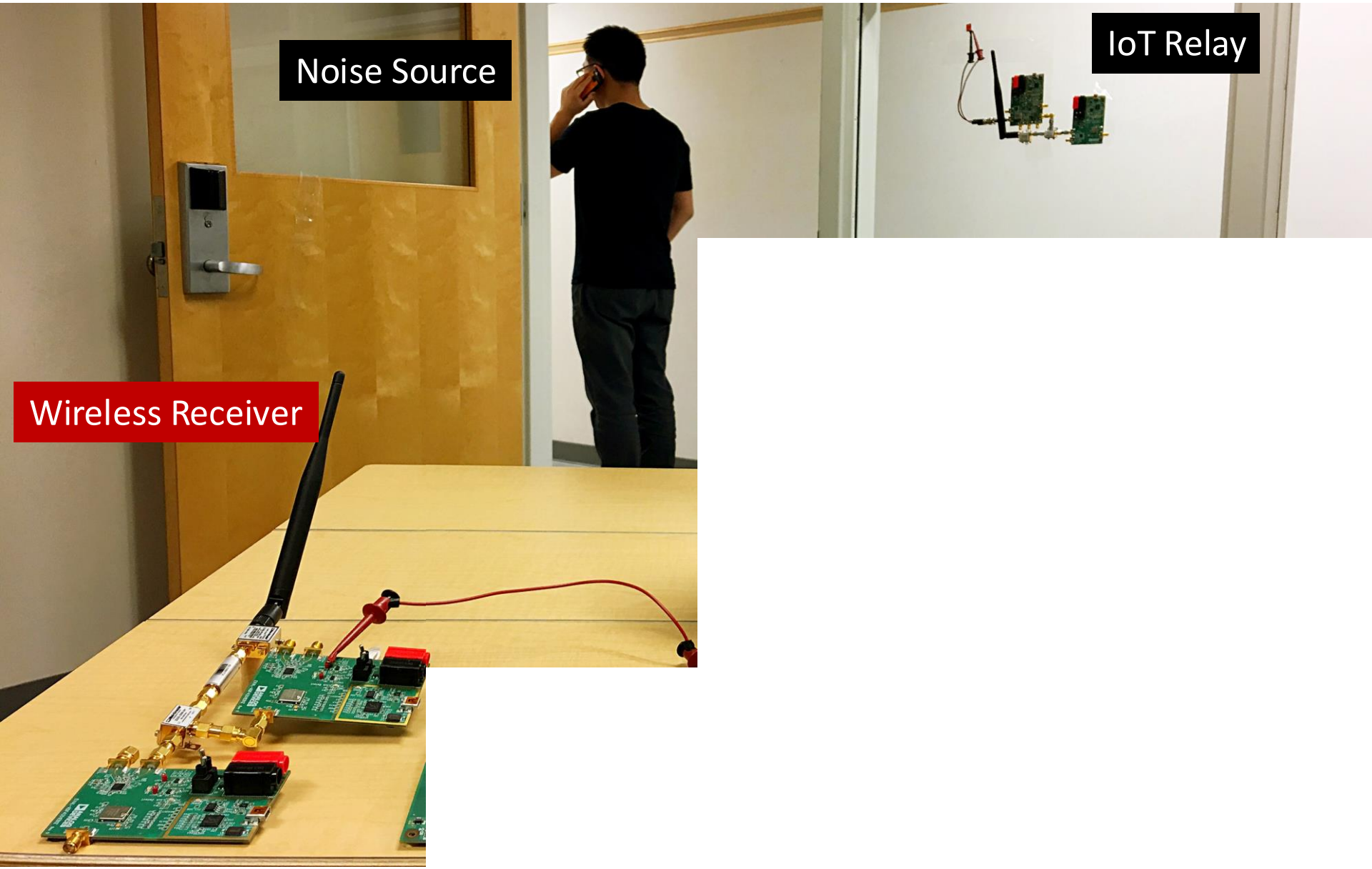
Noise Source



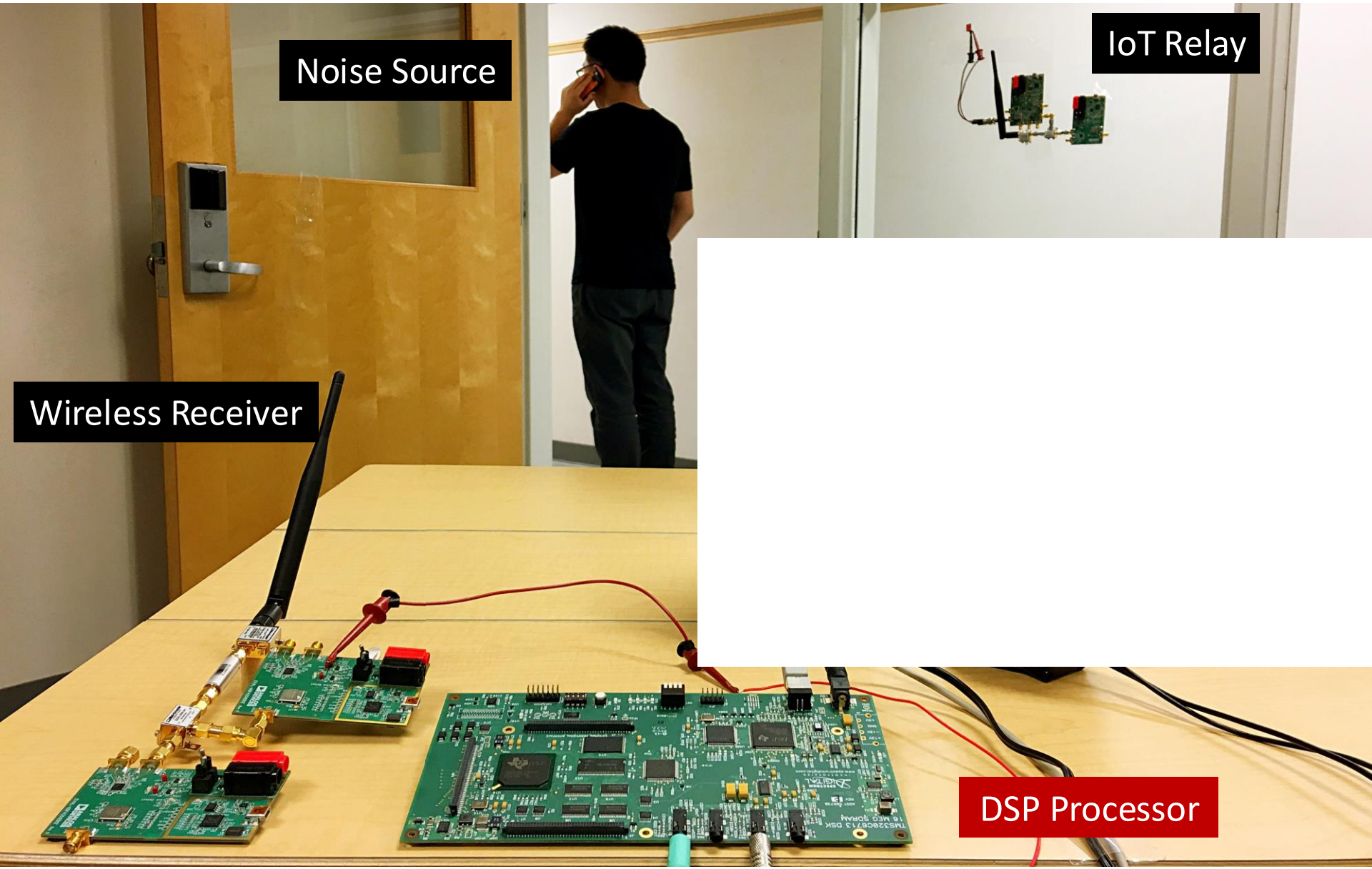
MUTE Platform



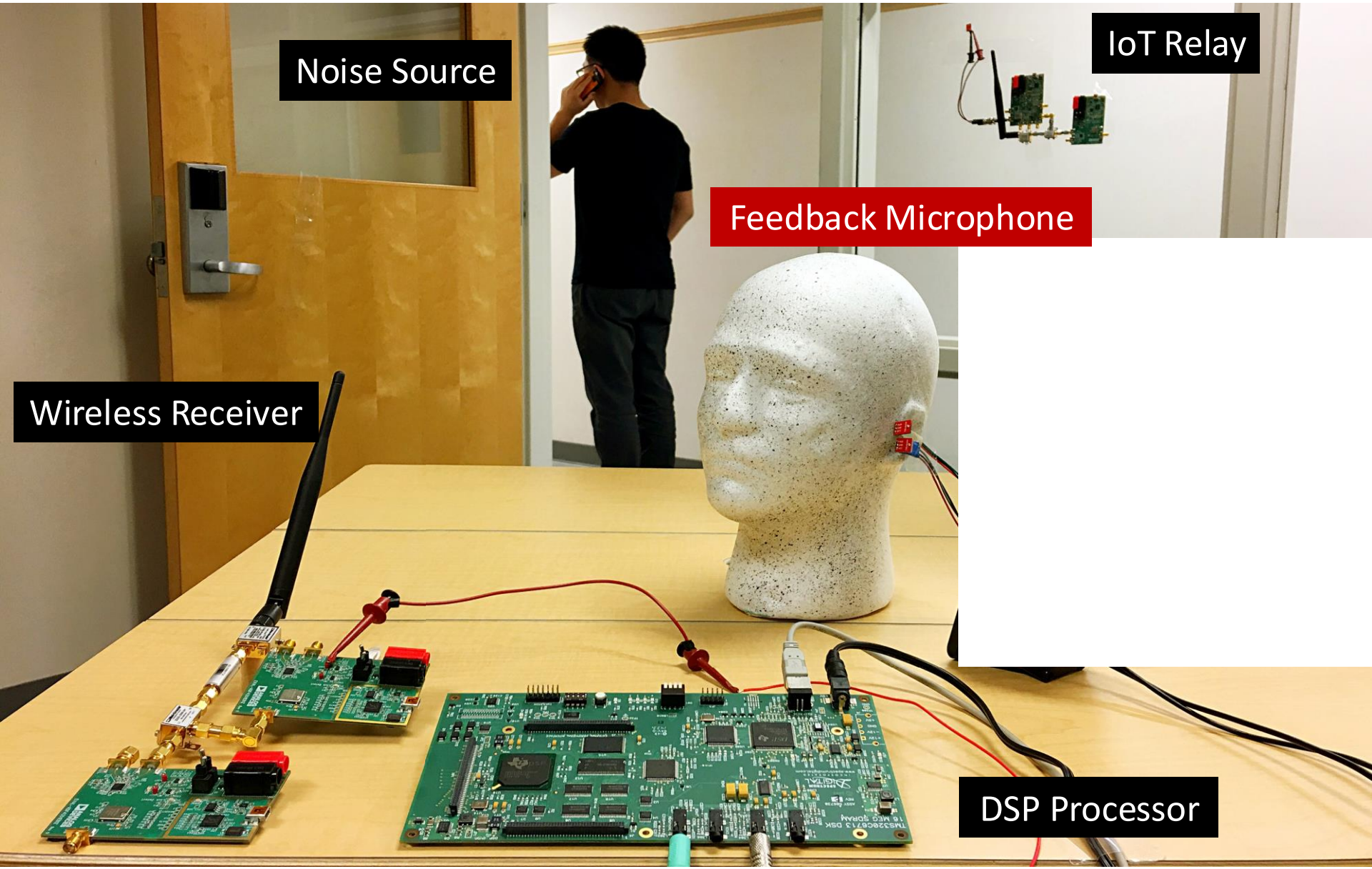
MUTE Platform



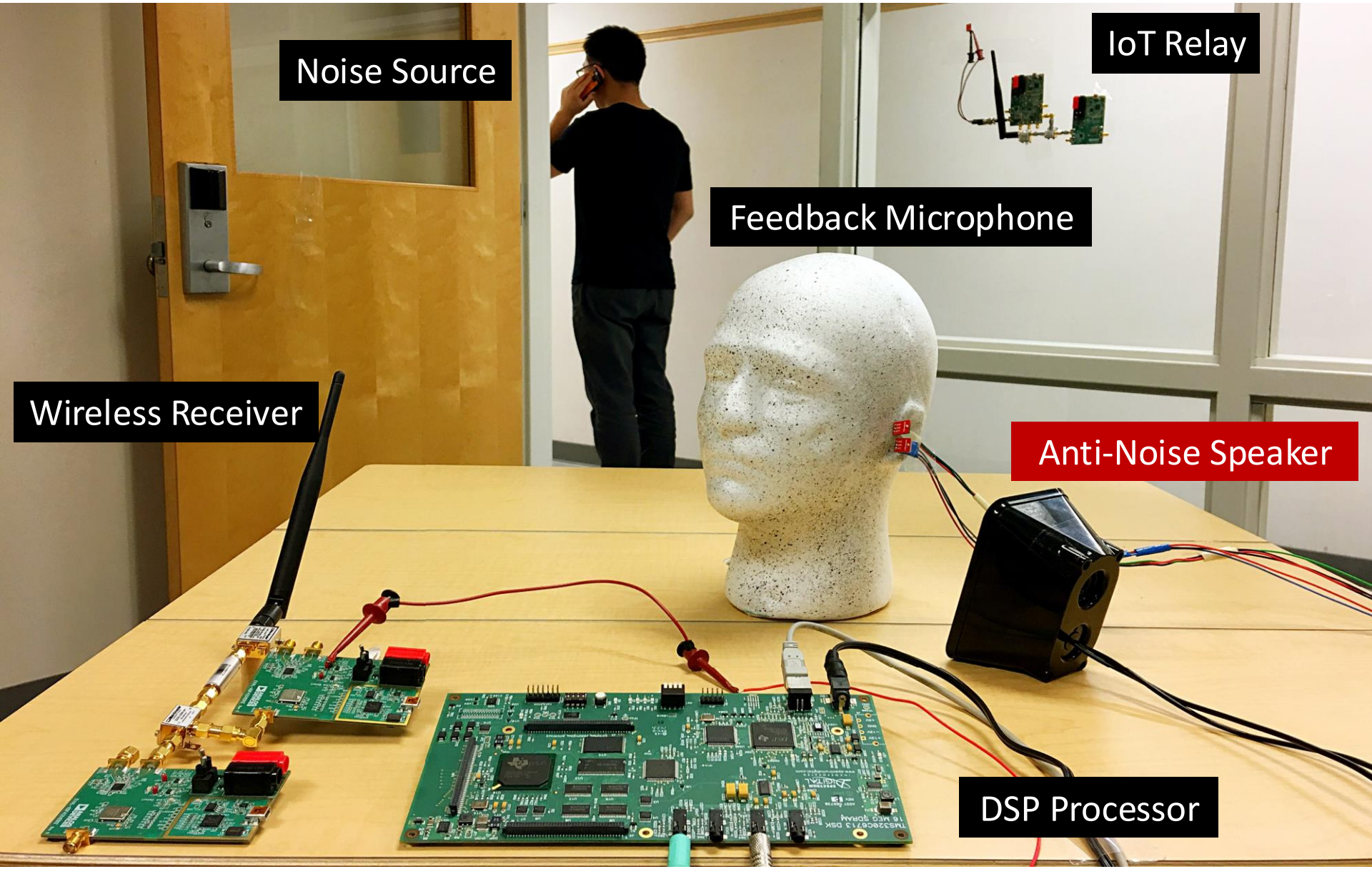
MUTE Platform



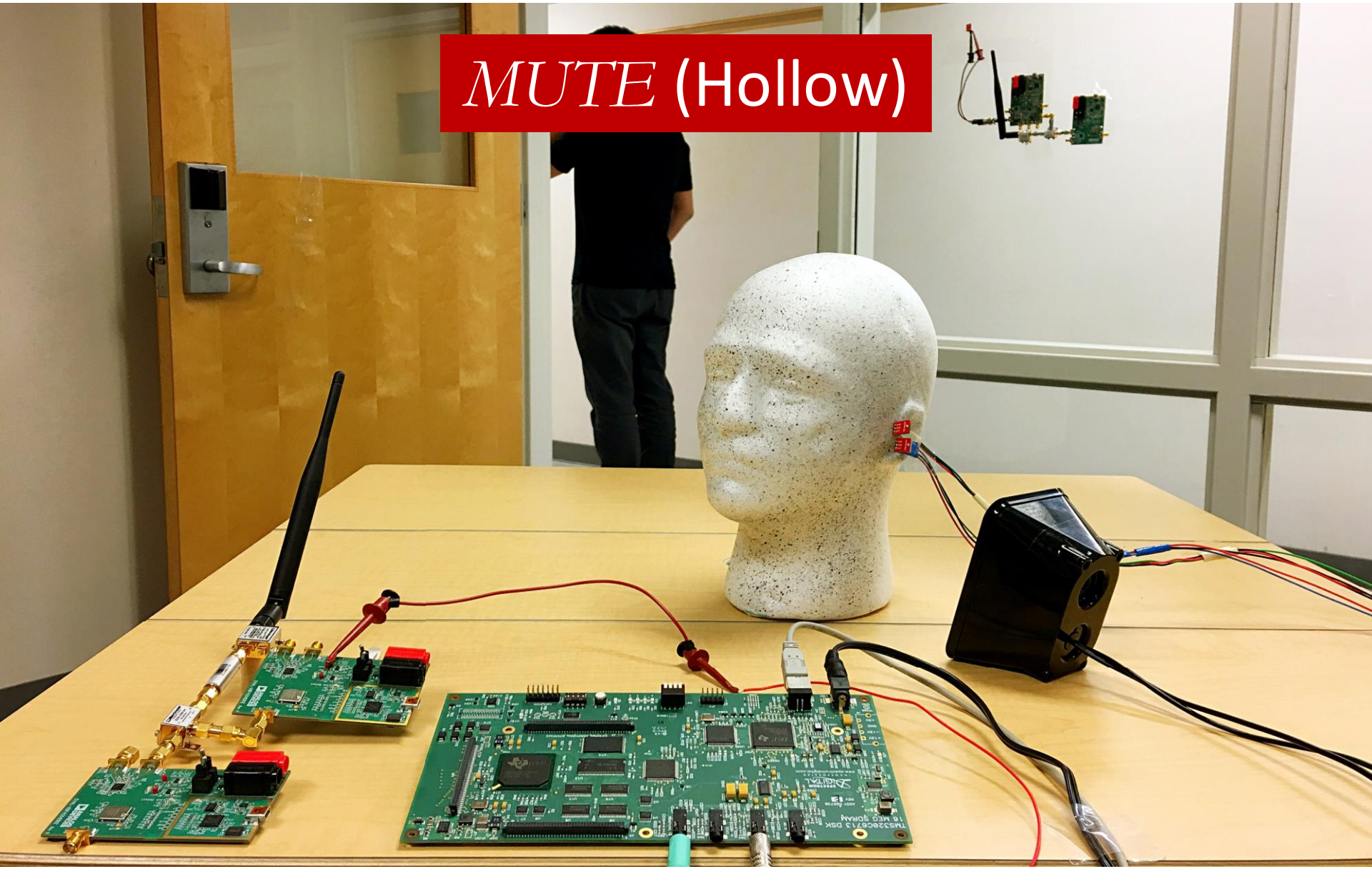
MUTE Platform



MUTE Platform

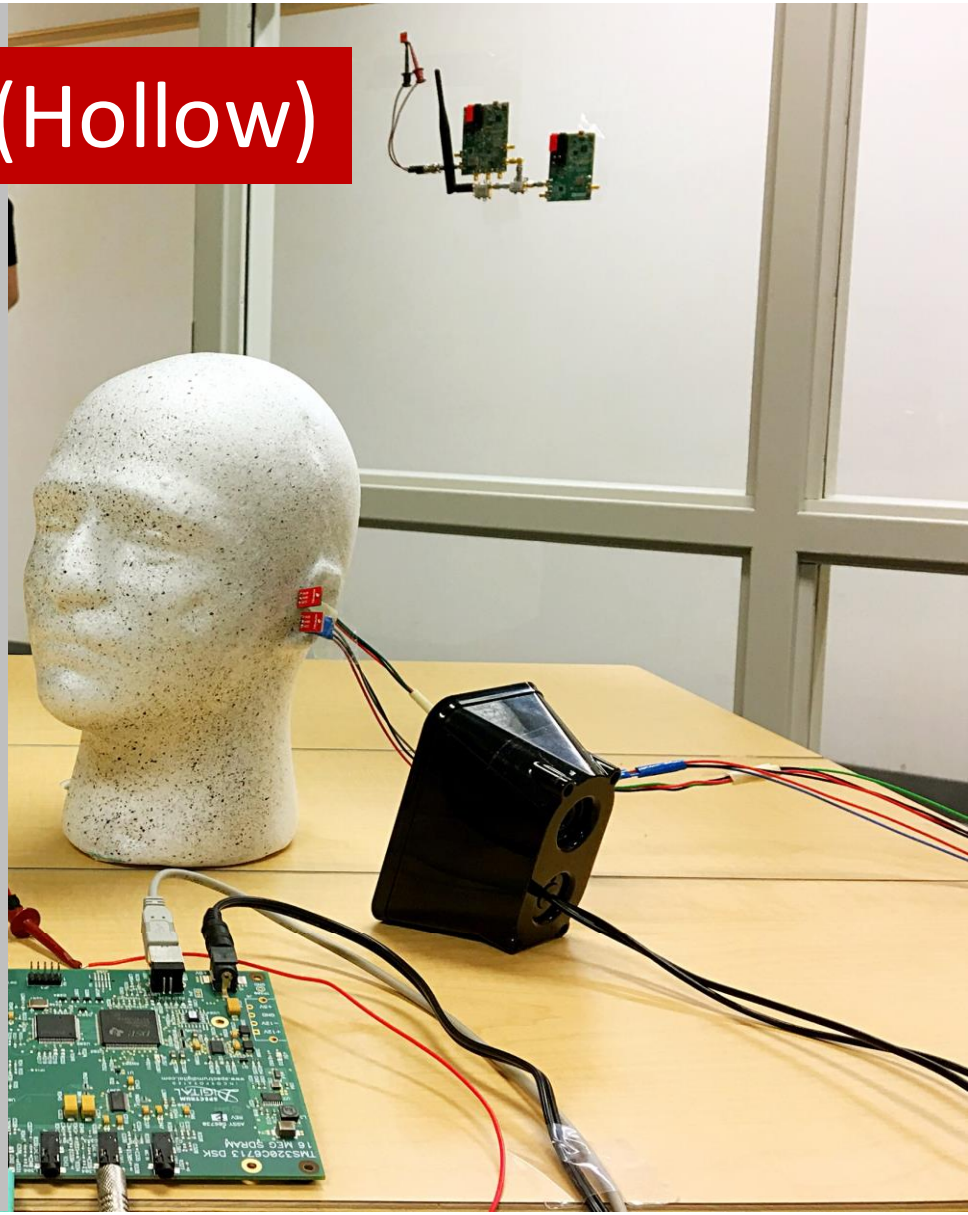


MUTE Platform



MUTE Platform

MUTE (Hollow)



Evaluation

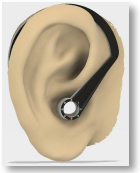
Goal: Comparable Performance

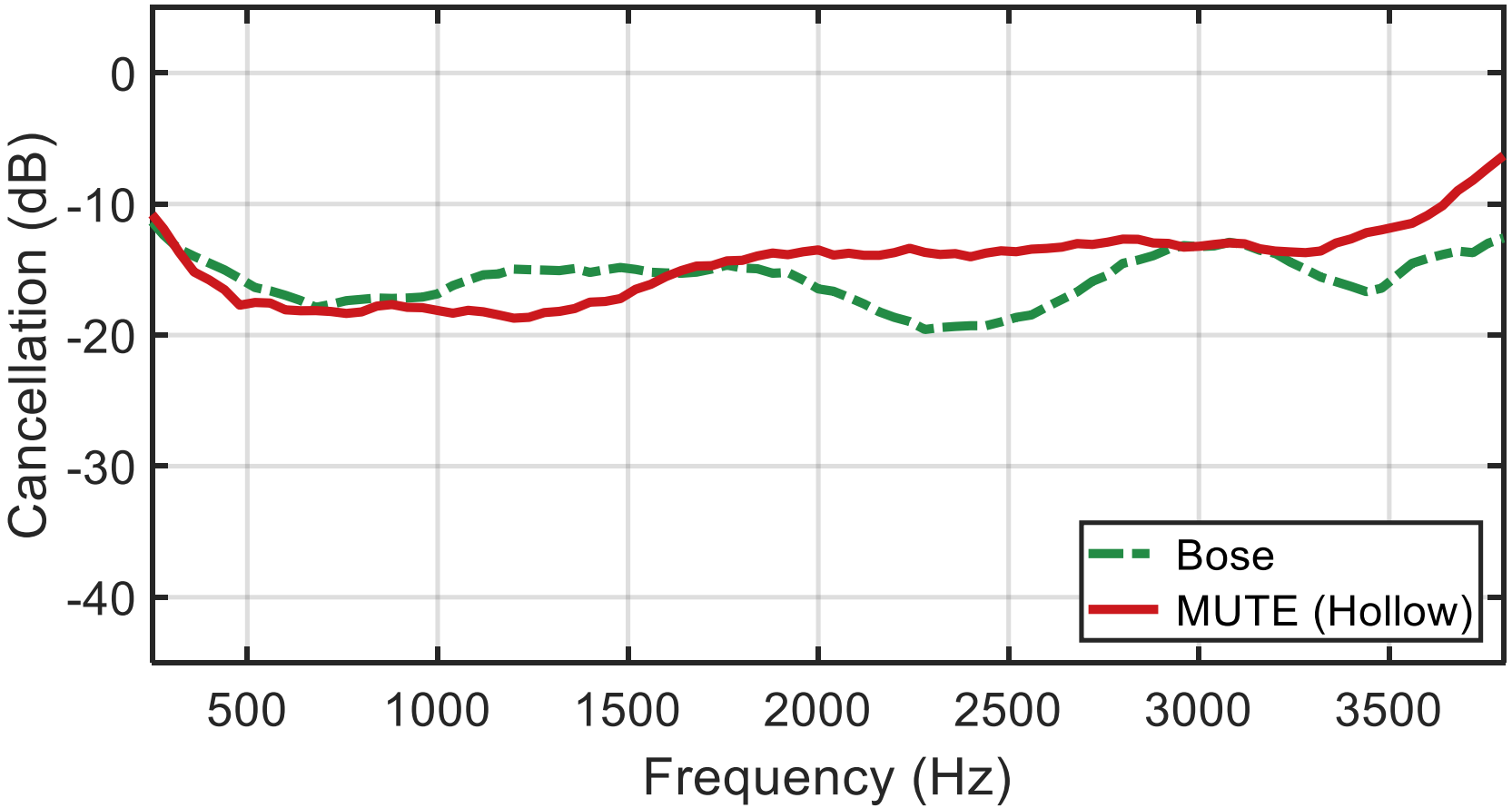
MUTE (Hollow)

Ear Blocking Headphone

1. Bose headphone

2. *MUTE* hollow design (comfort)

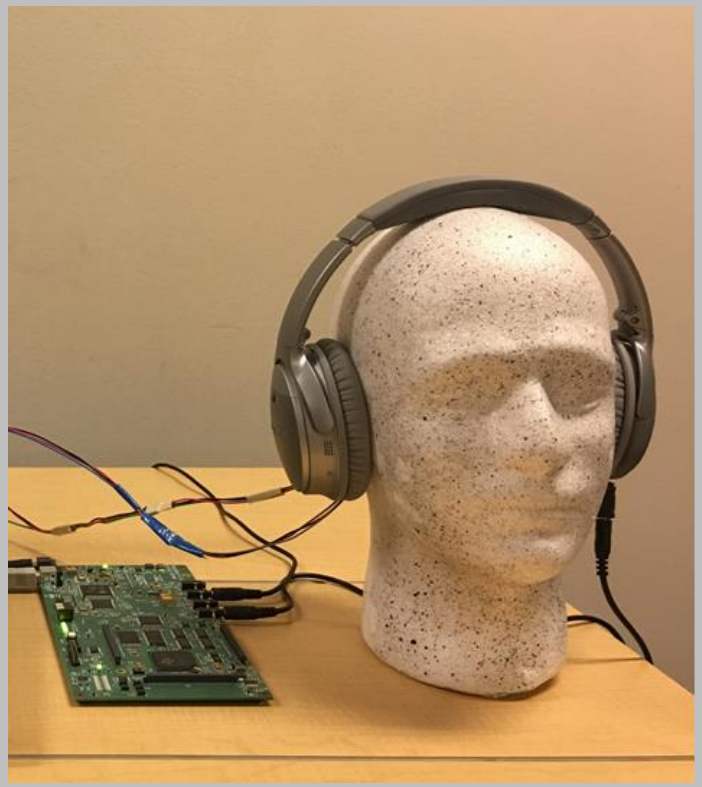




Evaluation

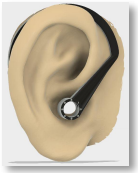
Goal: Better Performance

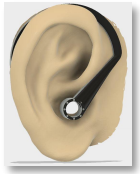
MUTE (Non-Hollow)

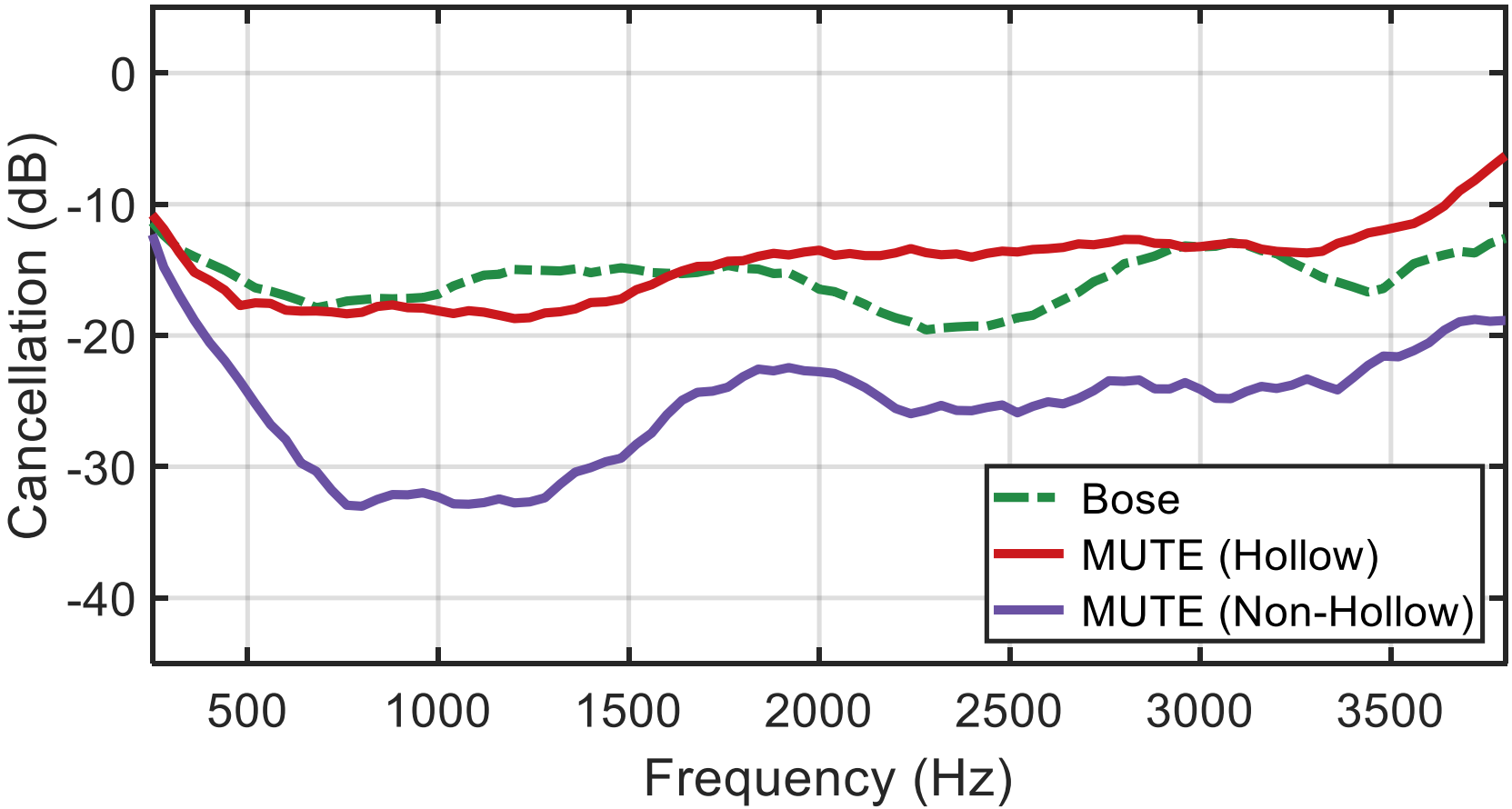


Ear Blocking Headphone

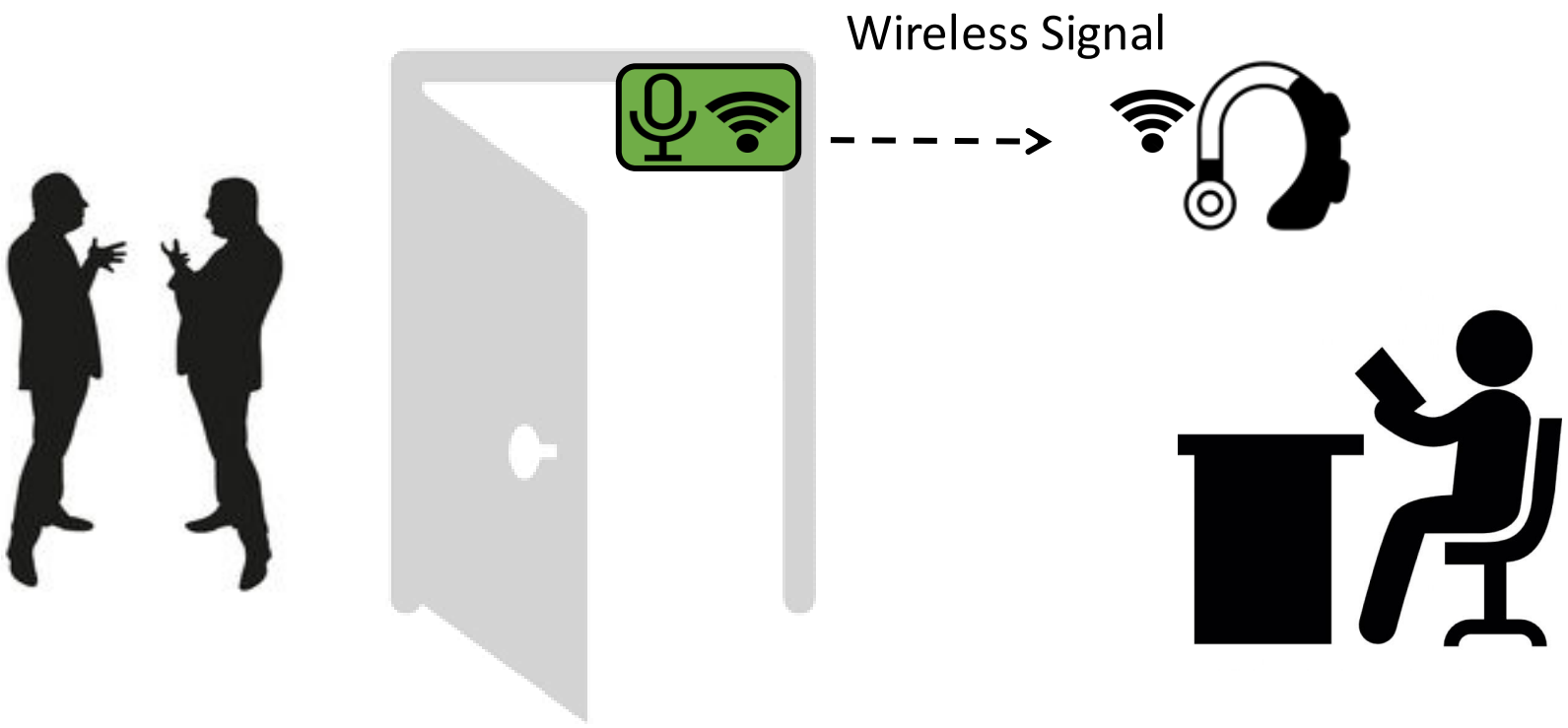
1. Bose headphone 

2. *MUTE* hollow design (comfort) 

3. *MUTE* non-hollow design (performance)  + 



Finishing up

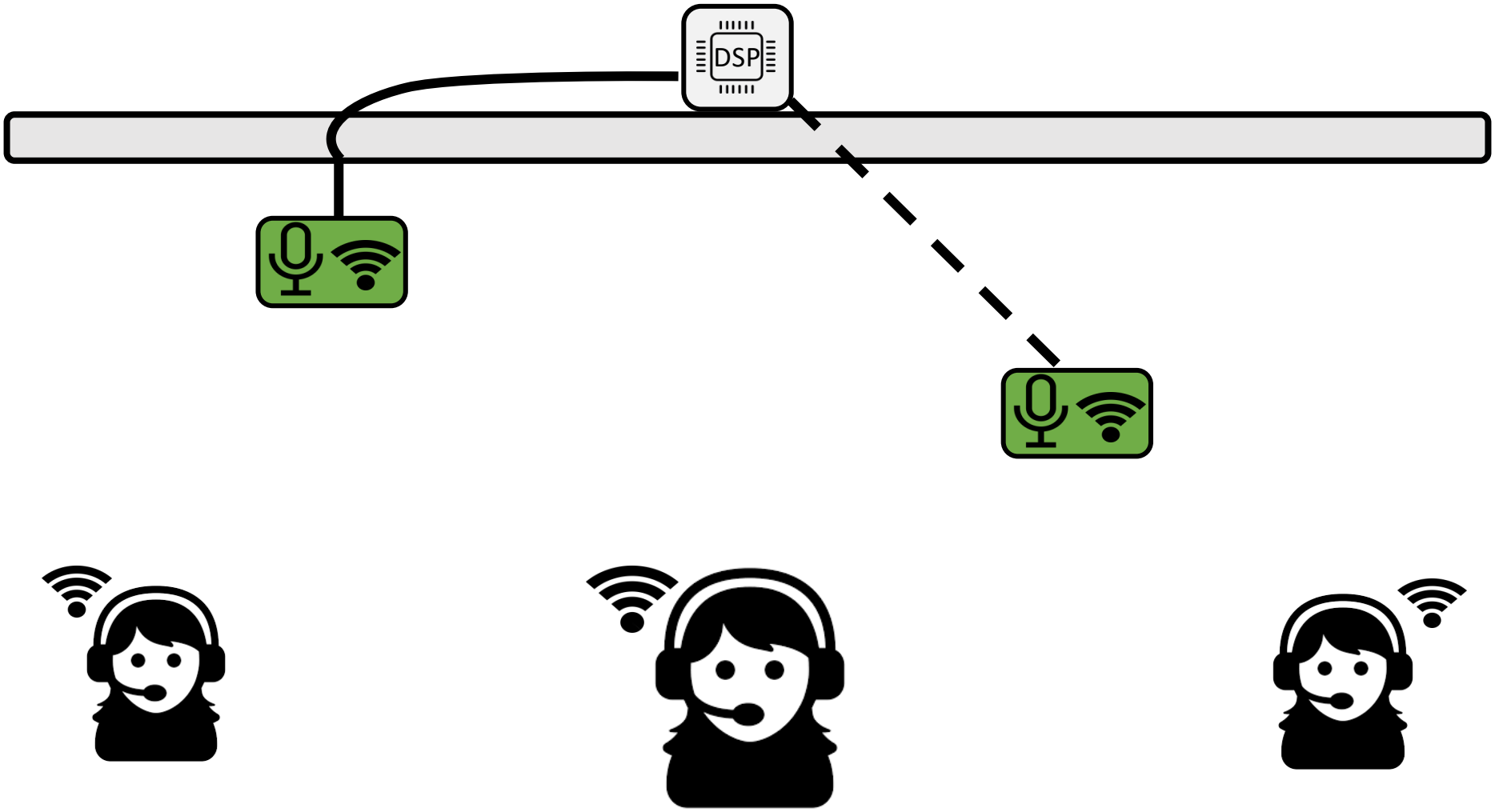

Wireless Signal

MUTE Tabletop Relay

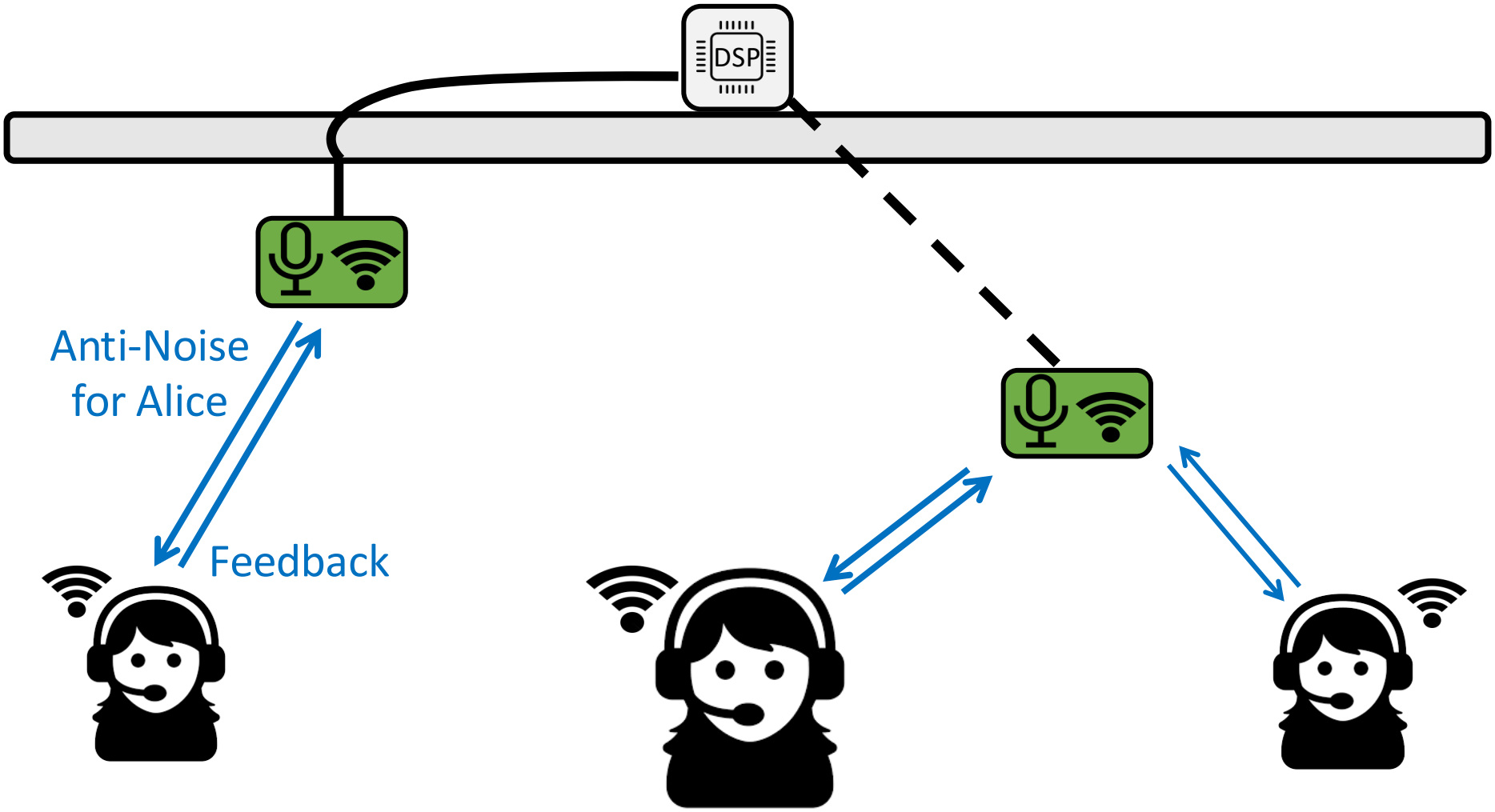
MUTE Tabletop Relay

MUTE Tabletop Relay

Noise Cancellation as an Edge Service

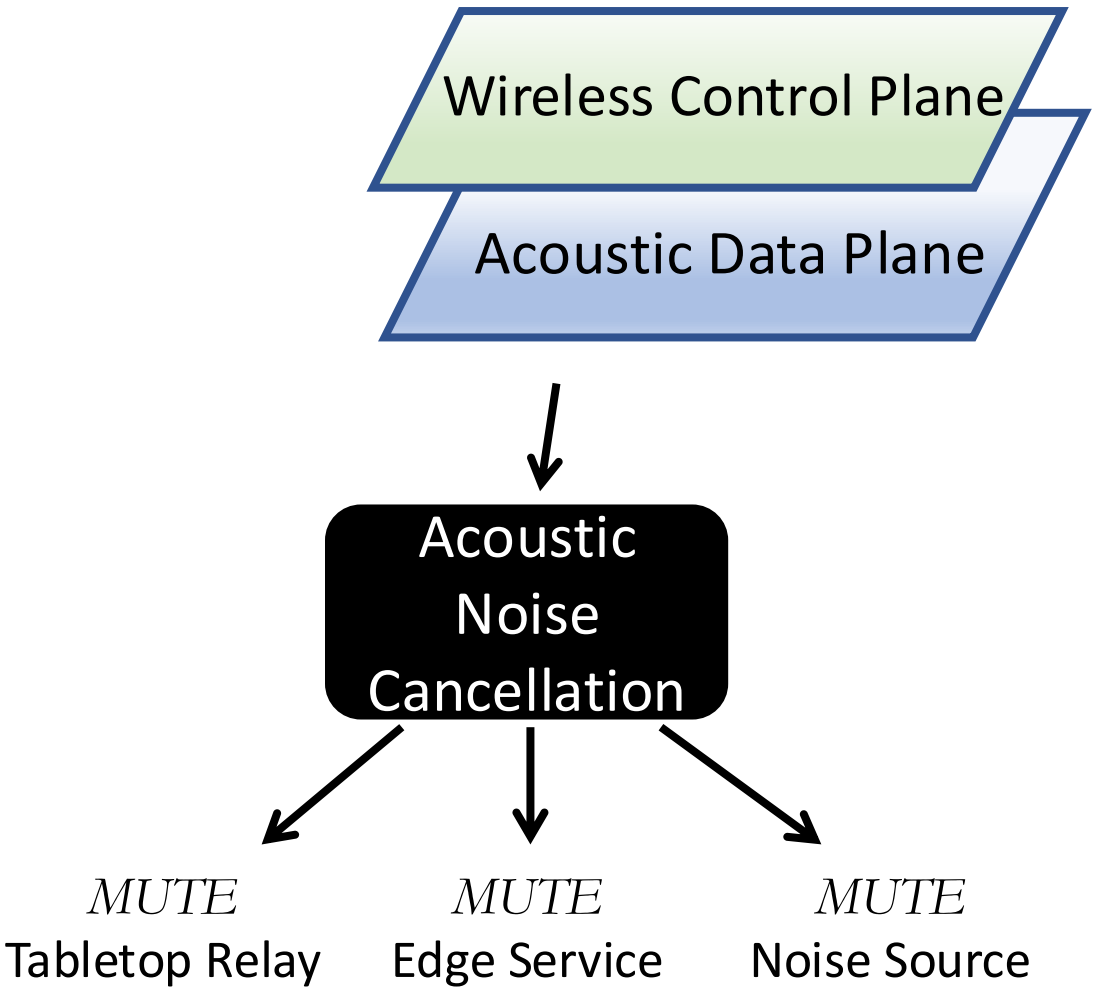


Noise Cancellation as an Edge Service

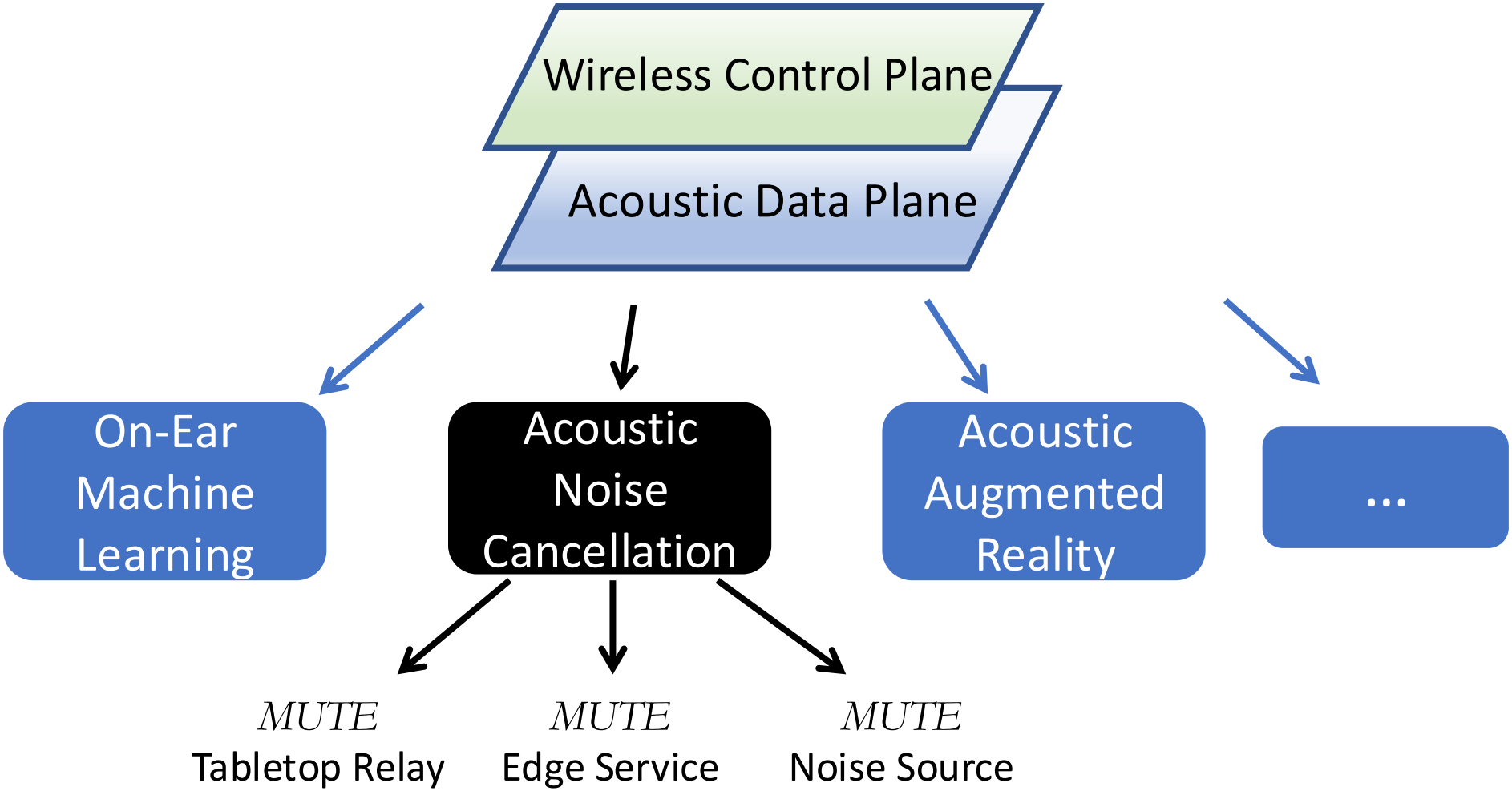


MUTE Enabled Noise Sources

Conclusion


Wireless Control Plane
Acoustic Data Plane
Acoustic Noise Cancellation
MUTE
Tabletop Relay
MUTE
Edge Service
MUTE
Noise Source

Conclusion



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