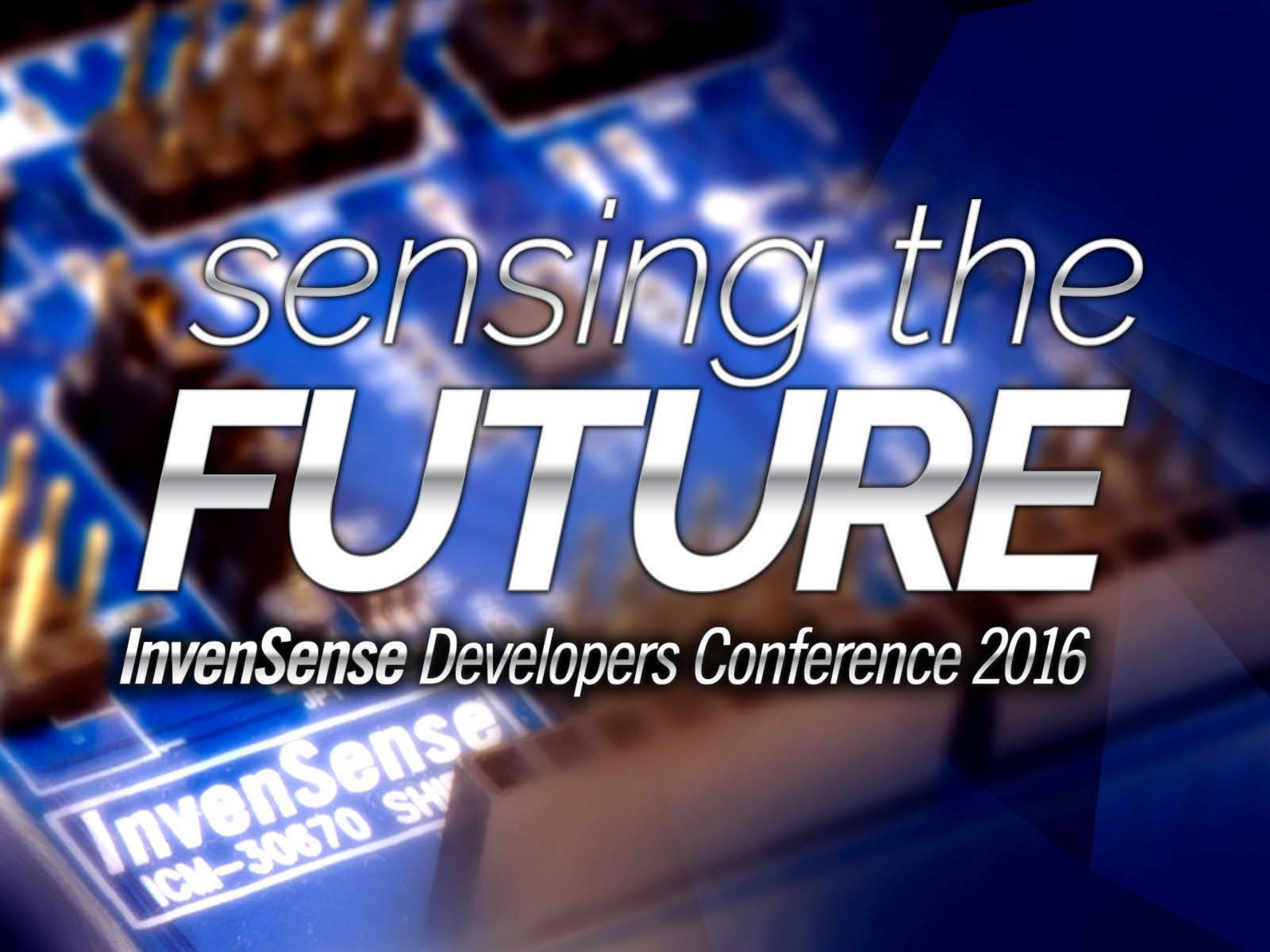
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InvenSense Developers Conference 2016
InvenSense
ICM-30670

Voice-controlled Connected Home

InvenSense Developer's Conference
October 21, 2016

Presenter Bio

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Today's Presenter: Paul Schreier
Eastern North America Sales Director
Based in Boston, MA

Experience

- Present: Responsible for all sales in Eastern North America
- Prior
  - WW Marketing, MEMS microphones, Analog Devices
  - WW Marketing, Linear Power, Texas Instruments
  - Americas Marketing, Multimarket Semiconductors, NXP Semiconductors
  - Account Manager / Distribution Sales Manager, National Semiconductor

Education:
MBA, Boston College
Computer Engineering, University of Nebraska
Finance, University of Nebraska

Session Goals / Agenda

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Session Goal: Familiarize participants with microphone, audio signal chain, and industrial design considerations associated with voice controlled devices proliferating throughout the home

Agenda

- Motivation for Voice Control in home
- High Level Design considerations
- Microphone Directionality Considerations
- Microphone specifications & impact to directionality
- MEMS microphone attributes
- Example signal chain architectures
- Industrial Design / Production concerns

Topics not covered

This session will not cover . . .

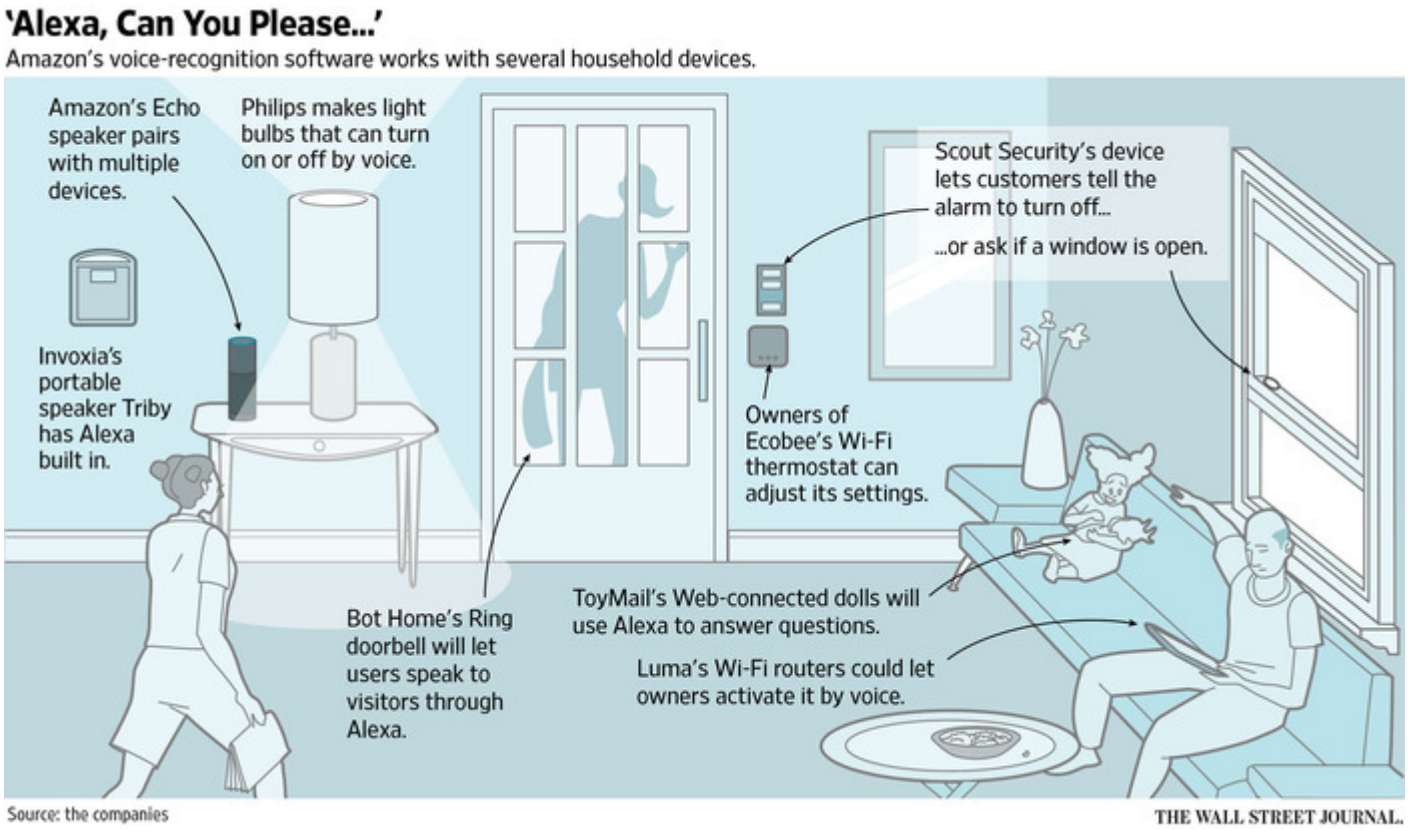
- Advanced Beam-forming methods or patterns
- DSP code for audio filters, beam-forming, etc.
- Processor/DSP selection criteria

Smart Home Adoption

- Smart home devices have been growing quickly
- Primary interface has been smart phone / tablet

Voice control may be the killer app that drives these applications from the “early adopters” to the main stream.

Voice assistants



WSJ, May 16, 2016

Voice Control: Cut out the middle man!

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- Why have a designated voice controller? Why not make many other devices voice controlled – or make every device a gateway to your smart home?
  - Smart Speaker (Alexa, etc.)
  - Thermostat
  - TV
  - Coffee Maker
  - Dishwasher
- Key requirements for voice control
  - Microphone Array
  - Beam Forming
  - Key Word Detect
  - Connection to Voice Recognition Services

Voice Control Interface Design Considerations

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- Space
- Power Consumption
  - Line powered? Battery powered? Rechargeable?
- Wake Method
  - Tap/touch? Keyword?
- Typical distance from user
  - Wall Mounted? What size room?
- Ambient noise (other than desired voice)
  - Kitchen? Bedroom? Garage? Outdoors?
- Industrial design
  - Water or dust proof?
- Manufacturing flow
  - PCBs?
- Signal chain
  - Integrated microphones? Discrete elements?

Microphone Considerations

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Directionality: Omnidirectional or “other” (cardioid, etc.)

Omnidirectional microphones
Responds equally to sounds coming from all directions

Omnidirectional benefits	Omnidirectional drawbacks
• Size: Omni mics are smaller • Single port hole • Adaptable response to noise source or environmental changes • MEMS!	• Undesired noise could degrade the signal • Additional DSP capability required for directionality • Multiple mics required for any pattern

Directional microphones
Picks up sound in a specific field of space, usually in an arc in some pattern around the microphone

Directional mic benefits	Directional mic drawbacks
• Native response may fit use case without post-processing • Single mic implementation for directional possible	• Fixed pattern • Size: Larger package size • Multiple port holes • No adaptability to different directions or environment changes • Few MEMS options

End-fire Beamforming vs. Directional mic

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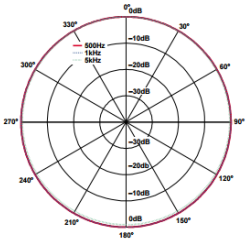
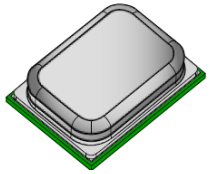
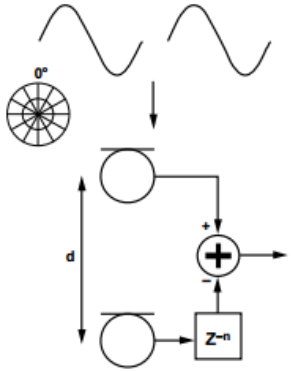
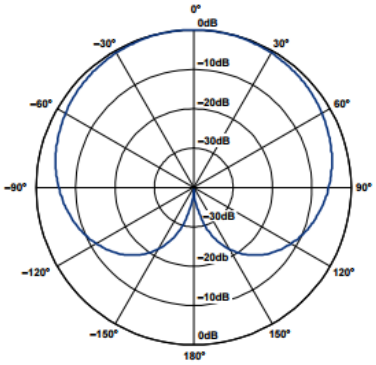
DSP-based directional pattern, using omni mics



Individual mics are omnidirectional

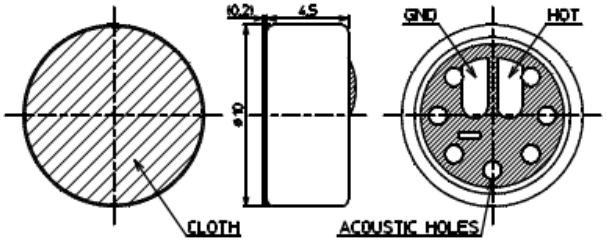




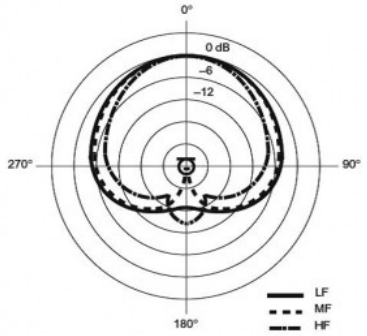


Individual omni mics are summed or delayed to produce a digital output audio stream with directionality

Directional pattern



Electret microphones are available in native cardioid responses



Typical polar plot of cardioid microphone

System-level directionality

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- Voice assistants today primarily use an array of omnidirectional MEMS microphones
  - Directionality is (usually) required
  - MEMS mics are ideal for arrays of post-processed response patterns
  - Other applications may find a single directional mic is suitable
- Arrays in consumer IoT voice assistants are typically between 2 and 7 mics in size – but could be 100 or more mics, depending on the application and sound quality required

MEMS Mics: Perfect fit for voice control

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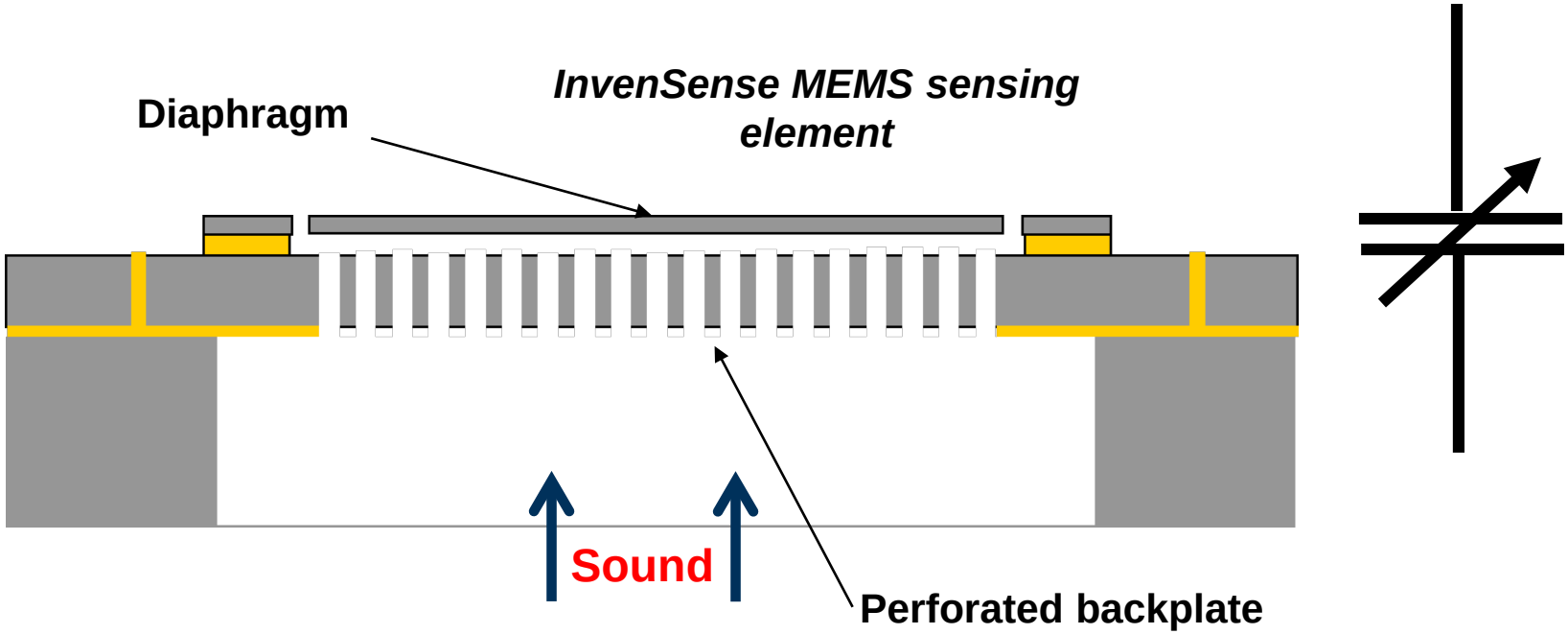
MEMS mics today are “condenser” microphones, just like legacy “electret condenser microphones” (ECMs).



- Diaphragm and backplate electrodes form a capacitor
- Sound pressure causes the diaphragm to vibrate and change the capacitance
- Capacitance change is amplified and converted to analog or digital output

SNR, Sensitivity, & Dynamic Range

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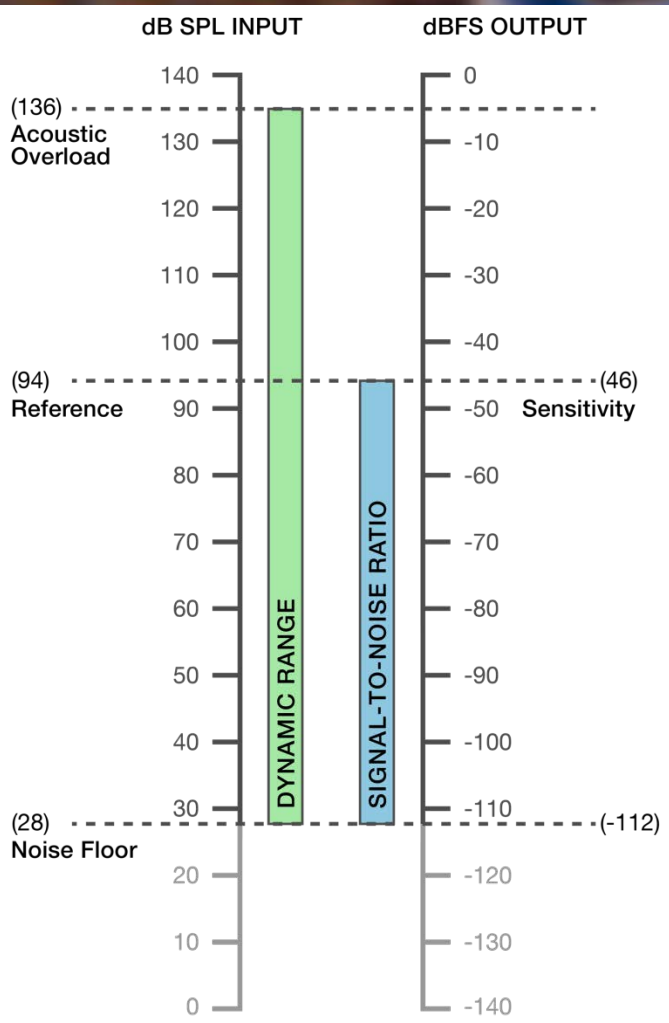

Sound sources (noise) Examples with distance	Sound pressure Level L_p dB SPL
Jet aircraft, 50 m away	140
Threshold of pain	130
Threshold of discomfort	120
Chainsaw, 1 m distance	110
Disco, 1 m from speaker	100
Diesel truck, 10 m away	90
Kerbside of busy road, 5 m	80
Vacuum cleaner, distance 1 m	70
Conversational speech, 1 m	60
Average home	50
Quiet library	40
Quiet bedroom at night	30
Background in TV studio	20
Rustling leaves in the distance	10
Hearing threshold	0

- SNR is measured relative to a *standard pressure*
  - 94 dB SPL at 1 kHz (1 Pa rms)
- Sensitivity – reference output of the microphone (in dB FS or dB V) to a 1kHz tone @ 94dB SPL
- Dynamic Range – measures the difference between the *maximum acoustic input* and the noise floor

Want more info on mic specs? See App note AN-1112 at InvenSense.com

Why is SNR critical for home voice control?

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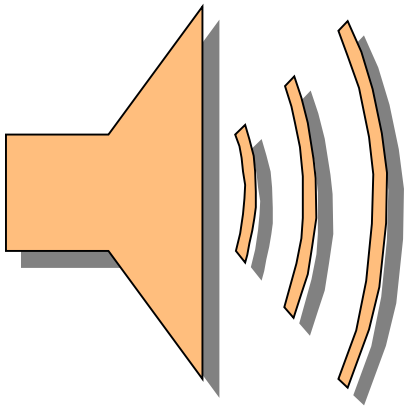
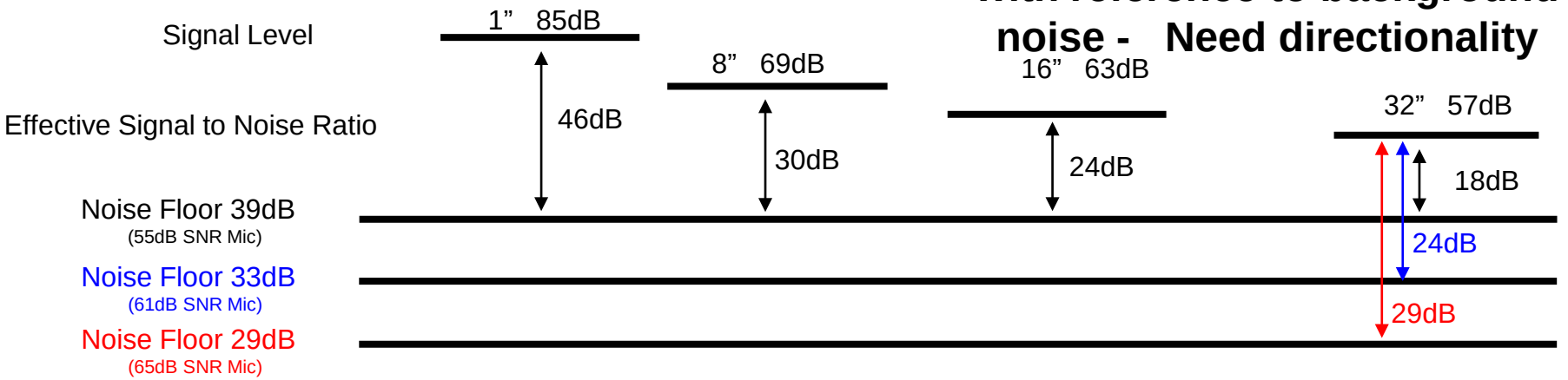


For close talking an Omni-directional microphone is adequate

At distance the signal level is low with reference to background noise - Need directionality



High SNR: Summing Omni Mics

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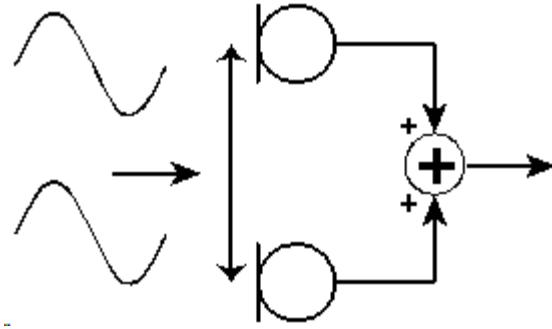
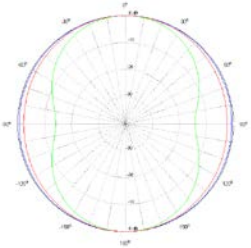
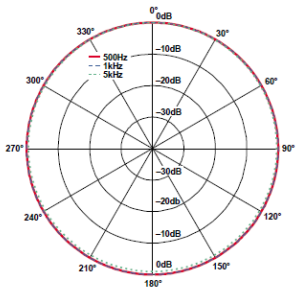
- Mic Summing = higher SNR, still omni (mostly)
  - Every doubling of mics of same SNR provide additional ~3dB SNR when used in an array
  - Example: 2 x 62dB SNR Mics = Mic Array with 65dB SNR
  - Single 65dB SNR mic achieves similar SNR, without attenuation inherent in multiple mics
- High SNR mic arrays yields even better
  - Example: 2 x 65dB SNR Mics = Mic array with 68dB SNR!
- Multiple Mic Array: Better SNR with Attenuation
  - If better SNR is main goal, mics are placed as closely together as possible
  - Inherent directionality with multiple mics
- Single high SNR MEMS Mic stays omnidirectional



2 mic array broadside
Very close together



2 mic array response, as above



Single Omnidirectional Mic Response

High SNR Array: “Beam-forming”

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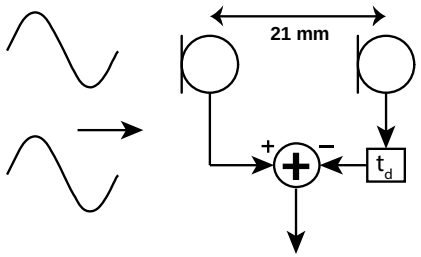
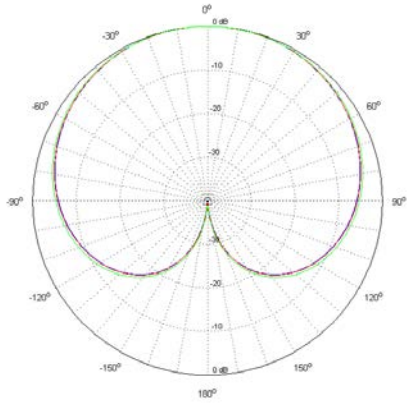
- Beam-forming
  - To achieve directionality, beam-forming uses multiple mics to “shape” area of highest response from mic
- Example: 2 Mics, endfire spaced 21 mm apart
  - Yields cardioid response pattern
  - Reduces gain from sound picked up from behind mic
- Beam-forming benefits from highest SNR mics available
  - Beam-forming reduces SNR because mic signals are subtracted
    - Signal goes down, noise floor stays the same
  - 2 mic array with 65dB SNR mics = beamforming array with net 62dB SNR



2 mic array endfire



2 mic array response, as above

Benefits of MEMS Mics for Voice Control

1. Performance Density

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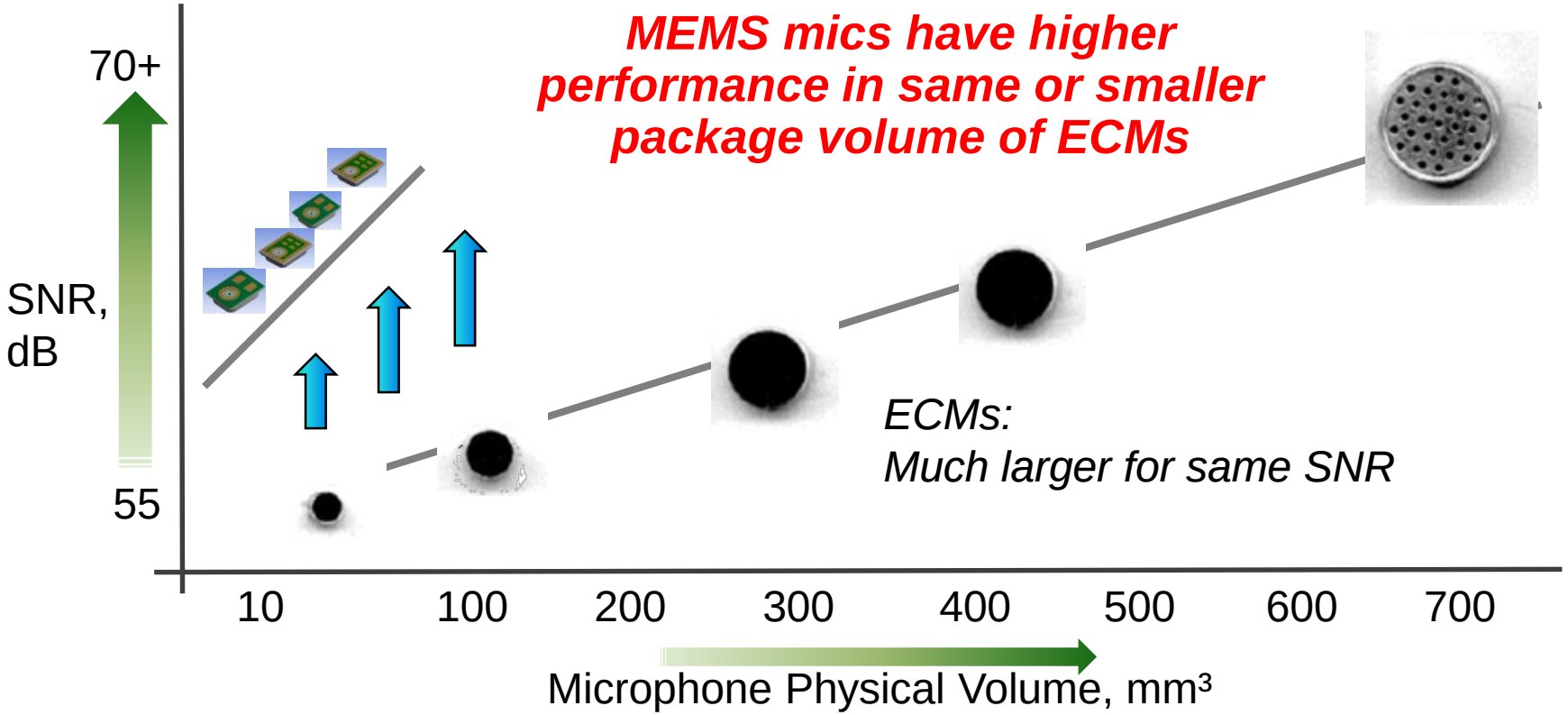

Voice Control Array Benefit

MEMS mics are superior for space constrained and/or multiple microphone applications.

Benefits of MEMS Mics for Voice Control
2. Robust to reflow solder attach

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Voice Control Array Benefit

- *MEMS mics can be treated as standard semiconductor components and are placed on prior to board reflow, with minimal additional handling concerns*
- *Electret microphones require a separate, manual board attach process – increasing production cost and lowering yield.*

Key Point: MEMS Mics have a hole in the package!

Special handling (even with standard pick and place and reflow equipment) is needed.

But cost is minor compared with trouble/effort of ECMs.

Benefits of MEMS Mics for Voice Control
3. Less Sensitivity Variation vs. Temperature

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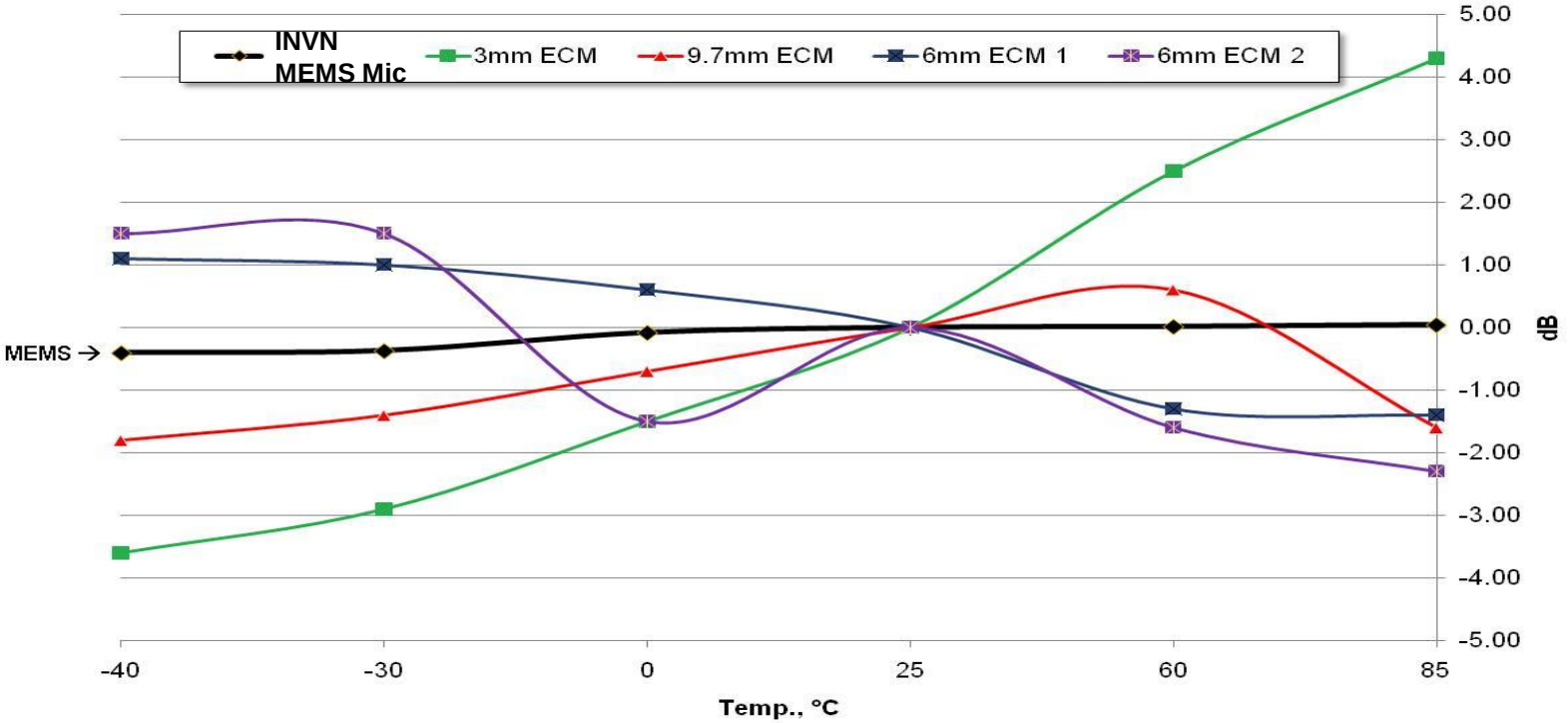

Voice Control Array Benefit

- *MEMS mics provide consistent, highly accurate output across entire temp range – making them ideal for sensing devices exposed to high or low temps*

Benefits of MEMS Mics for Voice Array
4. Better Part-to-Part Matching

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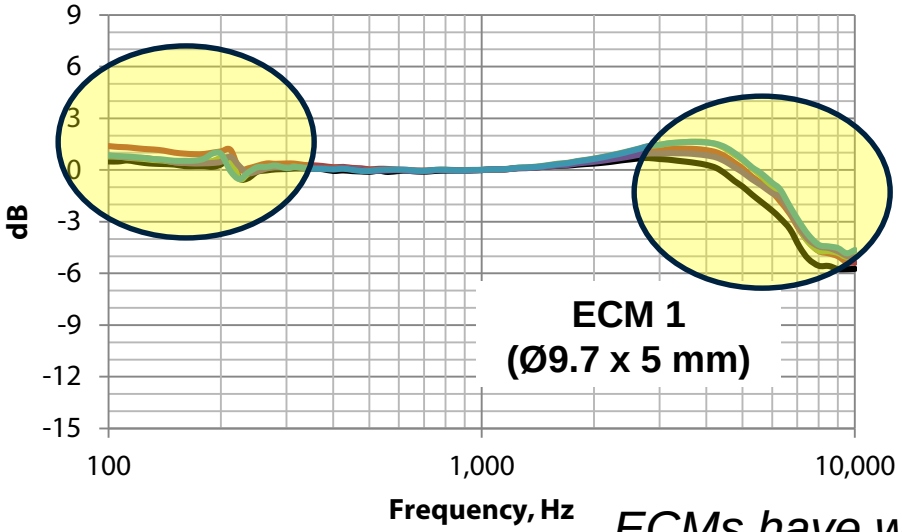
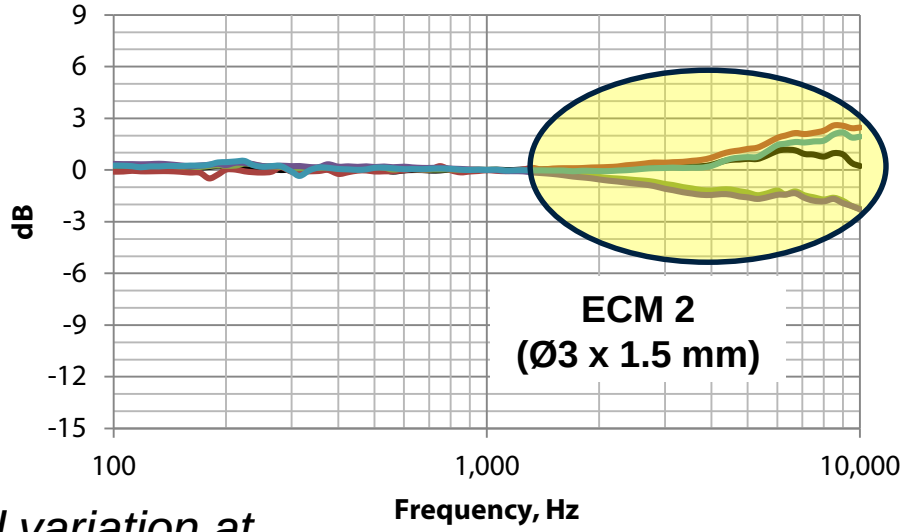
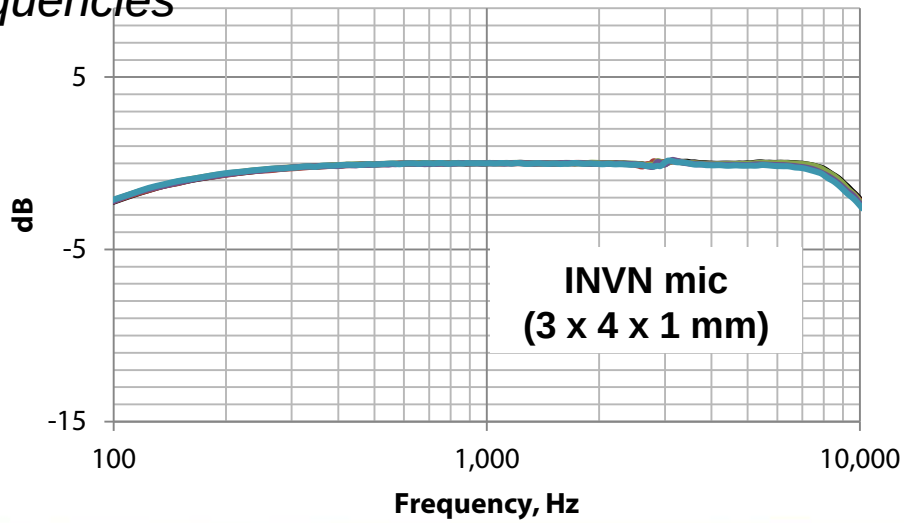




ECMs have wild variation at high/low frequencies

Voice Control Array Benefit

- *Dramatically less calibration required*
- *Only minimal production testing necessary to ensure functionality*



Next Steps

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- Assumptions for remainder of session:
  - MEMS Mic Array will be chosen for directionality
  - Largest Dynamic Range for mic array is desired
  - Production cost must be kept low
- Mic output type options
  - Analog-output / Digital Output
- Signal Chain
- Industrial Design / Production Considerations

ICS-40618: Wide DR Analog-Out Mic

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Features

- Listening Mode consumes 55µA with 67dB SNR
- High SNR of 67 dB / 27 dB SPL EIN
- Acoustic Overload Point (AOP) of 132dB SPL
- Sensitivity of -38 dBV (+/-1dB tolerance)
- Package size 3.5mm x 2.65mm x 0.98mm

Benefits

→ Low power state continues to acquire audio data

→ Supports far-field (conference phones, video conf.)

→ Enables clear audio capture in loud conditions: wind, rock concerts, close range speaking, etc.

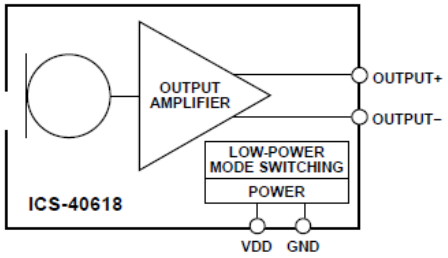
→ Analog, differential output supports entire range

→ Industry standard size

SPEC	HIGH PERFORMANCE MODE	LOW-POWER MODE
SNR	67 dBA	67 dBA
Current	165 µA	55 µA
AOP	132 dB SPL	128 dB SPL

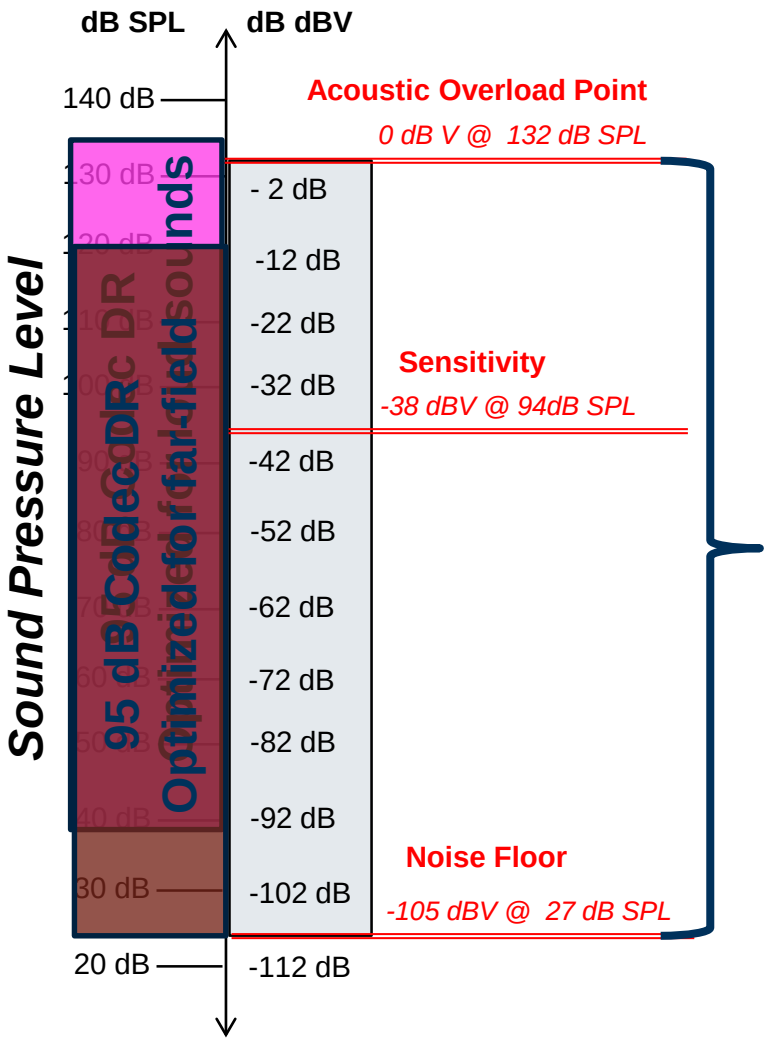
ICS-40618 points of interest

1. Huge Dynamic Range (105dB)
2. Differential Output
3. Standard voltage rage (1.8V to 3.3V)
4. Bottom port
5. Small Size (3.5 x 2.65 x 0.98mm)



ICS-40618 is perfect for apps that could see very loud sounds yet also need far field voice capture

Mic Dynamic Range vs. Signal Chain



ICS-40618 analog mic has one of the largest dynamic ranges:

ICS-40618 dynamic range is 105 dB

But many codecs' dynamic range may only be 95-105!

Your signal chain SNR is limited by the codec

But you don't need that whole dynamic range at the same time, right?

Analog front ends do allow you to shift from one portion of the mic DR to another to fit inside your signal chain.

Microphone Signal Chain & Interface

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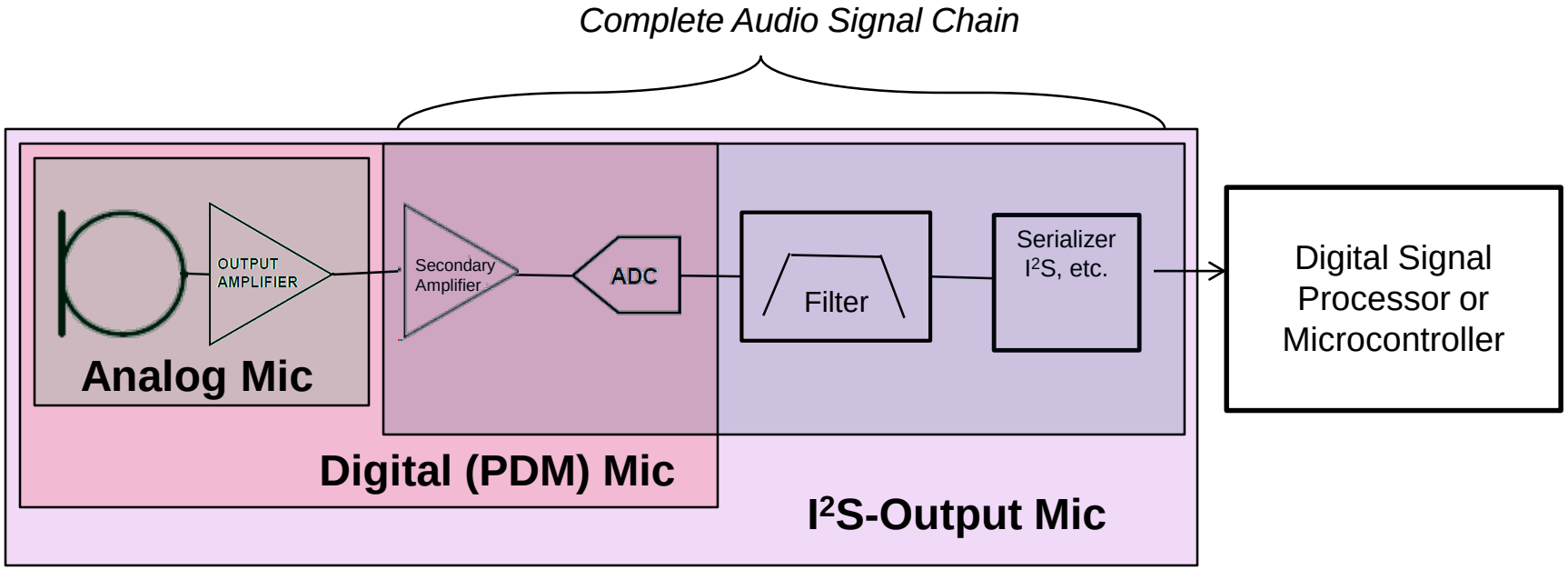
Typical Audio Ecosystem

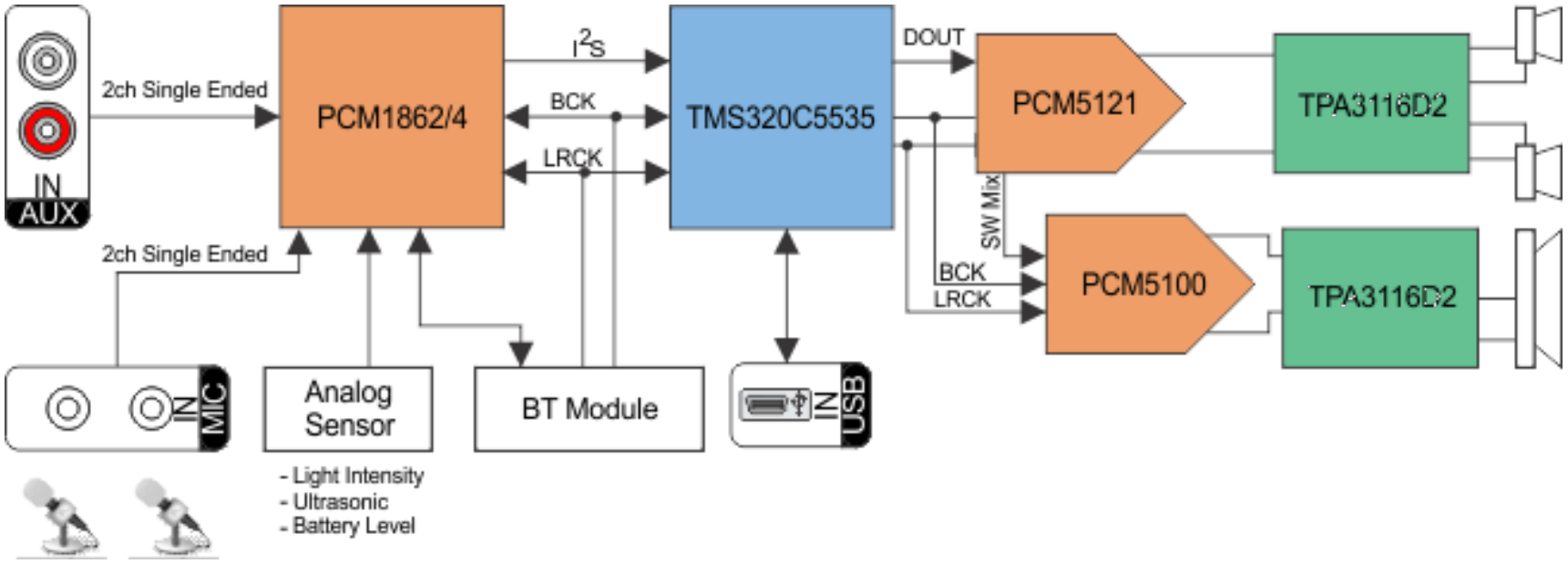
- Analog-output mics integrate an output amp, Example: ICS-40618
- Digital-output (PDM) mics integrate an ADC and provide a single bit output stream, Example: ICS-41350
- ICS-43434 provides full I^2S output – ideal for applications without a codec



PDM = Pulse Density Modulation

Audio Signal chain

- TI's PCM1862/4 serves as next stage for microphone input
- Universal Front End can be configured to apply dynamic range



Benefits of PDM over Analog

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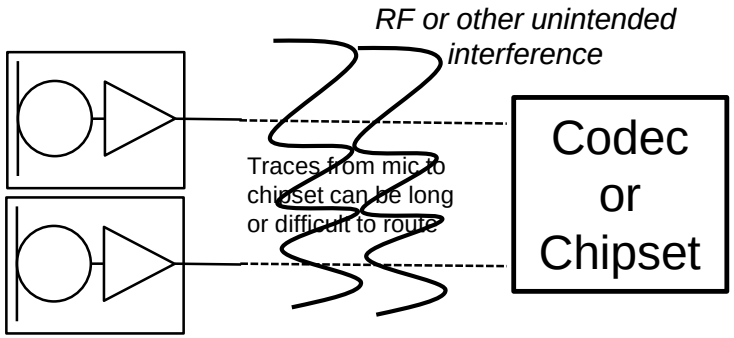
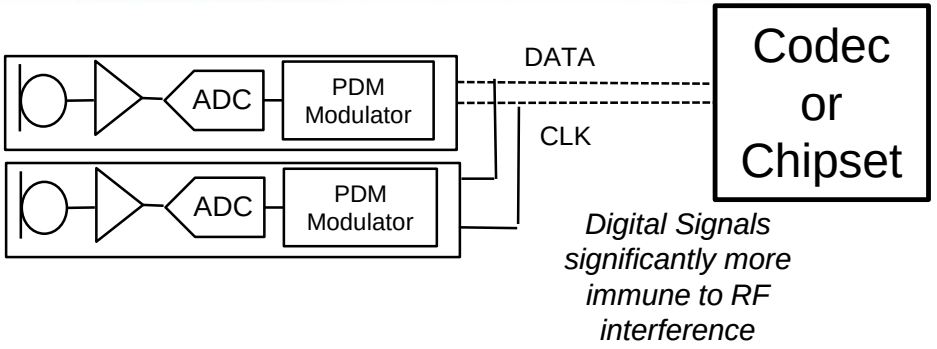


Typical Analog Dual Mic implementation



Typical PDM Dual Mic implementation

What is PDM?

- Single bit digital bitstream with 1 or 2 mics per data line
- Integrates ADC, but bitstream still must be decimated at codec/chipset DSP
- Commonly supported interface on mobile chipsets / audio codecs

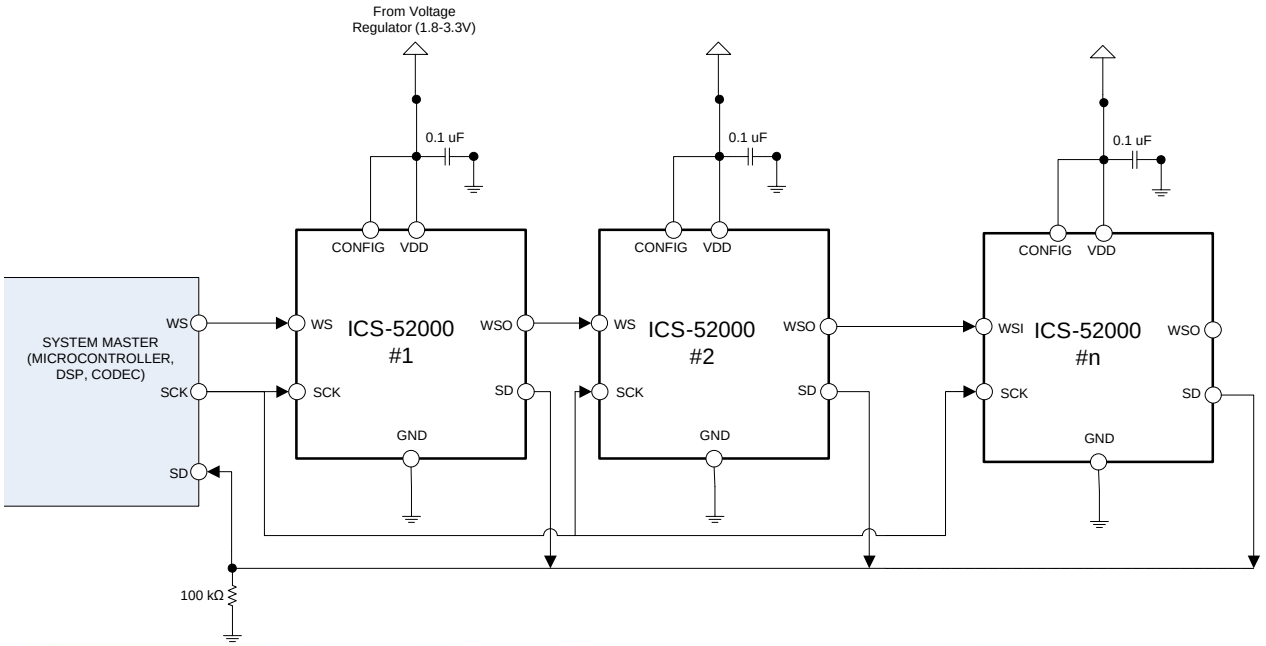
Pulse Density Modulation (PDM) vs. Analog Mic

Analog Mic Advantages	PDM Mic Advantages
Simple interface, easy to optimize signal	Lower system power!
Slightly less expensive	Digital signals are significantly more immune to RF interference
Slightly smaller package vs. PDM	2 mics on signal data line (with shared clock) reduces trace count for 3 or more mics

Want more info on PDM sensitivity & dynamic range? See Sensitivity App Note.

What is TDM?

- TDM allows many discrete channels to be transmitted on a common bus
  - This is a standard 3-wire audio interface supported by audio DSPs and codecs
  - The ICS-52000 is the first microphone with a TDM interface
  - Up to 16 microphones share common clock signals and drive a common data bus.



ICS-52000 Example Schematic

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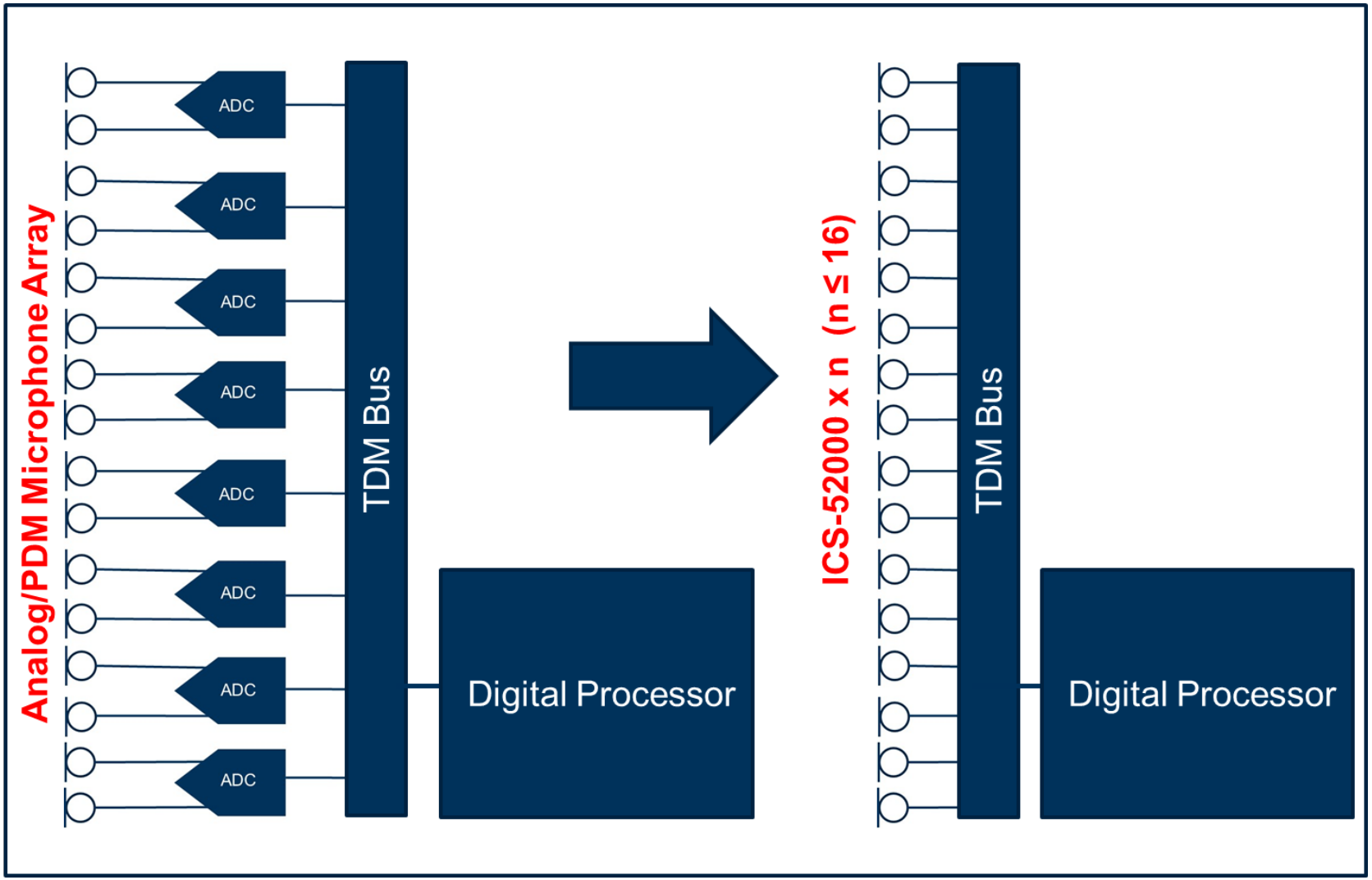

ICS-52000: TDM Microphone

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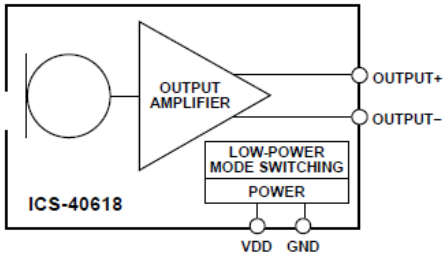
Features	Benefits
• Completely integrated signal chain	→ Integrates mic, amplifier, ADC, filter, and TDM serializer
• High SNR of 65 dB / 29 dB SPL EIN	→ Supports far-field (conference phones, video conf.)
• Acoustic Overload Point (AOP) of 116dB SPL	→ Standard AOP allows standard dynamic range
• Sensitivity of -26 dB FS (+/-1dB tolerance)	→ Analog, differential output supports entire range
• Package size 4mm x 3mm x 1mm	→ Industry standard size

ICS-52000 points of interest

1. Slightly smaller dynamic range
2. Dynamic Range (91dB) works well for most audio signal chains
3. Standard voltage rage (1.8V to 3.3V)
4. Bottom port



ICS-52000 provides a good balance of integration versus acoustics performance.

TDM: Summary

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- ICS-52000 provides significant BOM reduction by integrating ADC, decimation filter, and TDM serializer
  - Decreases time to market and cost for most projects
- Analog-output (or PDM output) mics may increase overall performance, but will likely be costlier and more complex to integrate in order to fit within standard codec or 16 bit audio dynamic ranges

Typical mic array design cycle

Sensing Everything

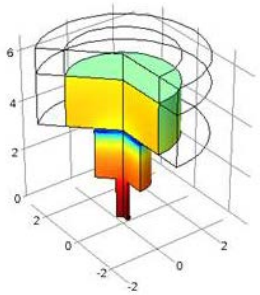
Initial Product Architecture

Docs required:
- Promotional Presentations
- Datasheets
- App Notes
- Technical Articles

Technical Evaluation

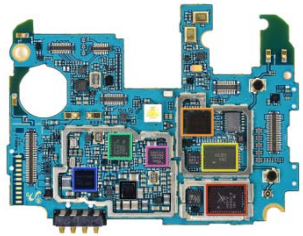
Materials required:
- Evaluation Boards: mics mounted on flex for easy eval
- Individual samples

Board Layout / ID



Vendor Support
- Applications questions on electrical behavior
- Possible acoustics modeling review or feedback on design

Initial Prototype Mfg



Vendor support:
- Production handling guides
- Visit from vendor quality engineer to monitor production line
- FA as needed

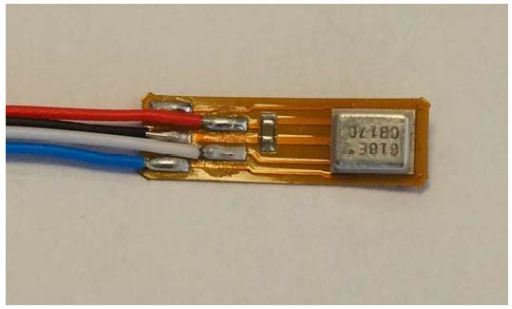
Full Mass Production

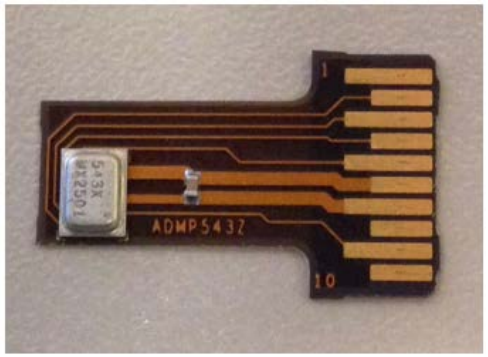
Vendor Support:
- Intermittent FA support to ensure process stability
- INVN customer quality provides ongoing process improvement feedback

Evaluation Platforms

Sensing Everything

InvenSense in-house Eval Boards





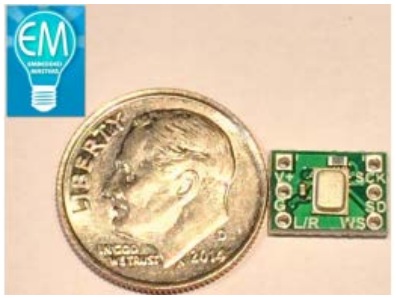
MEMS Mic mounted on flexible PCB

- Easy installation in prototype industrial design
- Easy interface with 3rd party codec/uC/DSP evaluation boards
- Available for all mics

Considerations

- Analog mics have hand-soldered wires
- I^2S mics have large landing pads

CDI Eval Boards



MEMS Mic mounted on small, rigid PCB

- Quick & simple evaluation vehicle
- Customer has to hand attach wires to leads
- Only $15 resale

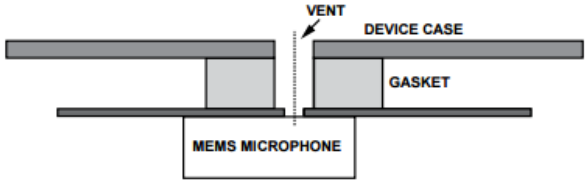
Only available for:

ICS-43432
INMP621
INMP522

Industrial Design & Production

Sensing Everything

- Industrial design & mounting is important for all mic designs
  - See AN-1003 for information
  - *Before* layout/ID are complete



Example ID considerations

- Concerned about Water & Dust?
  - See AN-1124 for design ideas and examples
  - Acoustic mesh is commonly used
    - Example vendor: Saati

- MEMS Microphone handling guide is critical
  - Every customer & CM needs to review AN-100 carefully
  - Even with controlled production, some loss (<1%) should be expected
  - Microphone subassembly test is necessary to catch fall-out

- Top port versus Bottom port
  - Bottom port is ideal in most cases: Top port ICS-40619 available

Production impact on product selection

Sensing Everything

- MEMS Microphone fall-out in production (<1%)
  - Significant concern when you have 6+ mics per board
- First: In-line acoustic test is required
  - Simple “go” and “no-go” test to determine if mic survived production
  - 1kHz, ~94dB SPL tone for each mic
    - Catches nearly every damaged mic
- Handling failures: Discard or rework?
  - Discard: Plan for it. Make a mic board of minimal value.
  - Rework: Bottom port hand-solder is challenging
    - Top Port Mic may have benefit with rework strategy

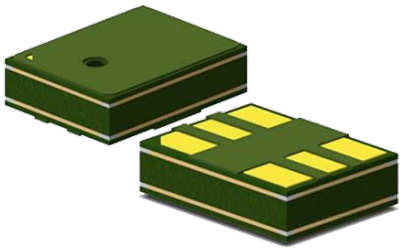
ICS-40619: Top port, high performance analog mic

sensing the FUTURE

Features	Benefits
• Top port equivalent of ICS-40618	→ Mic available with EITHER top or bottom port configuration supports ideal industrial design
• Listening Mode consumes 55µA with 67dB SNR	→ Low power state continues to acquire audio data
• High SNR of 67 dB / 27 dB SPL EIN	→ Supports far-field (conference phones, video conf.)
• Acoustic Overload Point (AOP) of 132dB SPL	→ Enables clear audio capture in loud conditions: wind, rock concerts, close range speaking, etc.
• Sensitivity of -38 dBV (+/-1dB tolerance)	→ Analog, differential output supports entire range
• Package size 3.5mm x 2.65mm x 0.98mm	→ Industry standard size

ICS-40619 points of interest

1. Top Port ~identical~ to ‘618
2. Top port, but still high performance
3. Top Port may be easier to hand solder / rework versus bottom port



ICS-41350: Multi-mode PDM Mic

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Features

- Low power mode consumes 185uA
- High SNR of 65 dB / 29 dB SPL EIN
- Standard (120dB SPL) and High AOP (126dB SPL) modes available via clock frequency selection
- Sensitivity of -26 dB FS and -32dB FS (+/-1dB)
- Clock speed used to select modes

Benefits

→ Low power ADC enables low system power

→ Supports far-field (conference phones, video conf.)

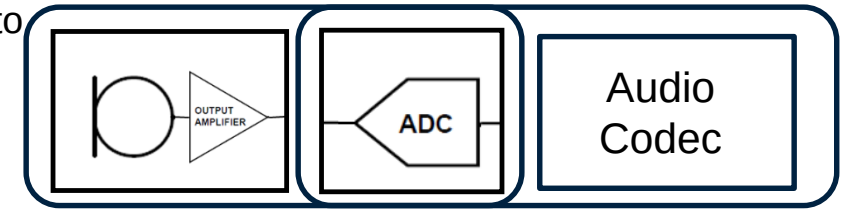
→ Enables clear audio capture in loud conditions, while still supporting standard dynamic range

→ Sensitivity will vary by required dynamic range

→ No additional I/O required for mode select

Applications

- Mobile/Wearable devices
- Larger devices with long trace to codec
  - Tablets/Displays
  - Ruggedized computing
- STB/Smart TVs
- Remote Controls



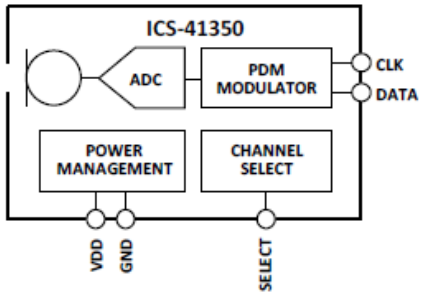
Analog mic takes 60-180uA

ICS-41350 pulls 470uA in HP mode

Digital fab process for codec is not optimized for ADC – pulls much more current (~2mA)

Codec burns ~1mA less with PDM mic than analog mic

ICS-41350 saves 500uA+ current draw



Conclusion

sensing the FUTURE

- MEMS microphones are both the enabling technology and dominant choice for consumer voice control applications in the home
- Directional mic array design requires careful signal chain consideration, but integrated microphones (such as ICS-52000) can ease implementation
- MEMS mics are much easier for ID and production – but certain handling and test considerations are critical

Thank You