Sound Direction Indicator

Assistive Device for Deaf and Hard-of-Hearing Individuals

Design Rationale & Engineering Evaluation

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Abstract: This document presents the complete design of a sound direction indicator — from architectural trade-off analysis through analog circuit design, PCB layout, and firmware planning. The core innovation is choosing envelope-based amplitude comparison over traditional time-difference-of-arrival (TDOA), which eliminates the need for high-speed ADC, FFT, and complex DSP. This single architectural decision enables the entire system to run on a $1 ATtiny24A microcontroller with under 1 KB of firmware and under 30 bytes of RAM. The device uses four microphones with analog envelope detection to determine sound direction, displayed via a 12-LED ring on an 80 mm circular PCB. Unit cost is approximately $10.

Contents

1. Executive Summary

1.1. The Problem

Deaf and hard-of-hearing individuals often miss important environmental sounds — doorbells, alarms, someone calling from another room. Existing solutions are expensive, require dedicated smartphone apps, or involve complex setup.

1.2. The Solution

A compact, affordable device that:

- Detects sounds from any direction (claps, knocks, alarms, speech)
- Shows direction visually via a 12-LED ring (30° resolution)
- Indicates intensity through color (blue for moderate, red for loud)
- Works with any USB power bank or smartphone via OTG
- Requires no app, no pairing, and no configuration

1.3. Design Goals and Outcomes

Goal	**How Achieved**
Cost	~$10 per unit, ~106 common components
Simplicity	Analog preprocessing eliminates DSP entirely
User experience	USB-C power — works with power banks and phone OTG
Compact size	80 mm circular PCB with integrated LED ring
Manufacturability	0805 passives, SOIC packages, hand-solderable
Scalability	Architecture transfers directly to wearable glasses form factor

2. The Core Architectural Decision

The most impactful engineering decision in this project was not a component choice or a circuit optimization — it was reframing the problem.

2.1. Two Approaches to Sound Localization

Time-Difference-of-Arrival (TDOA): Measures when sound arrives at each microphone. The closer microphone receives the signal first. Requires very fast sampling, large buffers, and complex digital processing (FFT or cross-correlation).

Amplitude/Envelope Comparison: Compares how loud the sound is at each microphone. The microphone facing the source receives a stronger signal. Only requires slow DC measurements and simple math.

2.2. Trade-off Analysis

Aspect	TDOA	Envelope (selected)
Principle	Measure arrival time difference	Compare loudness at each mic
Sample rate	100 kHz or higher	10–100 Hz sufficient
Signal bandwidth	Full audio (20 kHz+)	~1.6 Hz after envelope
Trace matching	Critical (1 cm = 29 μs error)	Not critical
Noise immunity	Low (wideband pickup)	High (inherent filtering)
Firmware	FFT, cross-correlation	Read 2 ADCs, compute atan2
RAM	Large buffers required	Under 30 bytes
MCU	ATmega328P or better	ATtiny24A sufficient
PCB layout	Difficult (matched traces)	Relaxed

2.3. Why Envelope Comparison Wins

By converting audio signals to slow DC envelopes *before* comparison, the design achieves every goal simultaneously: reduced component count, simpler firmware, lower MCU cost, minimal peripheral requirements, and relaxed PCB layout constraints.

This single architectural decision is what makes a $10 device possible instead of a $30+ one.

3. System Architecture

3.1. Block Diagram

Block	Implementation
Sensing	4× electret mics (2-pin, internal JFET) at N/E/S/W
Preamp	MCP6004 (U1), non-inverting, gain = ×23
Envelope	BAT54 Schottky + RC (10 kΩ × 10 μF), τ = 100 ms
Differential	MCP6004 (U2), gain = ×33
Processing	ATtiny24A reads X/Y analog, computes atan2
Output	12× WS2812B LED ring
Power	USB-C 5V, ferrite bead isolates analog rail

3.2. Signal Flow

1. Four microphones capture sound from N/E/S/W directions
2. Each signal is amplified ×23 by a non-inverting preamp
3. BAT54 Schottky diodes and RC filters extract the amplitude envelope (~1.6 Hz bandwidth)
4. Differential amplifiers compute:
   - X axis: 33 × (Envelope East − Envelope West)
   - Y axis: 33 × (Envelope North − Envelope South)
5. MCU computes: angle = atan2(Y, X), maps to 1 of 12 LED sectors
6. LED color indicates intensity: blue (moderate) or red (loud)

4. Analog Signal Chain

4.1. Preamplifier Stage

Each electret microphone feeds a non-inverting amplifier (MCP6004) with a gain of ×23. The MCP6004 was chosen for:
- Rail-to-rail input/output (operates from 2.7–5.5V)
- Quad package — one IC provides four identical channels
- Wide availability and low cost

Biasing: 2.2 kΩ pull-up to VCC for electret self-bias. AC coupling via 1 μF capacitor. Mid-rail (2.5V) reference from buffered voltage divider.

4.2. Envelope Detection

Each preamplified signal passes through a BAT54 Schottky diode followed by an RC filter (10 kΩ × 10 μF):
- Time constant: τ = 100 ms
- Bandwidth: ~1.6 Hz
- The diode rectifies the audio; the RC filter extracts the slowly-varying amplitude

This extremely narrow bandwidth is the key to the system's noise immunity.

4.3. Noise Rejection

The 100 ms envelope filter provides massive rejection of high-frequency interference:

Noise Source	Rejection
WS2812B LED switching (800 kHz)	> 100 dB
RF pickup (MHz range)	> 100 dB
Audio-frequency EMI (1 kHz)	~56 dB
Mains hum (50/60 Hz)	~30 dB
Random broadband noise	Averages to zero over τ

4.4. Differential Direction Extraction

Two differential amplifiers (gain = ×33) extract directional information:
- X = 33 × (Envelope East − Envelope West)
- Y = 33 × (Envelope North − Envelope South)

Common-Mode Rejection: A critical advantage of this topology is immunity to power supply noise. If the USB cable picks up interference that ripples onto the analog rail, the envelope detectors will rectify this noise into a DC offset. However, this offset appears equally on all four channels. The differential subtraction cancels it:

$$(V_{\text{North}} + V_{\text{Noise}}) - (V_{\text{South}} + V_{\text{Noise}}) = V_{\text{North}} - V_{\text{South}}$$

Power supply noise — even after being rectified — cannot trigger a false directional reading.

4.5. Adjustable Response Time

The envelope time constant can be tuned by changing a single capacitor:

Capacitor	Time Constant	Use Case
10 μF (default)	100 ms	Balanced response and stability
4.7 μF	47 ms	Faster response
1 μF	10 ms	Very fast, may be less stable

No circuit redesign required — just a component swap.

5. Component Selection

5.1. Selection Criteria

Every component was evaluated against: technical suitability, cost, availability, and ease of hand assembly.

5.2. Key Choices

Component	Part	Rationale
Op-Amp	MCP6004	Rail-to-rail I/O, 2.7–5.5V, quad package, low cost
MCU	ATtiny24A	2 KB flash, 8 ADC channels, 14 pins — minimal but sufficient
LEDs	WS2812B	Single data wire for 12 LEDs, integrated driver
Envelope diode	BAT54	Low forward voltage Schottky for reliable detection
Microphones	POM-2738P-R	2-pin electret with internal JFET, simple biasing
Ferrite bead	BLM21BD272SN1L	1 kΩ at 100 MHz, 1.5A, 0805 — analog rail isolation
USB connector	USB4110-GF-A	USB-C for universal compatibility

5.3. MCU Selection Logic

The envelope approach enabled a minimal MCU. This is a direct consequence of the architectural decision:

MCU	Capability	Verdict
ATtiny13A	1 KB flash, 5 usable pins	Too constrained
ATtiny24A	2 KB flash, 8 ADC, 14 pins	Optimal — just enough
ATmega328P	32 KB flash, 23 GPIO	Overkill

6. Power Architecture

6.1. Power Rails

Rail	Description
+5V	USB-C input — supplies LEDs and MCU
AV5	Ferrite-isolated analog supply for op-amps (1 kΩ at 100 MHz)
VREF	Buffered 2.5V mid-rail reference for biasing
AGND	Analog ground, connected to GND via 0 Ω bridge
GND	Digital ground for MCU and LEDs

6.2. Why External Power Bank (No Built-in Battery)

Built-in Battery	External Power Bank
Adds weight	Device stays lightweight
Requires boost converter (switching noise)	Clean 5V — no converter noise
Battery degrades over time	Power bank easily replaced
Needs charger IC, protection, fuel gauge	Simple USB-C input
Fixed capacity	User chooses capacity

The device draws ~270 mA, which is within the 500 mA limit of smartphone OTG — enabling quick demonstrations directly from a phone.

7. Firmware Architecture

7.1. Overview

The firmware runs on ATtiny24A at 8 MHz using the internal RC oscillator. The analog preprocessing reduces firmware to a simple loop: read ADC, compute angle, update LEDs.

7.2. Algorithm

Step	Action	Details
1	Read ADC	Sample X, Y, and intensity channels
2	Threshold check	If intensity below minimum → clear LEDs, wait
3	Center values	Subtract 512 (VREF midpoint) from X and Y
4	Compute angle	angle = atan2(Y, X)
5	Map to sector	sector = (angle + 15°) / 30° → 0..11
6	Select color	Blue if moderate, red if loud
7	Update LEDs	Send data via WS2812B protocol
8	Delay	50 ms loop period

7.3. Resource Usage

Resource	Available	Used
Flash	2 KB	~1 KB
RAM	128 bytes	< 30 bytes
ADC channels	8	3
GPIO	12	4 (1 LED data + 3 ADC)

7.4. Peripherals Used

Peripheral	Purpose
ADC	3 channels: X, Y, intensity (10-bit)
GPIO	WS2812B LED data (bit-banged)
Timer0	Loop timing
Internal RC	8 MHz system clock

7.5. Peripherals NOT Required

The envelope architecture eliminates: high-speed ADC, DMA, hardware capture timers, SPI, I2C, UART, and large RAM buffers. The ATtiny24A's basic ADC and a single GPIO pin are sufficient.

8. PCB Layout

8.1. Board Specifications

Parameter	Value
Shape	Circular, 80 mm diameter
Layers	2 (top: components, bottom: power/ground)
Packages	0805 passives, SOIC ICs — hand-solderable

8.2. Component Placement

Zone	Components
Outer ring	12× WS2812B LEDs at 30° intervals
Perimeter	4× microphones at N/E/S/W
Center	Op-amps, MCU, decoupling

8.3. Routing Strategy

Design Choice	Rationale
Zero-via mic traces	High-impedance mic signals routed on top layer only — no vias — to minimize parasitic inductance and preserve signal integrity
+5V ring on bottom	Long trace acts as inductive choke, filtering 800 kHz WS2812B switching noise before it reaches analog circuits
Digital GND ring on top	Low-impedance return path keeps LED currents on the perimeter, away from the analog center
Split ground with single bridge	AGND and GND joined via 0 Ω resistor at USB entry — prevents ground loops and isolates digital switching from analog sensing
100 nF at every mic and LED	Local decoupling compensates for long circular traces

8.4. Silkscreen

Designators removed from silkscreen due to high component density. Polarity and Pin-1 markings retained for correct assembly.

9. Bill of Materials

9.1. Active Components

Part	Description	Qty
ATtiny24A-SSU	8-bit MCU, SOIC-14	1
MCP6004T-E/SL	Quad op-amp, SOIC-14	2
WS2812B (5050)	RGB LED	12
BAT54 (SOD323)	Schottky diode	4
Blue LED	Power indicator	1

9.2. Passive Components

Value	Type	Qty
0 Ω	Resistor (ground bridge)	1
2.2 kΩ	Resistor (mic bias)	4
5.1 kΩ	Resistor (USB-C CC)	2
10 kΩ	Resistor (various)	14
40 kΩ – 330 kΩ	Resistor (gain setting)	20
100 nF (X7R)	Ceramic capacitor	24
1 µF – 10 µF	Ceramic capacitor	11
200 µF – 470 µF	Electrolytic capacitor	3

9.3. Connectors and Transducers

Part	Description	Qty
USB4110-GF-A	USB-C connector	1
POM-2738P-R	Electret microphone	4
BLM21BD272SN1L	Ferrite bead, 0805	1
Header 3×2	ISP programming	1

9.4. Summary

Category	Count
Integrated circuits	3
LEDs (WS2812B + power)	13
Diodes	4
Microphones	4
Resistors	41
Capacitors	38
Connectors / headers	2
Ferrite beads	1
Total	**106**

Estimated unit cost: **~$10** including PCB fabrication at volume.

10. Evaluation

10.1. Key Specifications

Parameter	**Value**
Preamp gain	×23
Differential gain	×33
Envelope bandwidth	~1.6 Hz (adjustable)
Direction resolution	12 sectors (30° each)
Response time	100–150 ms (adjustable)
Power consumption	~270 mA typical
Component count	~106
Unit cost	~$10

10.2. Design Goals Assessment

Goal	**Result**
Cost	~$10 per unit with common, readily available components
Simplicity	Two quad op-amps handle all analog processing; firmware under 1 KB
Size	80 mm circular PCB — compact, self-contained
User experience	USB-C power input works with any power bank or phone OTG
Noise immunity	1.6 Hz envelope bandwidth + split ground + differential CMRR
Flexibility	Response time adjustable via single capacitor change
Assembly	0805 / SOIC packages — hand-solderable or pick-and-place compatible

10.3. Known Limitations

Limitation	**Mitigation**
Fixed sensitivity	Add gain potentiometer in future revision
Small mic spacing (8 cm)	Acoustic baffle in housing; solved in glasses version
RC oscillator drift	Add external crystal if timing issues observed
Not yet fabricated	PCB sent for manufacturing — will update with test results

11. Future: Wearable Evolution

This desktop prototype validates core technology for evolution into a wearable form factor.

11.1. Proposed Form Factor: LED Glasses

Component	**Location**
LED ring	Integrated into glasses frame perimeter
Microphones	4 mics on glasses temples (~15–20 cm spacing)
Processing unit	Pocket module with power bank and analog electronics
Connection	Thin 4-wire cable: VCC, GND, LED data, shield

11.2. Advantages

Advantage	**Detail**
Wider mic spacing	15–20 cm (head width) vs. 8 cm — larger amplitude differences, better accuracy
Lightweight	Only LEDs and mics on head; heavy components in pocket
Natural orientation	Direction shown relative to where user is looking
Discrete appearance	Normal-looking glasses with subtle LED accents
Same analog chain	Preamp, envelope, differential stages transfer unchanged

11.3. Development Roadmap

V1	Desktop prototype	Validate envelope approach (this design)
V2	Wearable prototype	Split architecture with head-mounted microphones
V3	Integrated glasses	Custom frame, refined aesthetics
V4	Product	Miniaturization, wireless option, app configuration

12. Conclusion

This design achieves all stated goals through one key architectural decision: **envelope-based amplitude comparison** instead of time-difference-of-arrival.

12.1. Summary of Results

Goal	Result
Cost	~$10 per unit, 106 common components
Simplicity	Two quad op-amps for all analog processing
Compact size	80 mm circular PCB with integrated LED ring
Firmware	Under 1 KB flash, under 30 bytes RAM
MCU cost	ATtiny24A — only basic ADC and GPIO needed
User experience	USB-C, works with power banks and phone OTG
Noise immunity	1.6 Hz envelope bandwidth + split ground + differential CMRR
Flexibility	Adjustable response time via single capacitor
Future path	Direct transfer to wearable glasses form factor

12.2. The Key Insight

By moving direction detection from the time domain to the amplitude domain, complexity shifts from PCB layout and firmware to a simple analog filter. This reframing of the problem enabled every other design goal to be met simultaneously — and reduced a $30+ DSP problem to a $10 analog one.

12.3. Path Forward

The prototype validates core technology for a practical assistive device. The analog signal chain transfers unchanged to a wearable glasses form factor. Head-mounted microphones will provide wider spacing and improved accuracy. The same architecture supports future refinements — gain adjustment, wireless link, app configuration — without fundamental redesign.

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