AZD135 - On-Ear Wear Detect Design Guide

Design Guide for On-Ear Wear Detection

Contents

1 Introduction

The aim of this document is to give a step-by-step guide on how to design capacitive sensors for on-ear wear detection applications. The Azoteq technology used for this application provides an intuitive low power detection solution.

A summary of the design process is shown below:

Figure 1.1: Design Process Summary

This design guideline aids designers with integrating ProxSense® technology into new and existing designs. The guideline will give general recommendations for a quick-start design of detecting wear in an on-ear configuration. Please take note that this document should only guide you towards a final design. Designs discussed in this document should not be scaled directly to suit your application, and all considerations should be kept in mind. The design guidelines are for designs that employ both self-capacitive and/or mutual capacitive sensing. For a more in-depth explanation of capacitive sensing refer to AZD004.

The document is structured as follows: Chapter 2 outlines the design specifications for on-ear wear detection. Chapter 3 describes the capacitive proximity solution offered by Azoteq. Chapter 4 provides various resources to aid in the design of wear detection solutions. Chapter 5 demonstrates an example design of a on-ear wear detection solution utilizing the IQS318. Chapter 6 provides a process for validating the keyboard proximity design to ensure the requirements are met. Chapter 7 describes the interface between the master MCU and the sensor. Chapter 8 discusses important considerations for moving the wear detection solution into production.

2 Design Specification / Product Requirements

This chapter outlines the key specifications for the On-Ear detection sensor that needs to be considered during the design process.

2.1 Mechanical Specification

In on-ear headphone designs, the driver — also known as the speaker or transducer — is specifically engineered to align with the user's ear. It's only natural to leverage this existing mechanical design when incorporating a wear detection electrode. The driver is typically enclosed in a perforated plastic housing to allow sound transmission. This housing is often cushioned and enveloped with fabric for comfort and aesthetics. Consequently, this plastic enclosure emerges as the prime location for the electrode.

Considering the typical diameters of on-ear drivers, which range from 30mm to 40mm, the wear-detection electrode should cover at least 30% of the driver's surface area.

2.2 Electrical Interface Specification

The specifications for sensor electrical and interface design are listed in the table below.

Table 2.1: Electrical Specifications

Specification	Requirement
Supply Voltage (V_{DD})	1.8V - 3.3V
Internal Regulation (V_{REG})	Digital and analogue domains (requires external decoupling capacitors)
Communication Interface	I^2C (SCL & SDA) + interrupt / data-ready (RDY active-low) for event indication
Master Reset Control	MCLR (some devices time share functionality on the same pin as RDY)
Additional Outputs	Optional, Up to 3x outputs with custom configurable logic and output assignment
ESD protection	HBM up to class 3A and -B or IEC 61000-4-2 standard level 4 (contact and air discharge) System level qualification of finished product with the necessary protection can be achieved with the recommended series resistance on sensor (CRX) pins and the use of exposed ground traces and pours/floods for safe discharge. Extreme measures incorporates the use of TVS diodes to clamp nodes when and where necessary.
Radiated noise immunity	IEC 61000-4-3 standard test level 2 and 3 (3 V/m – 10 V/m) Appropriate capacitive decoupling and sensor series resistive elements (low-pass filter) component implementation and the placement thereof towards effective decoupling ground sites which are sufficiently stitched and commonly connected in a system are crucial for improved radiated immunity. Consider antenna placement and feed lines with higher energy flow
Current consumption	Application use of different sensors, UIs and response rate requirements may influence the current budget minimum allocation and brief periods of increased consumption. Optimisation of low power (sleep) current drawn should be minimised for extended idle periods. Current consumption for wear detection applications are dependent on the response rate. A higher response rate requires higher current consumption and vice versa. It is possible to achieve sufficient performance below 10 µA in some cases.

2.3 Operational Environment Specification

The specifications for sensor operational environments are listed in the table below.

Table 2.2: Operational Environment Specifications

Specification	Self-capacitive	Mutual capacitive
Typical product temperature range	-10°C to +60°C	-10°C to +60°C
Product operational relative humidity range	30- to 70 %RH	30- to 70 %RH
Usable charge transfer frequency range	125 kHz – 1 MHz	500 kHz – 4 MHz

2.4 Sensing Range

In wear detection systems for on-ear headphones, where the electrode is aligned with the driver, user proximity and considerations regarding air gaps are essential to ensure accurate sensing. Factors such as electrode positioning, the thickness of the plastic surround and the choice and arrangement of foam or fabric can impact the system's efficacy. Typically, such an on-ear design has a sensing range that spans between 15mm and 25mm from the electrode to the user.

2.5 Report Rate and Wake-up Response Time

Table 2.3: Report Rate and Wake-up Response Time

Specification	Requirement	
Sensor Configuration Start Up Time	$<$	1000 ms
Active Mode Report Rate	$\geq$	50 ms[i]
Low Power Mode Report Rate	$\leq$	160 ms
Activation Timeout	0 ms	(Never)

The activation timeout should be set to zero. In wear detection applications, the system is designed to accommodate prolonged periods of either activation or deactivation. Intuitive release algorithms manage the transition from activation back to deactivation.

2.6 Communication Interface

For I2C solutions, use "Event Mode" to prompt an interrupt (through the RDY line) to the master solely when an event, such as a Wear or Wear Release, is detected. This approach conserves power and reduces MCU processing demands.

In a standalone configuration, a GPIO level can be used to indicate the activation or wear detection state.

2.7 Test Points

Exposed copper test points are required for VDD, GND, SDA, SCL and RDY. The test points are used during production testing for rapid debugging of the proximity sensor.

[i] A higher report rate can be set to achieve better responsiveness but with an increased current consumption.

3 Proposed Solution

This chapter provides a high-level overview of Azoteq's on-ear wear detecion solutions, including a a brief overview of different sensing methods, system diagram, a mechanical stack-up, and a list of recommended Azoteq part numbers.

3.1 Typical On-Ear Layout

Wear detection for on-ear products is inherently consistent across applications, as they all interface with the user's ear. While the detection distance might vary due to specific design nuances, the proposed solution is versatile and can be easily adapted for different scenarios.

Figure 3.1: Typical On-Ear Headphone Representation

The electrode pattern typically follows the cut-out cavity between the speaker and the speaker grille.

3.2 Sensing Methods for On-Ear Designs

For on-ear designs, a self-capacitive sensing electrode pattern paired with a self-capacitive reference pattern is advised. While projected capacitive designs are an alternative, they're best suited for specific scenarios:

- when the signal strength obtained from user interaction is lower than anticipated,
- when the distance between the ear and sensor exceeds expectations, or
- when the humidity inside the cup significantly surpasses the norm (> 90%).

In standard conditions, the use of self-capacitance remains the preferred approach.

3.3 System Description

On a high level the system overview is comprised of three main sections:

- The user
- The sensor solution

- The host (main controller / processor)

The sensor slave controller (IQS device IC) is required to accommodate customisable setup(s) specific to hardware designs and UI requirements and will operate as required to sense, process and qualify detection of low-level measurement data while also doing the validation for user interaction events. Only when a valid event interaction is registered, the host will be interrupted to service and read the reported event state and detail via the dedicated communication interface, thus minimising the data transfer, latency, processing overhead and service priority (ISR) required so that other more important tasks on the host side can be handled with optimal/required resource allocation.

Figure 3.2 provides a system block diagram of a generic I2C on-ear implementation with wear detection.

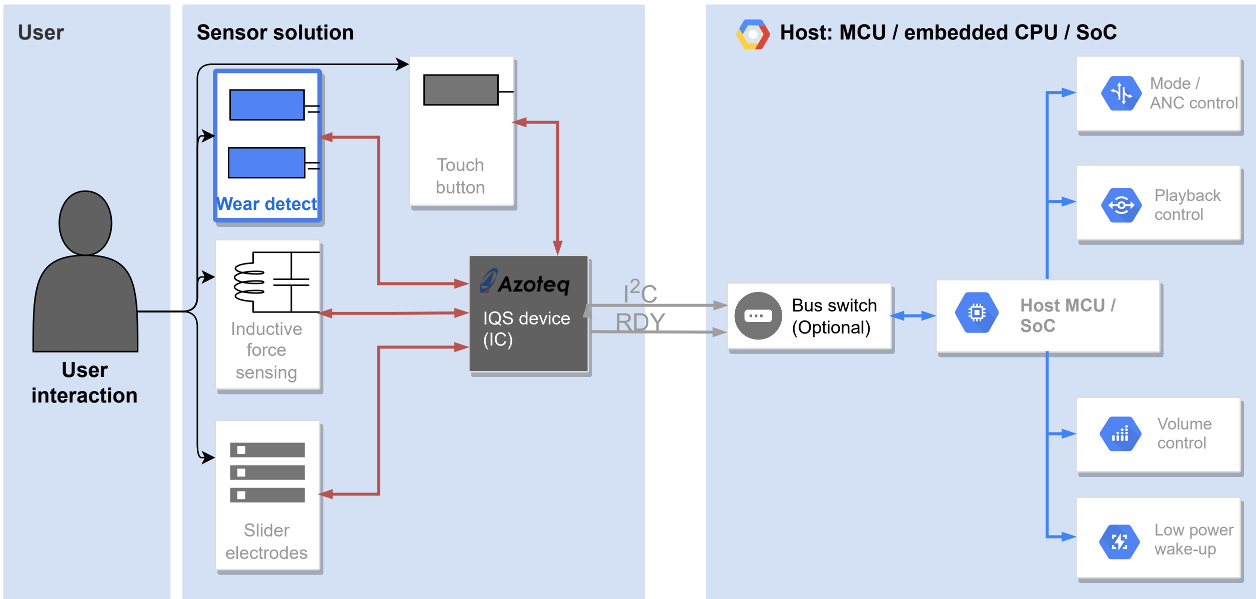

Figure 3.2: System Block Diagram

3.4 Mechanical Stackup

The design of on-ear headphones provides an optimal setup for incorporating wear detection. The driver, also known as the speaker, is nestled within an acoustically ventilated plastic enclosure, cushioned, and enveloped in fabric. For best wear detection results, it's recommended to position the sensor directly on the speaker grille. This strategic placement efficiently senses ear presence and significantly reduces interference from users gripping the earphones.

To enhance audio quality, it's essential to incorporate a notable proportion of PCB/FPC cut-outs in the design, which can ideally mirror the speaker grille's outline. The IC, which processes sensor data, should be situated close to the sensing pattern, optimizing performance, and streamlining the final validation and robustness testing process. If the IC is on the main PCB and not the sensing board, it's vital to use a shielded cable or twisted pair for the sensor line connection, ensuring minimal interference.

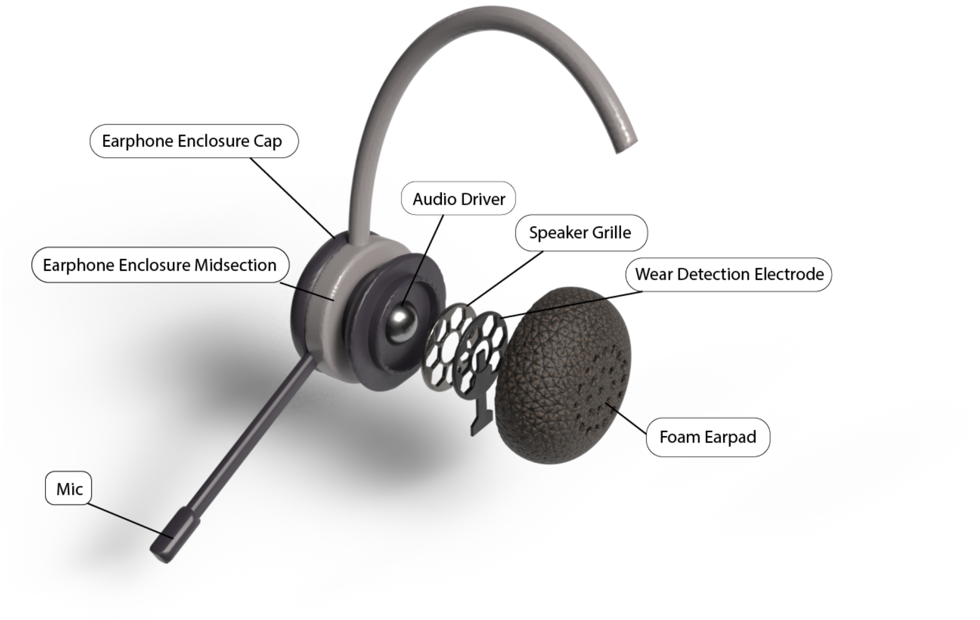

Figure 3.3: Typical On-Ear Assembly

3.5 Azoteq Device Selection Guide

The following listed devices are Azoteq's recommended on-ear wear detection solutions.

- IQS7222C (WLCSP18 [1.62 x 1.62 x 0.5 mm] QFN20 [3 x 3 x 0.5 mm])
  - Up to 4 self-capacitive channels
  - Up to 4 mutual capacitive channels
    - Differential mutual capacitance available
  - Arduino Example code available
- IQS323 (WLCSP11 [1.48 x 1.08 x 0.345 mm] DFN12 [3 x 3 x 0.75 mm])
  - Single channel self-capacitive sensor
  - Built-in signal processing options:
    - Standalone proximity output
    - Movement user interface
    - Release user interface
  - Arduino Example code available
- IQS318 (WLCSP11 [1.48 x 1.08 x 0.345 mm] DFN12 [3 x 3 x 0.75 mm])
  - Single channel self-capacitive sensor
  - Built-in signal processing options:
    - Standalone proximity output
    - Release user interface

Comparison Table

Product	Features	Integration Level	Reference
IQS7222C	High integration, Can add additional buttons and slider, Many reference MP products	High	Validated in numerous mass-produced products
IQS323	Similar to IQS7222C, Can add capacitive touch or inductive button	Medium	Similar to IQS7222C
IQS318	Integrated UI for multi-direction detection	Specific for on-ear applications	1-Channel I2C / GPIO options available

4 Design Resources

For all sensor design resources please refer to the Azoteq website: ProxFusion combination sensors

4.1 Datasheets, Application Notes and User Guides

- IQS Device Datasheets
- AZD004 - Azoteq Sensing overview
- AZD044 - Azoteq MSL and Reflow specifications
- AZD125 - Capacitive sensing design guide
- AZD102 - Series resistance limit of self capacitance charge transfers

4.2 Hardware Design Resources

- IQS7222CzzzQNR [QFN20] SCH symbol and PCB footprint
- IQS7222CzzzCSR [WLCSP18] SCH symbol and PCB footprint
- IQS323zzzDNR [DFN12] SCH symbol and PCB footprint
- IQS323zzzCSR [WLCSP11] SCH symbol and PCB footprint
- IQS318zzzCSR [WLCSP11] SCH symbol and PCB footprint

4.3 Software, Tools and Example Code

- Arduino Example code and user guide
- Graphical user interface software and tools
- CT210A Azoteq Configuration tool

5 Design Implementation

This chapter describes the design implementation of wear detection in an on-ear headphone configuration.

5.1 Sensor Design

Given the inherent need for cut-outs in the sensor electrode to meet acoustical requirements, it's vital to ensure they maintain comprehensive sensor coverage and robust signal amplitude. Bearing this in mind, utilizing a self-capacitance sensor with a copper pour can yield an optimal layout within the available real estate. While a thin FR4 substrate is recommended, FPC alternatives can also be effective.

Implementing a wear reference enhances the effectiveness in counteracting capacitance drift, which can arise from material variations and environmental factors such as temperature and humidity. For more detailed guidance on implementing a wear reference, refer to section 7 of AZD125.

For the most effective signal-to-drift ratio, especially in long-term wear applications, the recommended placement of the IC is directly on the sensor pad. Conversely, positioning the sensor IC on the primary PCB can yield adequate results, provided the distance remains minimal and there's effective management of the GND shielding capacitance drift. For instance, when the sensor and reference traces run adjacent but in separate time slots, they can function as a GND shield for one another. In such configurations, the use of a twisted or shielded wire pair is advocated. It's imperative to mitigate any mechanical impacts on this wire to avert inadvertent capacitive shifts during regular usage.

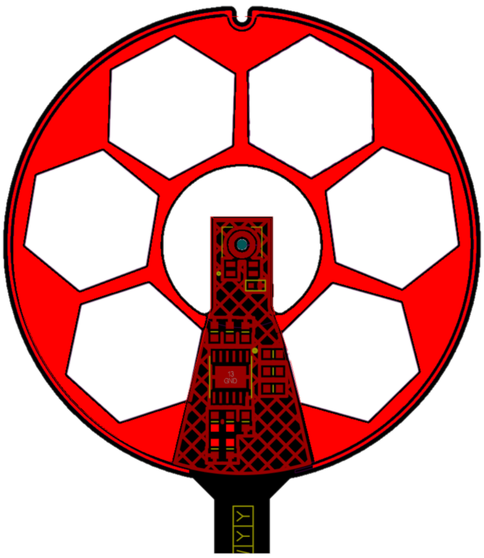

Figure 5.1: Wear Detection Electrode Design

In previous sections, it was established that the wear detection electrode for an on-ear headphone design typically aligns with the outline of the speaker grille. This principle is evident in the design depicted in Figure 5.1 above, where the FPC not only mirrors this outline but also houses the noise-cancelling microphone and speaker terminals. The main wear detection electrode is highlighted in the figure. Additionally, the thin reference channel encircling the outline is also emphasised.

5.2 Circuit Design

A circuit was designed with the IQS323 (DFN12 package) and a simplified schematic diagram is shown in figure 5.2 below. Note that CRX0 is the sensor trace and CRX1 is the reference trace.

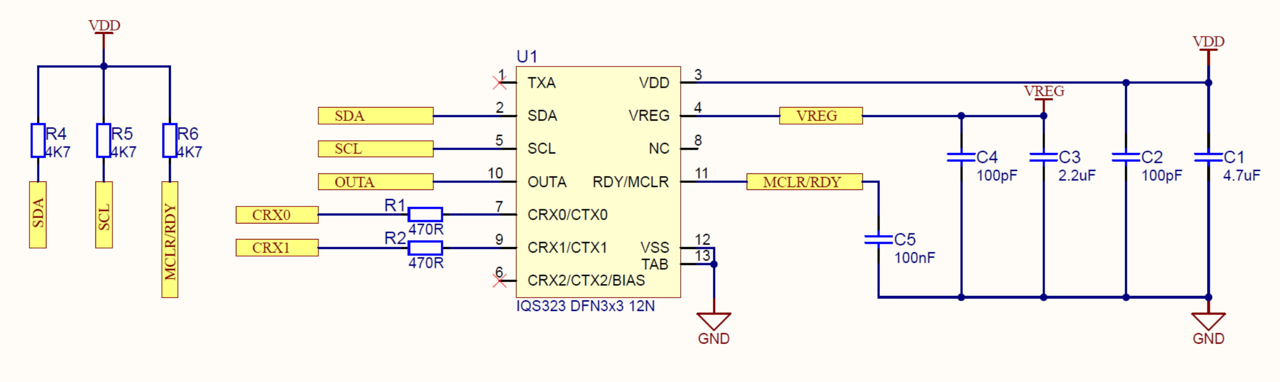

Figure 5.2: Simplified Schematic Design for Wear Detection Solution[i]

5.2.1 Power Supply Decoupling and Regulation

All IQS devices require external decoupling capacitors on their supply (VDD) as well as internal regulation (VREG) pins. Please refer to IQS device specific datasheets for implementation and guidance for optimal component selection, size and placement/routing considerations.

5.2.2 Capacitive Sensor Nodes

All the self-capacitive sensor inputs (CRX) are supplied with a standard series resistance to increase radiated immunity and will sense the connected electrodes accordingly (please refer to AZD125 for fundamental design discussions; AZD015 for considerations of radiated/RF immunity; AZD102 on using resistive paths higher than the recommended). A TVS diode should be added on the sensor inputs to suppress any induced voltage spikes.

5.2.3 Routing

Digital signals such as PWM signals, I2C or SPI are active during a capacitive measurement, therefore it is recommended that the digital signals be kept a minimum of 4 mm away from the capacitive sensor traces, preferably on the bottom layer of the PCB. Refer to AZD125 for more details on routing.

5.2.4 Connections

Test points are essential for efficient design development, debugging, and validation. They're recommended when they can be situated on an FPC tail or when the sensor PCB components occupy minimal space. When the sensor IC is placed on the main board, adding test points nearby for power and communication simplifies troubleshooting during production.

[i] Although this design makes use of the IQS323, the IQS318 can also be used as they are pin compatible. The IQS7222C can also be used in a similar schematic configuration.

5.3 PCB Layout Design

Figure 5.3 provides a visual representation of the on-ear wear detection solution's printed circuit board (PCB).

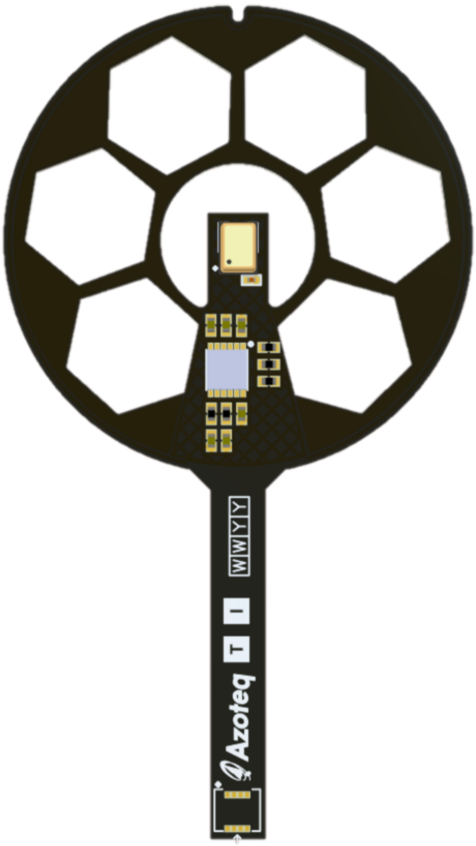

Figure 5.3: On-Ear Wear Detection Solution PCB

5.4 IC Setup

The graphical user interface (GUI) is a powerful support/design tool to simplify the process of configuring the IQS device with the parameters required for optimal performance for customer-specific hardware.

An introduction on how to use Azoteq's debug and display tool can be seen in this video.

The latest GUI can be obtained from the relevant product page on Azoteq's website as listed in Chapter 4.

The settings below are shown on the GUI for the IQS323, however these concepts also apply to the IQS318 and IQS7222C.

5.4.1 Channel Settings

Channel sensor settings can be seen in figure 5.4 below.

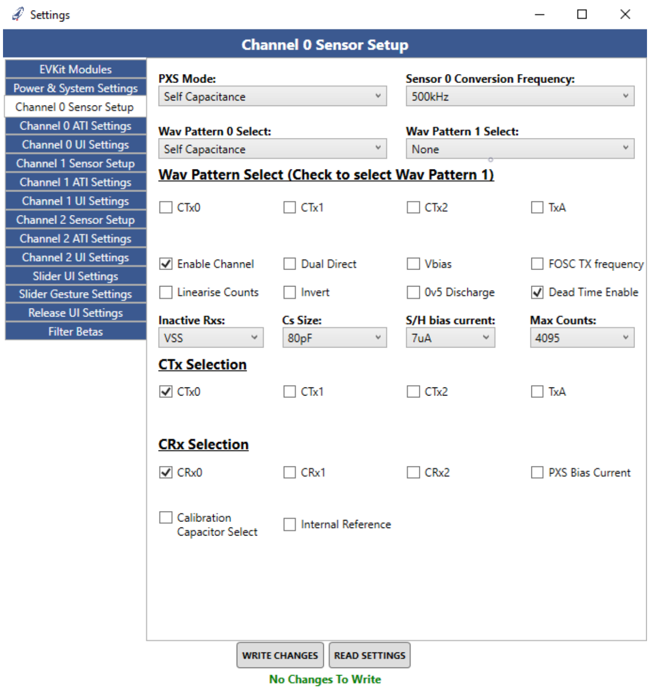

Figure 5.4: Channel Sensor Setup

The selection of CTx and CRx can be altered to designate the Sensor Cx pin for the desired channel, providing more flexibility in the PCB layout by enabling the choice of alternative pins if necessary. It's important to note that for self-capacitance applications, like the one discussed in this design guide, it is imperative to select both the CTx and CRx pins.

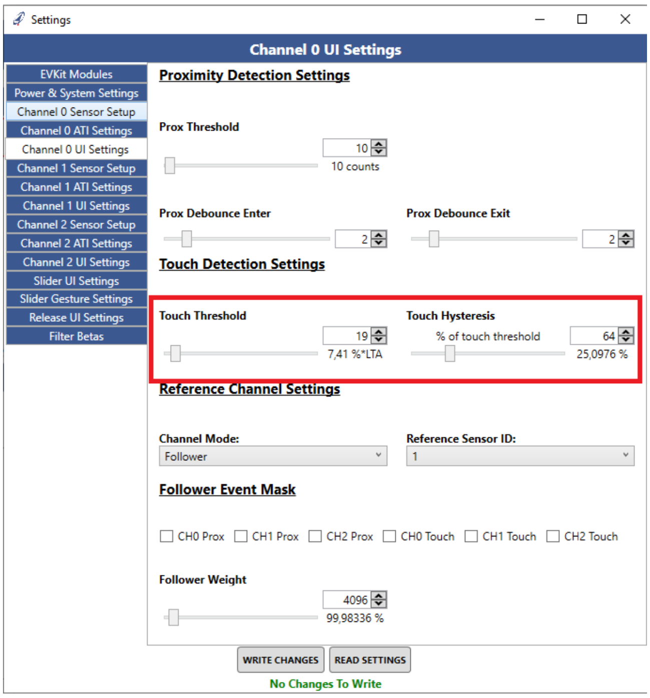

Figure 5.5: Channel UI Settings

Channel UI settings can be seen in figure 5.5 above. Here the channel activation thresholds can be adjusted.

5.4.2 System Settings

Power and System settings can be seen in figure 5.6 below. Here power mode timeouts, report rates and event settings can be configured.

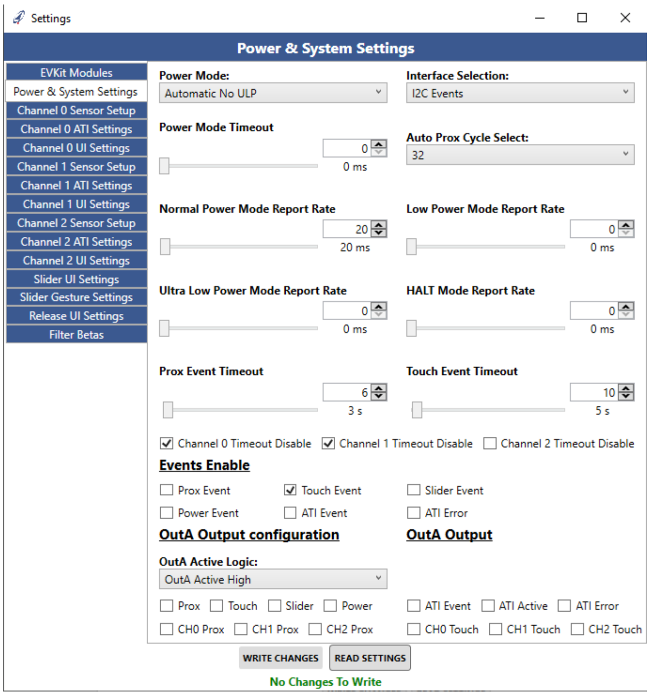

Figure 5.6: Power and System Settings

Event Mode should be enabled to prevent the master MCU from being interrupted unnecessarily.

Firstly, configure which events should be generated in event mode. In this case, the channel activation event will generate an event only when a channel activation occurs due to proximity or touch. Data can be read when a communication window opens due to the event occurring.

Enable the Event Mode bit when the MCU has finished the I^2C initialisation process.

The report rate and power mode timeout should be adjusted to meet the response and current consumption specification. A lower report rate will result in higher current consumption and vice-versa.

6 Design Verification

This chapter describes the general procedure that should be followed to validate whether a design meets the original requirements. This is done during the engineering stage. Using the numerous configurations available on the Azoteq device, small adjustments can be made to optimise and improve the performance to meet the requirements.

With the design verified, similar performance will be expected in mass production due to the on-chip calibration (ATI) technology, an individual verification of each of these items is not needed in mass production testing phase.

6.1 Test Setup

Design verification is done using the product GUI. Connect the power, I^{2}C and RDY lines of the IQS7222C / IQS318 / IQS323 to the CT210A USB dongle as shown in the table and figure below. Now connect the CT210A via an USB-micro cable to an available USB port on a PC.

Table 6.1: CT210A Pin-out

IQS Pins	CT210A Pins
GND	Pin 1
VDD	Pin 3
MCLR	Pin 5
SDA	Pin 7
SCL	Pin 9
RDY	Pin 10

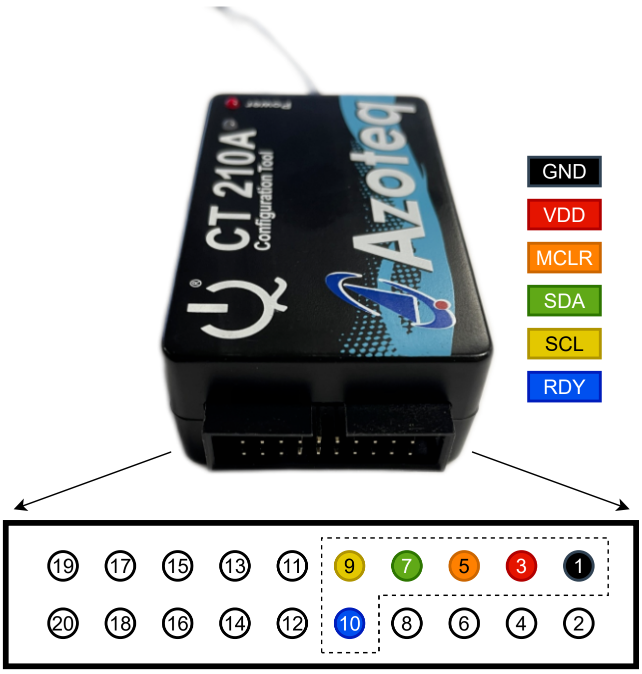

Figure 6.1: CT210A Power, I^{2}C And RDY Connections

The typical procedure to evaluate a device is as follows:

- Open the device-specific GUI software
- start up the device by clicking the "START STREAMING" button
- Initiate the streaming of device data by clicking the "ACK RESET" button
- Load the application-specific configuration settings using the "IMPORT H FILE" button, or configure the device manually by pressing the "USER SETTINGS" button and using the various options available in the submenus
- Ensure that the ATI algorithm has executed correctly after the changes in the previous step have been applied
- View the channel or system response by means of the bar, scope or event indications
- Specific operating modes (such as low power sampling or event mode operation) can also be induced for example to measure currents or to monitor I^2C and RDY logic behaviour and event activities.

For further detailed information on the related device and/or GUI support please consult the necessary documents as listed in Chapter 4.

6.2 Response Output

Evaluating the response of a sensor in real-time is beneficial for rapid setup, tuning and prototyping.

For the IQS318, the wear and release signal are obtained through a single channel. On the IQS323 and IQS7222C, one channel is used for the wear signal and one channel is used for the release signal. The example in this section is based on this type of two channel solution.

Depicted below is the response output of a typical wear detection configuration where CH0 acts as the wear activation channel, CH1 acts as the reference channel for CH0, and CH2 acts as the wear release channel.

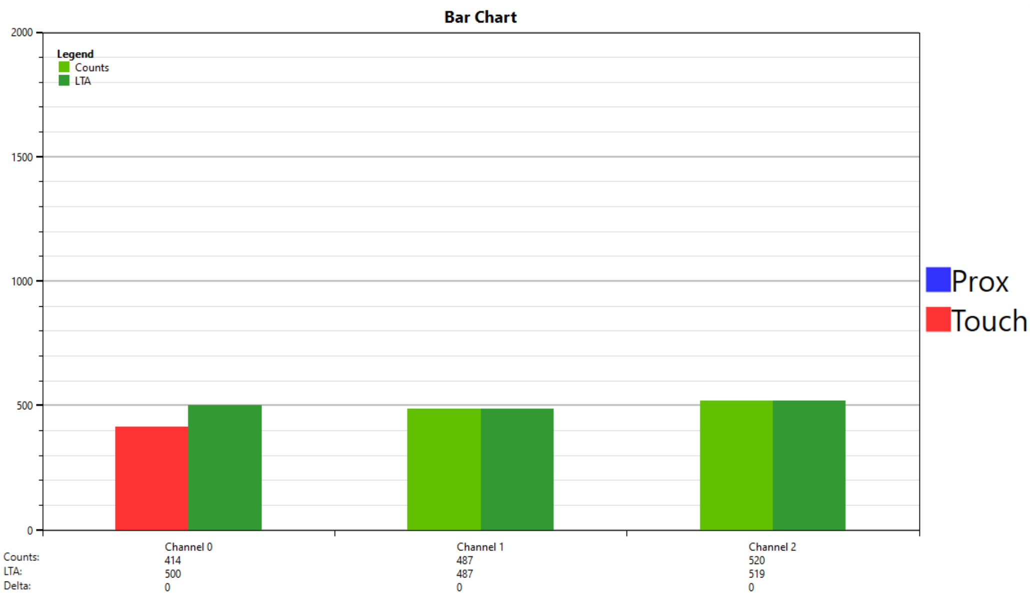

Figure 6.2: GUI Bar Output For Count And LTA Data while activated in Wear

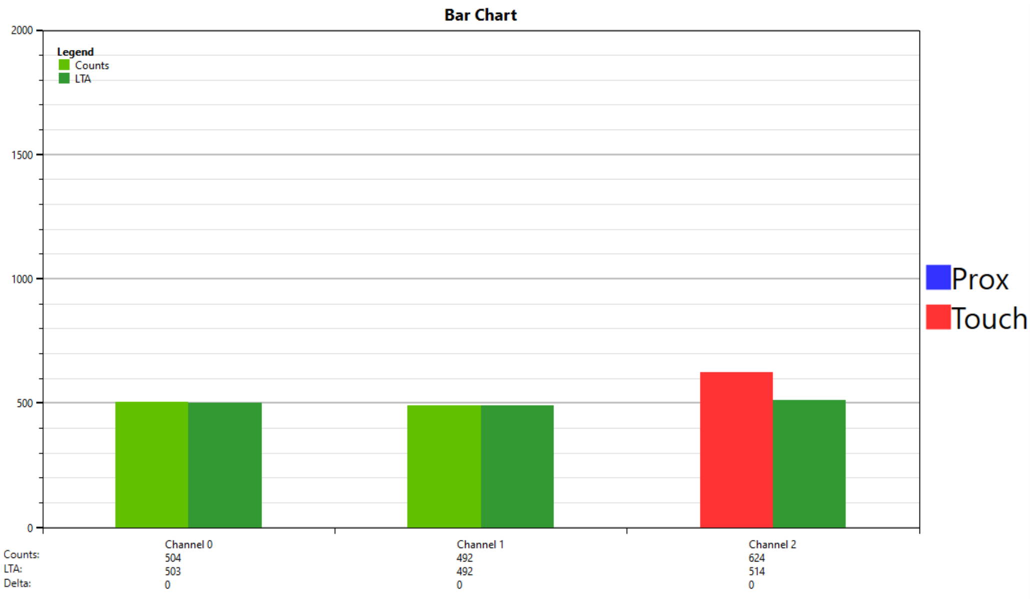

Figure 6.3: GUI Bar Output For Count And LTA Data when indicating release

Now putting the two together on the scope view - wear first followed by the release.

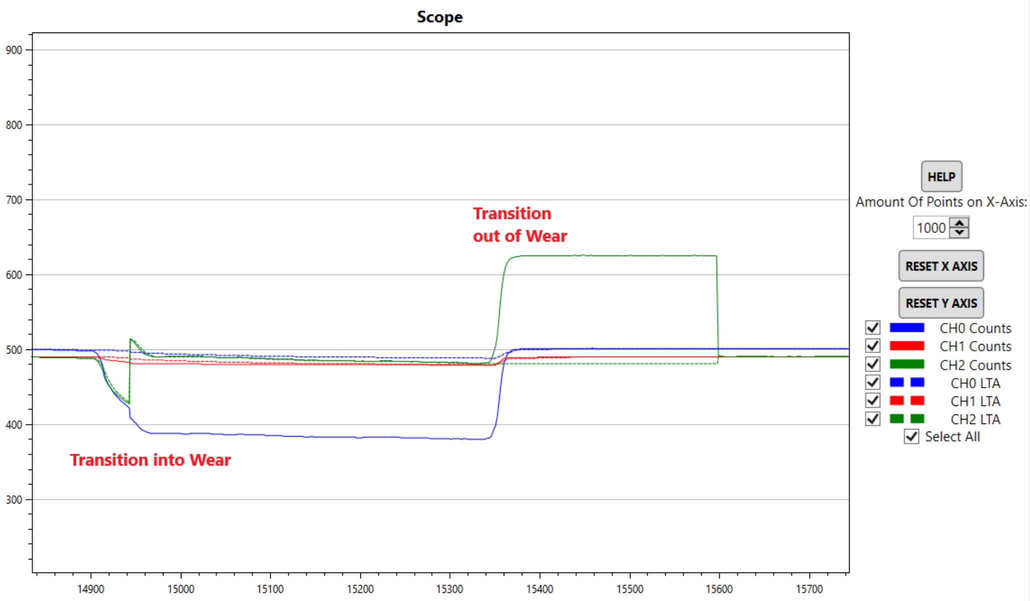

Figure 6.4: General GUI Scope Output For Count And LTA Data

In addition, the follow scope view shows what happens if an electrode is powered up while in wear and then released. The value of CH2 specifically detecting a release is shown here.

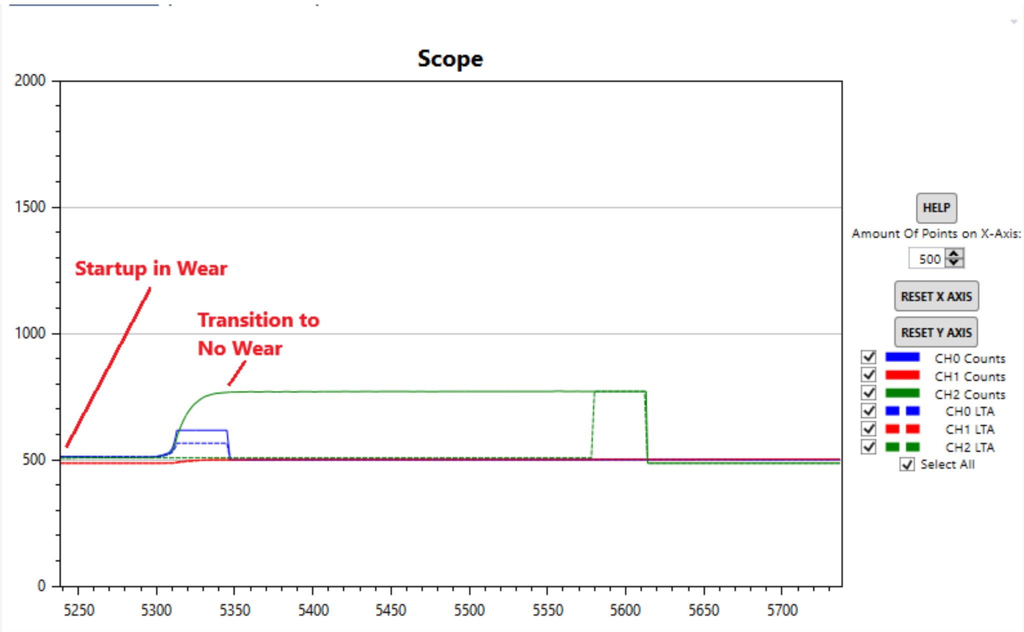

Figure 6.5: General GUI Scope Output For Count And LTA Data

This is a self-capacitive setup where the counts are not linearised and an increase in capacitance results in an decrease in counts. While still not linearised, the output of CH2 are inverted, which provides an wear release indication. This is especially useful if the device was powered-on while being worn and in wear. To save power, CH2 can be disabled after the first release event after power-on.

The outputs shown in figures 6.2, 6.3 and 6.4 are the results while the system ground is referenced to earth ground (USB Powered).The test setup can be seen in figures 6.6 and 6.7 below.

Figure 6.6: Proximity Range Test Setup

Figure 6.7: Proximity Range Test Setup

To thoroughly evaluate and analyze the response of the sensors, it is recommended to gather sample data through logging sessions. These sessions may involve extended activation periods, temperature or humidity variations, or other stimuli, depending on the specific use case or qualification being examined. To ensure a robust device, sample data should be collected where the headphones are placed on a diverse range of testers with regards to headsize, earsize and long vs short hair.

6.3 Temperature and Humidity Tests

A temperature and humidity controlled environmental chamber can be used to validate sensor reliability and performance within product operating specifications. However, this may not simulate the true environment for typical real life product use scenarios and dynamic combinations thereof. Some of the challenges typically experienced includes inducing wear versus out of wear state changes, body heat influence and other system operational influences. Practical use of the on-ear headphone product in different environments should form part of the functional testing during design validation.

6.4 Noise Tests

Normal product noise variation should be evaluated over numerous pre-production units/builds before starting mass production testing in order to gain performance metrics and statistics for establishing the upcoming production limits. An applicable noise failure limit must be considered to reject excessively noisy sensors with presumable quality or assembly issues. Standardised noise tests (whether aimed at radiated and/or conducted noise) as well as other product performance qualifications governed by international standards, should be considered according to the specific underwriting by the IEC body or other known standard body which the product needs to comply with.

7 Interface Description

This chapter provides some high-level information that should be beneficial to a firmware developer who wants to write a driver for one of Azoteq's ICs in a wear detection application. The chapter should be read in conjunction with the relevant device's datasheet.

7.1 Software Implementation

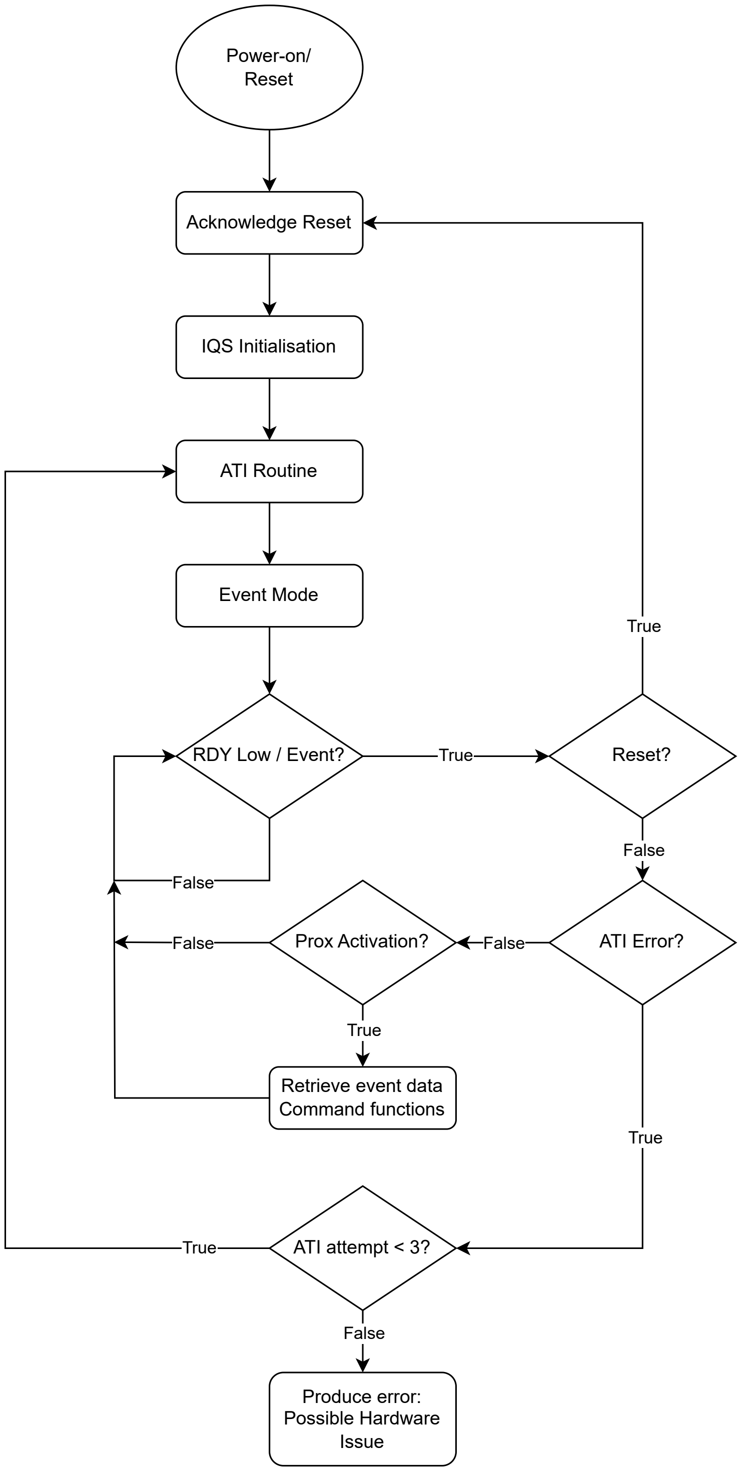

Figure 7.1: Software Flow Diagram

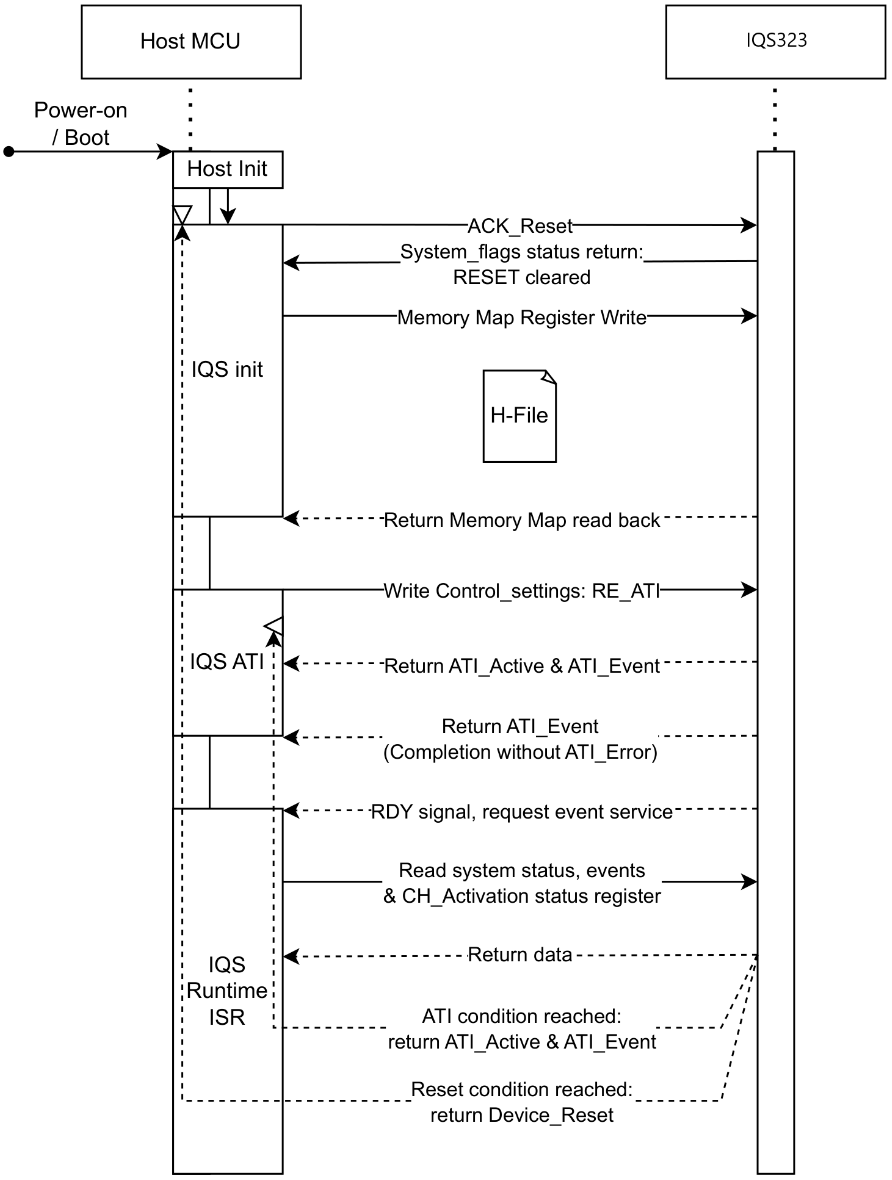

Figure 7.2: Host Software Sequence Diagram

Once the initialisation has been completed, the IQS323 will notify the master of events by pulling the RDY line Low. The master can then read the event flags and act accordingly.

7.1.1 Example Host Software Flow

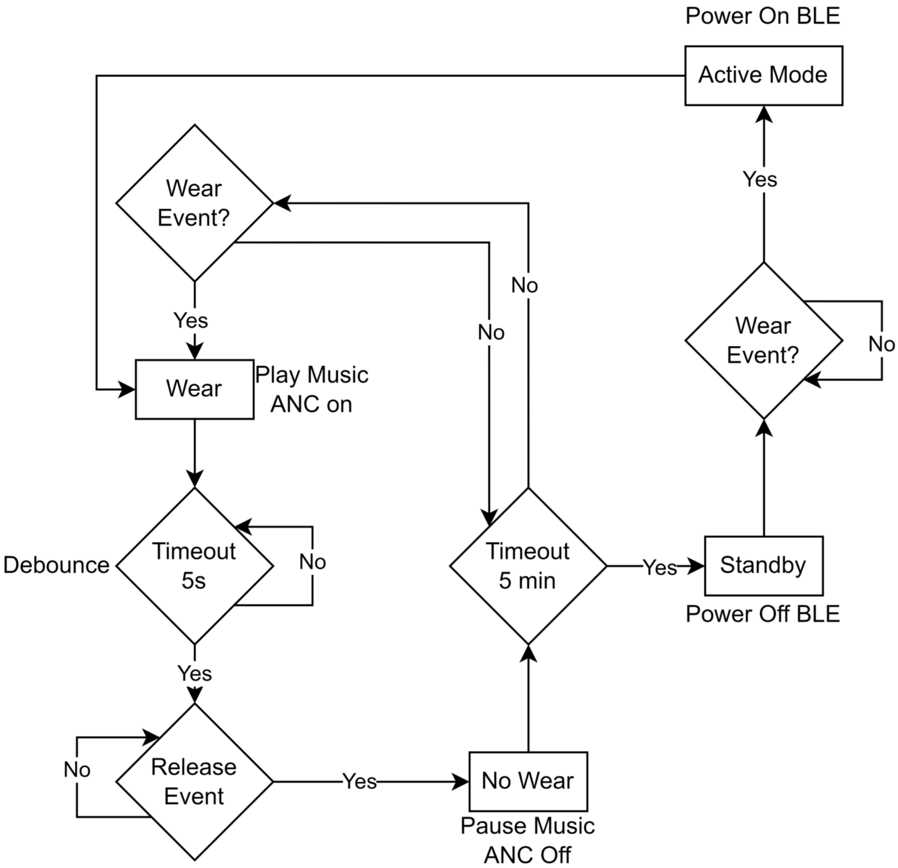

Figure 7.3: Example Host Software Flow

An example flow diagram of the headphone behavior can be seen in figure 7.3. Upon powering on the Bluetooth Low Energy (BLE), the system enters the active mode. If a wear event is detected, the music starts playing with Active Noise Cancellation (ANC) activated. After wearing the headphones, the system continues playing music for at least 5 seconds (due to debounce). If a release event is subsequently detected, the system transitions to a state where the music is paused, and the ANC is deactivated. In the absence of any wear event for a duration of 5 minutes, the system shifts into standby mode and turns off the BLE.

7.1.2 Communication Protocol

For examples of I^2C addressing, read, write, force communication requests and other communications related behaviour, please refer to the relevant device's datasheet I^2C interface section.

8 Mass Production Testing

This chapter provides information concerning testing during mass production.

8.1 In-circuit Testing (ICT)

PCBA testing should ideally be done with the product assembled to determine the effect of all auxillary functions such as bluetooth, etc. Ideally test should be done in the typical operating environment of the headphones. The testing environment should be free of any users or objects that could interfere with the ATI calibration routine.

Testing of the proximity sensor can be done via the on-board MCU. The following test parameters should be considered:

- Version information
  - Check device product number
  - Check device major and minor firmware version info
  - Confirm device communication and clear/acknowledge (*ACK RESET*) flag
- Application settings
  - Written configuration settings can be read back
  - ATI specific parameters are distinct and updated
  - ATI completion reached on all channels without any *ATI error* reported
- Functional testing
  - Procedural exercise of all functionality when sensors are activated (can have a test routine implementation)
  - Induced user activation assessment (signal of known or controlled benchmark for sensitivity and reactivity qualification)
  - Raw signal noise assessment
- Current consumption
  - Average current measurement over long periods is constant for normal device operation
  - The integration time period should be long enough such that starting or ending the measurement midway through an active cycle/conversion does not have a large effect on the measured average current

Pre-production builds of increasing quantities are a general sound practice used to choose applicable tests, gathering test data and establishing limitations thereof. Statistical means, standard deviations and typical outlier criteria may be used to discover and inspect certain units in detail to institute a basis for known risks or critical design aspects which should be evaluated, addressed and improved upon during the preparation leading towards final or mass production.

Testing should also be done where a unit is only battery powered and isolated from earth, and the case where the unit is earthed (example via USB). This is to determine whether satisfactory performance is achieved with all methods of operation.

8.2 Response vs Current Consumption

There exists a trade-off between the responsiveness of a sensor and the average amount of current being consumed to reach a specific response or sampling rate. End-product or UX design may dictate the specification for responsiveness but this ultimately impacts the overall system current consumption. Current measurement during production testing should allow for typical normal power mode operation as well as slower low-power mode current measurements to ensure acceptable consumption requirements are met and guarantee the stability of a specific mode without irregular/erratic behaviour such as unexpected wake-up from low-power modes or excessive high currents (short-circuit assembly issues).

Standard SMT production line practises and guidelines should always be followed with respect to IC device and sub-assembly handling, manufacturing, storage and transport to ensure quality, high yield and reliability.

9 Revision History

Release	Date	Comments
v1.0	2023/10/27	Initial document released

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