AuraGuard: A Wearable Proximity Alert System for Child Safety Using BLE and UWB

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I. Introduction

Child safety in crowded or hazardous environments remains a pressing concern for parents and guardians. A brief moment of distraction can result in a child stepping into dangerous areas such as traffic zones or becoming lost in a crowd. Conventional solutions like GPS trackers often rely on internet connectivity, which not only consumes significant power but also performs poorly indoors.

AuraGuard addresses these challenges by providing a point-to-point wearable proximity alert system that operates without internet connectivity. The system consists of a parent and child wristband pair, where the parent's device vibrates when the child moves beyond a predefined safe distance.

AuraGuard is implemented in two versions: Version 1, based on Bluetooth Low Energy (BLE) Received Signal Strength Indicator (RSSI), and Version 2, using Ultra-Wideband (UWB) modules (BU01/DW1000) for precise Time-of-Flight (ToF) ranging.

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II. Literature Review

Existing child tracking systems often rely on GPS, which performs poorly indoors and consumes significant power. BLE-based solutions have been widely explored due to their low power consumption and availability in consumer devices. However, BLE distance estimation based on RSSI suffers from multipath interference, signal attenuation, and fluctuations, leading to significant accuracy issues in real-world environments.

These performance limitations motivated the development of AuraGuard Version 2, which replaces BLE RSSI with Ultra-Wideband (UWB) Time-of-Flight ranging. Recent studies have demonstrated that UWB provides centimeter-level accuracy and robustness against multipath effects, making it highly suitable for safety-critical applications such as child proximity alerts. However, UWB adoption in consumer wearables is still emerging.

By first implementing a BLE-based solution and then addressing its limitations through UWB integration, AuraGuard demonstrates both the practicality of BLE and the performance advantages of UWB, bridging the gap between cost-effectiveness and accuracy in wearable child safety systems.

III. Materials and Methods

A. Hardware components

BLE Version (AuraGuard V1): Implemented using ESP32 development boards, which provided integrated Bluetooth Low Energy (BLE) functionality. The ESP32 modules were used for transmitting and receiving RSSI values, which were then processed to estimate distance.

UWB Version (AuraGuard V2): Implemented using the DW1000 NodeMCU-BU01 Development Board, which supports Ultra-Wideband (UWB) ranging. These boards exchanged packets to measure Time-of-Flight (ToF) between parent and child devices, enabling centimeter-level distance estimation.

B. BLE RSSI-Based Distance Estimation

In AuraGuard Version 1, distance between the parent and child devices was estimated using the Received Signal Strength Indicator (RSSI). The relationship between RSSI and distance is modeled using the log-distance path loss model [3]:

$$d = 10^{\frac{P_{TX} - P_{RX}}{10.n}} \qquad (1)$$

Definitions:

- d = estimated distance (meters)
- P_{TX} = transmitted power at 1 meter (dBm)
- P_{RX} = received signal strength (RSSI) in dBm
- n = path-loss exponent (environment-dependent, usually 2–4)

This formula provides a simple method for estimating distance, but the results are highly variable due to multipath interference and signal fluctuations.

C. Kalman Filter for Smoothing RSSI Readings

To improve stability of the RSSI-based distance measurements, a Kalman filter was applied. The Kalman filter recursively estimates the true state (the distance) by combining the predicted state and the measured state with a gain factor.

This smoothing significantly reduced short-term fluctuations in the BLE-based distance estimation, but could not fully overcome the accuracy limitations inherent to RSSI.

D. *UWB Time-of-Flight Ranging*

In AuraGuard Version 2, Ultra-Wideband (UWB) modules (BU01/DW1000) were used to perform two-way ranging based on Time-of-Flight (ToF). Unlike RSSI, which infers distance from signal strength, UWB directly measures the travel time of signals, achieving centimeter-level accuracy.

The devices exchange poll, response, and final messages, and the Time of flight of the signal is measured to compute distance:

$$d = \frac{c \,.\, ToF}{2} \qquad (2)$$

Definitions:

- d = estimated distance (meters)
- c = speed of light (3×10^8 m/s)
- ToF = Time-of-Flight

UWB uses very short pulses over a wide frequency spectrum, it can penetrate small obstructions (e.g., walls, furniture) with minimal signal degradation, providing reliable and stable distance measurements even in cluttered indoor environments.

IV. Results and Discussion

Version 1 (BLE): Demonstrated effective proximity alerts in open environments where there is a direct line of sight but suffered from inaccuracies in multipath-heavy indoor conditions and across barriers with typical error of ±1–2 meters and it was found to grow exponentially with distance. The RSSI based results were found be accurate within first 50 cm but subjected fluctuations.

Version 2 (UWB): Achieved significantly improved accuracy, with error reduced to ±10–20 cm in both indoor and outdoor tests as shown in Fig. 1. Across barriers and obstructions, the accuracy reduced to ±40–50 cm. The actual distance and the measured distance exhibit a linear relationship, as illustrated in Fig. 2.

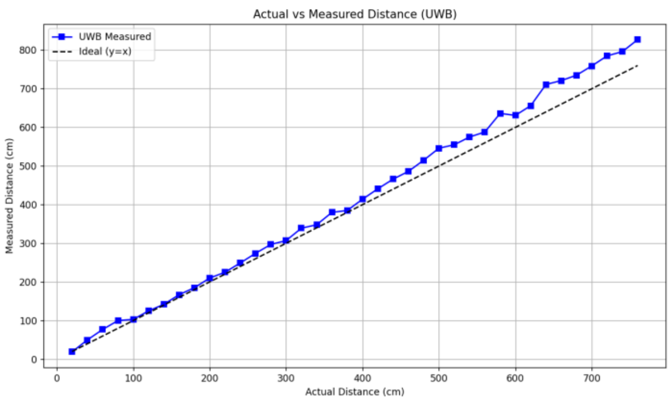

Fig. 1. Actual Vs Measured distance (UWB)

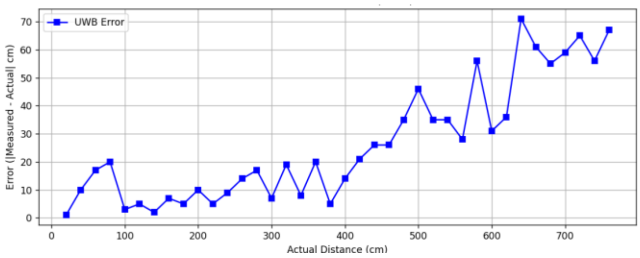

Fig. 2. Actual distance Vs UWB Error

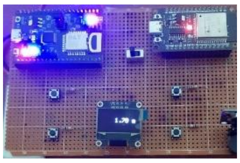

Fig. 3. Parent's wrist band prototype

Fig. 4. Child's wristband prototype

The error (Actual distance – Measured distance) of distance measured using UWB was found to be increasing with the actual distance as illustrated in Fig. 2.

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