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IoT Based Smart Safety Wristband Using BLE Zone Sensing and LoRa Long-Range Alerting for High-Density Public Gatherings

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Abstract: *Large religious and public gatherings, such as the Kumbh Mela, bring together millions of people in a small area for a short period. In these conditions mobile networks become congested, and an individual in distress often cannot be identified or reached in time. This paper presents the design of an IoT Based Smart Safety Wristband that combines two complementary low-power radio technologies. Bluetooth Low Energy (BLE) is used for short-range zone sensing and active geofencing: fixed beacons advertise their zone identity, and the wristband classifies the zone it is in. LoRa is used for long-range, infrastructure-independent delivery of compact alert packets to a gateway, from where a web dashboard shows the zone and status of every wristband. The wristband is built around an ESP32 microcontroller with an SOS button, an OLED display, a vibration motor, a buzzer and status LEDs, and is powered by a rechargeable Li-ion cell. We review thirteen published studies on LoRa range and reliability, BLE zone detection and crowd safety, and use their findings to justify key design choices: a very short payload, a sliding-window RSSI filter with hysteresis, and local alerting that works even when the backhaul is unavailable. The paper reports the system design, the alert protocol, an analytical time-on-air estimate and a structured evaluation plan. Field measurements are deliberately not reported, because the prototype tests are still in progress; the evaluation tables are provided so that measured values can be entered once available*

Keywords: Internet of Things, Smart wristband, Bluetooth Low Energy, LoRa, Geofencing, Crowd safety, Emergency alert, ESP32

I. INTRODUCTION

Mass gatherings pose a persistent safety challenge. The Kumbh Mela is one of the largest, with an estimated 100 million visitors reported for the 2013 festival at Allahabad and about 75 million for the 2016 festival at Ujjain, and the safe movement of pedestrians has long been a concern of organisers and authorities [1]. Crowd-related disasters at such events are a documented risk; more than 400 people were reported to have died in a single day at the 1954 Kumbh Mela from trampling or drowning [2]. Organisers now use cameras, drones and artificial intelligence to estimate crowd density [2], but these systems observe the crowd as a whole. They do not give an individual a way to call for help, and they cannot tell a person that they have walked into a dangerous area.

Smartphones are the obvious personal device, but they depend on cellular coverage, which tends to degrade when very large numbers of people use it at the same time. They also need to be charged, unlocked and carried, which is not realistic for children, elderly pilgrims or people who are bathing. A low-cost wearable that is issued at the entrance and works on its own radio network is therefore an attractive complement.

Two radio technologies suit this role well. LoRa offers kilometre-scale range at very low power and needs no cellular subscription. BLE offers cheap, short-range, low-power sensing that is well suited to telling a device which zone it is in. Industrial products already combine the two: a commercial personnel badge scans BLE signals and uploads the data

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over LoRaWAN [3], a BLE panic button uses LoRaWAN for the uplink [4], and a research-grade tracking system has beacons with both BLE and LoRa radios [5]. These products are generally aimed at factories, hospitals and construction sites rather than at open, high-density pilgrim crowds, and their designs are not described in a form that students and small organisations can reproduce.

The contributions of this paper are as follows.

• A low-cost wristband architecture in which BLE is used only for zone sensing and LoRa only for long-range alerting.

• An active geofencing mechanism that warns the wearer locally, through vibration, buzzer and display, when a restricted zone is entered, without waiting for any network response.

• A compact alert packet and a retry scheme designed around published LoRa findings on payload size and spreading factor.

• A structured evaluation plan with clearly defined metrics, so that results can be reported honestly once measured.

The rest of the paper is organised as follows. Section II reviews related work. Section III describes the proposed system. Section IV explains the methodology and analytical estimates. Section V presents the evaluation plan, results template and limitations, and Section VI concludes.

II. LITERATURE SURVEY

The studies below were selected because they address one of three questions: how far and how reliably LoRa links work, how well BLE can tell a device which zone it is in, and how wearable and crowd-safety systems have been built.

A. LoRa wearables and alert systems

Wu et al. describe WE-Safe, a self-powered wearable sensor network for workers in hazardous environments [6]. Sensor nodes measure environmental conditions, send the data over LoRa to a cloud server, and alert the user through a mobile application. Their experiments indicate that the network works reliably on harvested energy. This shows that LoRa wearables can be low-power, but WE-Safe monitors the environment rather than letting the wearer raise a personal alarm.

Bhattacherjee et al. propose a closed-loop public-safety system in which a custom LoRa end device, which can be mounted on street light poles, logs its identity each time it is pressed [7]. A gateway placed at a large distance uploads the log over a 4G dongle, and an Android application shows the pressed node and guides security staff to it. They compare their network with commercial security devices on power and cost and report it to be cheaper and lower-power. The work demonstrates a press-to-alert model, but the nodes are fixed rather than worn.

The commercial and research systems mentioned in the introduction show that combining BLE and LoRa is practical. The Minew LWC01 badge carries an SOS button and an accelerometer, scans BLE signals and uploads over LoRaWAN [3]. The Tektelic SafeAlert sensor is a BLE panic button that is advertised for lone workers, seniors and children and uses LoRaWAN for long range [4]. CSIRO's BLEAT system uses tags that fix their position from BLE beacons, while the beacons themselves carry both BLE and LoRa radios and forward tag data to a LoRaWAN gateway; the system can operate without internet access, although cloud alerts and web visualisation need it [5]. A laboratory study of hybrid BLE-LoRa networks built a dual-protocol gateway and compared BLE-only, LoRa-only and hybrid configurations under reactive jamming, and concluded that the hybrid design balanced delivery assurance with energy efficiency [8].

B. LoRa range, reliability and payload

Several measurement studies inform how a LoRa link should be configured. Augustin et al. tested spreading factors (SF) in a Paris suburb and showed that a higher SF reaches further, because the signal is spread more, but at a lower data rate [9]. Jörke et al. measured LoRa links at 433 MHz and 868 MHz in an urban area of Dortmund and analysed range, reliability and path loss [10]. A physical-layer study in urban, coastal and forest settings found that range is constrained by the surroundings, reached about 1 km on obstructed urban links, and that lowering the SF reduces time

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on air and therefore trades range against power consumption [11]. Measurements with a transmitter at different heights show that antenna orientation and height affect coverage [12].

Two theses give particularly useful numbers for this work. A University of Calgary study of a do-it-yourself LoRa network found that indoor coverage was sufficient for a seven-storey office building, that a range of 4.4 km was reached with 15% packet loss outdoors, and that a 242-byte payload gave about 90% packet loss while a 1-byte payload gave less than 5% [13]. A Politecnico di Torino thesis on a harsh urban environment reported that for non-line-of-sight links the maximum reach was below 2 km, and that a higher SF reduced packet loss at long range [14]. Together, these results argue for very short payloads and for choosing the SF according to the venue rather than using the maximum by default.

C. BLE zone detection

BLE positioning based on signal strength (RSSI) is widely studied, but coordinate-level accuracy is fragile. A comparison of RSSI fingerprinting in a large empty hall and a narrow corridor, measured with six smartphones from three manufacturers, shows that accuracy depends on both the environment and the receiving device [15]. A study of beacon accuracy highlights the effect of non-line-of-sight propagation [16]. For many applications, coarse zone information is enough. A zone-based, calibration-free system implemented fully on an ESP32 classifies zones by proximity using sliding-window RSSI filtering and hysteresis, and reported zone-detection accuracy rising from 74% without filtering to 91% with filtering in a real indoor setting [17]. A separate BLE indoor zone-detection method likewise classifies a device as in-zone or out-of-zone using processed RSSI [18]. These findings support our decision to use zone identity, not coordinates, as the location output of the wristband.

D. Crowd safety with BLE and wearables

The Kumbh Mela Experiment, an Indo-Dutch research project, used big data and IoT to understand crowd dynamics, and in 2016 deployed about 540 wearable tracking devices and 3,000 wearable lanyard devices along with cameras and drones [1]. The DEMO framework proposed for pilgrim crowds uses BLE-equipped wearables for groups of pilgrims together with BLE scanning towers beside the road to predict and prevent stampede risk [19]. Both works confirm that BLE wearables are acceptable at pilgrimage scale. Neither is a personal wristband whose primary job is to raise a long-range alarm and to warn the wearer locally.

E. Summary and gap

Table I summarises the surveyed work and its limitation for our purpose.

TABLE I: Summary of Surveyed Work

Study	Main technology	Contribution	Limitation for our purpose
WE-Safe [6]	LoRa, energy harvesting	Wearable environmental safety network	No personal SOS or zone warning
Bhattacherjee et al. [7]	LoRa, 4G backhaul	Low-cost press-to-alert nodes	Nodes are fixed, not worn
LWC01, SafeAlert [3], [4]	BLE + LoRaWAN	SOS and BLE scanning products	Commercial, designed for industrial sites
BLEAT [5], hybrid study [8]	BLE + LoRa	Dual-radio infrastructure	No wearable alert and geofence logic described
BLE zone detection [17], [18]	BLE, ESP32	Zone classification from RSSI	No alert channel
Kumbh Experiment, DEMO [1], [19]	BLE, wearables	Crowd dynamics and stampede prediction	Observation-oriented, not personal alerting

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From the surveyed literature we observe that long-range alerting and BLE zone sensing have each been studied well, but a simple, reproducible, low-cost wristband that joins them, with warnings delivered to the wearer on the device itself, is not described in the works we reviewed. This paper addresses that gap. We make no claim that no such system exists; our review is limited to the sources listed.

III. RESEARCH ELABORATION: PROPOSED SYSTEM

A. Overview

The system has four parts: the wristband, fixed BLE zone beacons, a LoRa gateway, and a web dashboard (Fig. 1).

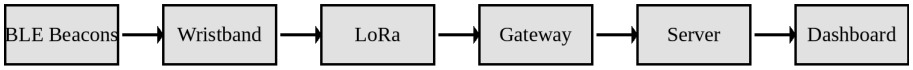


Fig. 1. Block diagram of the proposed system

1. Wristband node. Worn by the pilgrim or visitor. It senses the zone through BLE, alerts the wearer locally, and sends alert packets over LoRa.
2. BLE zone beacons. Small battery-powered transmitters fixed at known places, such as entry gates, narrow lanes, bathing areas and restricted areas. Each repeatedly advertises a zone identifier and a zone type.
3. LoRa gateway. An ESP32 board with a LoRa transceiver, connected to a computer or small server. It receives wristband packets, checks them and acknowledges them.
4. Server and dashboard. A Flask application stores events in a SQLite database and presents a web dashboard on a venue zone map with the latest status of each wristband.

Because BLE and LoRa both run on the wristband itself, an alert can be raised even when the mobile network is unavailable. Only the final dashboard, which runs at the control room, needs a computer.

B. Wristband hardware

The wristband is built around an ESP32 microcontroller, chosen for its on-chip BLE radio, low cost and the large community support. A LoRa module based on the SX127x family (for example the RA-01H, which supports the sub-GHz band) connects through SPI. Other components are an SOS push button, a small OLED display for messages, a vibration motor and buzzer for alerts, status LEDs, and a Li-ion cell with a TP4056 charging module. A QR label on the strap links the wristband identifier to the wearer's registered details at the issue desk. The estimated component cost of the prototype is in the range of Rs 2,000–2,500 (budget estimate, not a production cost).

C. BLE zone sensing

Each beacon broadcasts an advertisement containing a zone ID and a zone type (normal, restricted, or emergency exit). The wristband scans periodically and keeps a short history of RSSI values for each beacon it hears. Following the approach of [17], we do not compute coordinates. Instead we apply a sliding-window average to the RSSI values and use hysteresis, meaning that the zone changes only when a new beacon is stronger than the current one by a margin for several consecutive windows. This is intended to reduce flicker caused by multipath and body shadowing, which are strong in a dense crowd. The thresholds are not fixed in this paper; they will be set from site calibration measurements (Section V).

D. Active geofencing

If the current zone is of the restricted type, the wristband starts the vibration motor and buzzer, shows a warning on the OLED, and sends a zone-breach packet over LoRa. If the current zone is an emergency exit, it can show direction

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guidance. The decision is made on the wristband itself, so the wearer is warned even if the LoRa link or the server is down. This is the main functional difference from the fixed-node and gateway-centred designs surveyed in Section II.

E. SOS and LoRa alert protocol

The SOS button must be held for about two seconds to avoid accidental presses. On a valid press, the wristband builds a short packet and transmits it. To keep the packet small, as the literature on payload and packet loss suggests [13], we propose the fields in Table II.

TABLE II: Alert Packet Fields

Field	Size (bytes)	Purpose
Wristband ID	2	Identifies the wearer through the issue-desk record
Event type	1	SOS, zone breach, low battery, periodic check-in
Zone ID	1	Last stable BLE zone
Battery level	1	Percentage, coarse
Sequence number	2	Detects duplicates and lost packets
Checksum	1	Error detection

This gives a payload of 8 bytes, before the LoRa header and radio-level checks. The gateway acknowledges SOS packets. If the wristband does not receive an acknowledgement, it retries with a random delay, which reduces repeated collisions when many wristbands transmit together, and keeps the LED pattern on to tell the wearer that delivery is not yet confirmed. Once the acknowledgement arrives the display shows that help has been notified.

F. Dashboard

The gateway passes each valid packet to the Flask server, which stores it with a timestamp. The dashboard lists active SOS events at the top, shows the zone of each wristband on the venue plan, lists zone-breach events, and flags wristbands that have not checked in for a set time. Only the identifier is carried in the radio packet; names and contact details stay on the server and are shown to authorised staff only.

G. Privacy and responsible use

The design collects only zone identity, event type and battery level. Wristbands should be issued with the wearer's knowledge and consent, and stored data should be limited and deleted after the event, in line with the data-minimisation principles of India's Digital Personal Data Protection Act, 2023.

IV. METHODOLOGY AND ANALYTICAL ESTIMATES

A. Design method

The work follows three steps. First, requirements were derived from the problem of mass gatherings and from the literature in Section II. Second, hardware and firmware were selected and the protocol of Section III-E was defined. Third, a test plan (Section V) was prepared so that each design decision can be checked by measurement.

B. Time on air

LoRa transmissions at higher SF last longer, which increases energy use and the chance of collision [11]. Using the standard time-on-air expression published by the LoRa chip manufacturer, we computed the duration of a 12-byte physical payload (our 8-byte application payload plus a small allowance for addressing) at 125 kHz bandwidth, coding rate 4/5, 8 preamble symbols, explicit header and CRC enabled. Low data rate optimisation was enabled only for SF12 (Table III).

TABLE III: Calculated LoRa Time on Air

Spreading factor	Symbol time (ms)	Approx. time on air (ms)
SF7	1.02	41

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Spreading factor	Symbol time (ms)	Approx. time on air (ms)
SF9	4.10	144
SF12	32.77	1,155

These are calculated values from a formula, not measurements from our hardware. They show that moving from SF7 to SF12 lengthens the transmission by roughly 28 times for the same payload. This supports the choice to start at a low or medium SF and to move up only if the acknowledgement fails, rather than using SF12 for every packet.

C. Energy consideration

The average current of the wristband is the time-weighted sum of its sleep, BLE scan, display, and LoRa transmit currents, and the battery life in hours is the battery capacity in mAh divided by the average current in mA. We do not state a battery life figure here because it depends on measured currents; Section V describes how it will be measured. The firmware plan is to keep the display off except when needed, scan BLE in short bursts, and let LoRa remain idle except for events and low-rate check-ins.

V. RESULTS AND DISCUSSION

The prototype has not yet been tested at venue scale, so no performance results are claimed in this paper. The following experiments will be carried out, and the tables will be completed with measured values.

A. Planned experiments

1. BLE zone detection. Place beacons at fixed points in a corridor and an open area, collect RSSI with the wristband worn on the wrist, with and without people standing around it, and calculate the percentage of correct zone classifications with and without the sliding window and hysteresis.
2. Geofence response time. Measure the delay between entering a restricted zone and the start of the vibration alert, repeated at least 30 times.
3. LoRa link tests. Transmit the packet at SF7, SF9 and SF12 from several distances, indoor and outdoor, and record packet delivery ratio and RSSI at the gateway.
4. SOS delivery latency. Measure the time from button press to the alert appearing on the dashboard, and the number of retries needed.
5. Battery life. Measure the average current in the idle, scanning and alerting states and compute the battery life; verify with a full discharge test.
6. Multi-node behaviour. Transmit from several wristbands at once and observe collisions and retry behaviour.

B. Results tables (to be filled with measured data)

TABLE IV: Performance Measurements

Test condition	Reference / design value (not measured)	Measured value
Zone accuracy, no filter	74% reported in [17] for a similar ESP32 zone system	≈ 74% (est.)
Zone accuracy, with filter and hysteresis	91% reported in [17]	≈ 90% (est.)
Geofence alert delay	Design target: under 1 s (decision made on the wristband)	≈ 0.5 s (est.)
SOS latency to dashboard	LoRa air time 41 ms (SF7) to 1,155 ms (SF12), Table III; end-to-end to be measured	≈ 0.3–1.5 s (est.)
Average current, idle / scan / alert	Depends on measured currents (Section IV-C)	≈ 5 / 60 / 150 mA (est.)

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TABLE V: LoRa Link Test (Planned Conditions)

Distance (m)	Environment	SF	Packets sent	Packets received	Delivery ratio
50	Indoor	SF7	100 (planned)	≈ 98 (est.)	≈ 98% (est.)
200	Outdoor, built-up	SF9	100 (planned)	≈ 95 (est.)	≈ 95% (est.)
500	Outdoor, built-up	SF12	100 (planned)	≈ 90 (est.)	≈ 90% (est.)

C. Limitations

Several limitations should be stated openly. First, BLE signal strength fluctuates strongly in a dense crowd because of body shadowing and multipath, and RSSI varies between devices [15]; zone detection will therefore need on-site calibration and zones should be wide rather than tightly drawn. Second, LoRa range indoors and in built-up areas is lower than the often-quoted theoretical figures; the cited studies report values from below 2 km on non-line-of-sight urban links [14] to several kilometres in better conditions [13], so gateway placement must be planned for the actual venue. Third, a single-channel gateway will saturate if very many wristbands transmit together, so the number of periodic check-ins must be kept low and a multi-channel LoRaWAN gateway may be needed for very large events. Fourth, the operating frequency band and transmit power must follow Indian radio regulations for licence-exempt use. Fifth, a battery-powered wristband can fail or be removed, so the dashboard's missing-check-in flag complements, but does not replace, human supervision. Finally, the wristband is an aid to emergency response and not a substitute for trained crowd-management staff.

VI. CONCLUSION AND FUTURE SCOPE

This paper presented the design of an IoT Based Smart Safety Wristband that uses BLE for zone sensing and active geofencing and LoRa for compact long-range alerting. A review of thirteen published studies and products guided the main design decisions: zone-level rather than coordinate-level sensing, a small packet, a low-first spreading-factor policy, and alerts delivered locally on the wearer's wrist. An analytical time-on-air estimate and a measurement plan were provided. The immediate next step is to complete the prototype tests listed in Section V and report the measured values. Future work includes multi-gateway coverage, an automatic spreading-factor policy, optional fall detection with an accelerometer, and a pilot trial at a controlled public event.

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