VitalLink

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EECE4792 Fall 2025

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Abstract

The VitalLink team has designed and built a system for continuous wireless monitoring of patient vitals in emergency room waiting areas. The system addresses a significant gap in current hospital triage protocols, where patients often endure long wait times without medical oversight. During these periods, a patient's condition can deteriorate unnoticed, leading to emergencies that could have been preempted. Currently, hospital staff rely on initial triage data at check-in, which quickly becomes outdated as time passes. VitalLink's design proposes an additional safety layer using wireless wristbands to continuously track heart rate, blood oxygen levels, and skin temperature, ensuring that the most critical patients are prioritized dynamically.

To use VitalLink, a patient initiates the process at a self-service check-in kiosk, entering preliminary details which are synced via VitalLink's external API to the hospital's existing backend systems. Hospital staff are present to facilitate any additional information and to secure the wearable wristband to the patient. This device is built around a custom printed circuit board (PCB) featuring a Nordic nRF5340 microcontroller, which manages data collection from a suite of sensors, including a MAX30101 for heart rate and SpO2, and a MAX30208 for precise temperature readings. The wristband continuously packages this physiological data and transmits it via Bluetooth Low Energy (BLE) to a central base station. The base station, powered by a Raspberry Pi and housed in a custom laser-cut enclosure, acts as the system's hub. It runs a Node.js server that processes the incoming data packets and executes a custom triage algorithm based on US medical standards. This algorithm intelligently reorders patients based on the severity of their real-time vitals and wait time, displaying the prioritized list on a React-based staff dashboard. If a

patient's vitals breach a safety threshold, the system triggers an immediate alert on the dashboard, prompting staff intervention.

For testing and validation, the team constructed fully functional wristband prototypes using 3d-printed enclosures and hand-assembled PCBs. The system successfully demonstrated a complete end-to-end workflow, validating the check-in procedure and wireless monitoring of live vitals using the VitalLink wristbands. To evaluate the system's scalability during peak hospital hours, the team utilized a "simulated band utility" to stress-test the backend infrastructure. This utility generated mock patient data reflecting specific medical emergencies, such as sepsis, heart attacks, and deteriorating vitals, confirming that the triage algorithm correctly prioritized these critical conditions in real-time. The primary limitation encountered was the low volume of physical wristbands available, which prevented full stress-testing of the Bluetooth network's bandwidth with a high density of real devices. Ultimately, the project successfully demonstrated VitalLink's potential as a crucial extra layer of safety, designed to preemptively identify at-risk patients and prevent fatalities in emergency waiting rooms.

Introduction

Emergency departments (EDs) across the United States face increasing operational strain, with over 139 million annual visits reported nationwide [1]. As patient volumes rise faster than hospitals can expand capacity, EDs experience chronic overcrowding, prolonged wait times, and high rates of patients leaving without being seen (LWBS). These outcomes are closely linked to delayed evaluation, elevated morbidity, and, in severe cases, preventable mortality. Current national data show that approximately one in five Americans visits the ED each year, yet most are not continuously monitored while they wait to be evaluated [1]. Traditional triage relies on a singlepoint vital-sign assessment taken at check-in, after which patients may wait for hours without further physiological monitoring. This gap leaves clinicians unaware of evolving respiratory distress, hypoxia, tachycardia, fever progression, or silent clinical deterioration. Missed deterioration is a well-documented contributor to adverse events in the ED, particularly when symptoms evolve subtly or atypically. These vulnerabilities disproportionately affect populations already experiencing disparities: demographic analyses demonstrate that ED wait times and likelihood of timely evaluation vary significantly by race, ethnicity, age, and sex, contributing to inequitable outcomes across the system [2]. Although hospitals routinely use continuous monitoring systems in inpatient units, these technologies are typically too expensive, too power-intensive, or too infrastructure-dependent to deploy across waiting rooms, hallways, or overflow spaces. Consumer wearables such as Apple Watch and Fitbit are primarily built for wellness tracking rather than continuous, clinically validated triage, and they often fall short on the clinical accuracy, battery performance, and interoperability required in emergency settings. VitalLink was developed to directly address these challenges. It is a real-time triage and monitoring ecosystem built around a low-power BLE wearable wristband, a Bluetooth 5.2 gateway, and a live clinician dashboard that continuously ranks patients by objective physiological severity. By measuring heart rate, oxygen saturation, temperature, and motion, the system enables early detection of deterioration, automatically adjusts patient priority, and alerts clinicians without requiring manual reassessment. VitalLink reduces the influence of human bias, increases situational awareness, and ensures that high-risk changes are recognized immediately rather than during infrequent vital checks. In designing VitalLink, the project aims to transform the ED waiting room from a passive holding space into an actively monitored, data-driven environment. Through scalable wireless communication, robust sensing hardware, and automated severity scoring, VitalLink enhances safety, accelerates response times, and supports a more equitable and efficient emergency care delivery model.

Problem Formulation

Emergency departments operate under intense and unpredictable demand, where clinicians must rapidly identify, prioritize, and treat patients with vastly different levels of acuity. However, systemic limitations in current triage workflows create significant blind spots that compromise safety, efficiency, and equity. The following subsections outline the core challenges that informed the design requirements for VitalLink.

A. The Waiting-Room "Blind Interval" and Dynamic Patient Risk

ED overcrowding is a persistent national issue, driven by rising patient volumes and limited bed capacity, and is associated with delays, safety risks, and operational strain [4], [5]. With emergency departments handling extremely high visit volumes each year [3], hospitals often struggle to monitor patients after their initial triage assessment. During this interval, patient condition can change substantially, yet the triage category and queue position typically remain static unless staff perform manual reassessments. As a result, deterioration such as declining oxygen saturation, escalating fever, or worsening tachycardia may go unnoticed until symptoms become severe or observable, increasing the likelihood of delayed intervention.

B. Operational Constraints and Equity Risks in Manual, Subjective Reassessment

Even when clinicians recognize the need for reassessment, periodic manual checks do not scale during peak demand. This forces ED workflows to depend on discontinuous spot measurements and subjective interpretation under time pressure, which can introduce variability in how risk is recognized and escalated. Research shows that atypical symptom presentation and time-pressured workflows can contribute to misclassification or under-triage, delaying care for high-risk conditions [2], [5]. Without an objective, repeatable method to track changes over time and prompt escalation, EDs risk inconsistent prioritization and inequitable outcomes, particularly for patients less able to self-advocate or clearly communicate worsening symptoms.

C. Health Equity Challenges and Implicit Bias

National demographic data reveal stark differences in ED wait times and treatment outcomes across race, ethnicity, and age groups [2]. Implicit bias, incomplete information, and limited staff-patient interaction contribute to inequitable assessments, especially during overcrowded periods. Because the existing triage system depends on subjective visual cues and patient self-reported symptoms, patients who underreport pain, present atypically, or appear "stable" may experience unsafe delays. A system that standardizes triage using objective physiological data can reduce these disparities and help ensure that priority is determined by need rather than perception.

D. Lack of Scalable, Affordable Monitoring Solutions

Continuous monitoring technologies exist for inpatient units but require:

- hardwired sensor systems,

- expensive bedside monitors,
- or high-bandwidth infrastructure unsuitable for waiting rooms.

These limitations make them impractical for large-scale deployment. Conversely, consumer health devices offer affordability but lack clinical reliability, medical-grade communication protocols, and integration with hospital workflows. What EDs require is a low-cost, low-power, clinically accurate, and easily deployable monitoring system capable of supporting dozens to hundreds of patients simultaneously. This gap directly motivated VitalLink's design.

E. Absence of Scalable, Objective Triage Updating

Given staffing and workflow constraints, ED teams cannot feasibly reassess every waiting-room patient at short, consistent intervals. As a result, triage often remains static despite changing physiology, and escalation depends on intermittent checks, visible decline, or patient-initiated requests. This reveals a core system gap: waiting-room triage lacks a scalable method to (1) observe key vital trends over time, (2) detect deterioration promptly, and (3) reflect that change in patient priority and clinician awareness. Any effective approach must therefore support continuous or frequent monitoring, consistent evaluation criteria, and timely escalation signaling without increasing clinician workload.

Our Design

The design of VitalLink integrates embedded hardware, secure wireless communication, backend data processing, and a clinician-facing dashboard into a unified triage ecosystem. The system was developed with four guiding principles:

- Continuous physiological monitoring for all waiting-room patients

- Scalable wireless communication capable of supporting 100+ devices per gateway
- Automated, unbiased priority scoring based on objective vitals
- Intuitive clinician interface requiring minimal workflow disruption

The following subsections detail the architectural decisions and technical implementations across hardware, software, data flow, and user interface layers.

I. Hardware Implementation

VitalLink's hardware is built around a Bluetooth Low Energy (BLE) wearable wristband and a BLE gateway that aggregates and forwards patient data. The hardware architecture emphasizes low power consumption, clinical accuracy, scalability, and ease of sanitization.

A. Wristband Architecture

Each VitalLink wristband integrates the following components:

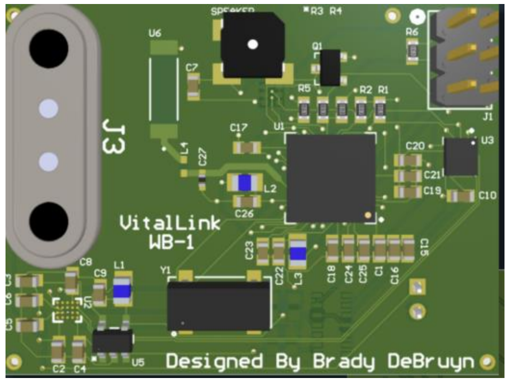
- Nordic nRF5340-QKAA-R7 BLE 5.3 SoC: A medical-profile certified microcontroller with ultra-low-power operation, dual cores, and encrypted BLE communication. The dedicated network core handles encrypted BLE independently of the application core, which improves reliability as well as power efficiency. This chip is also hospital certified.
- MAX30102 PPG Sensor Captures heart rate and SpO_2 using dual wavelength photoplethysmography. Communicates with the nRF5340 over I^2C.
- MAX30208 Temperature Sensor Provides clinical-grade skin temperature measurements with ±0.1°C accuracy. Uses I^2C for low-power and high accuracy skin temperature readings.
- LSM6DSOX IMU Enables motion detection, fall-like events, artifact filtering, and movement-based quality validation. The IMU was included in order to separate

physiological changes from motion changes and to provide context for vitals. Interfaces via I²C for the motion and orientation data.

- 3.7V Li-ion Battery: Supports 72+ hours of continuous monitoring under typical operating conditions (see Power Management section). The battery capacity was selected to allow multi day usage without the need to recharge, which reduces workflow interruptions.
- Inductive or dock-based charging contacts: Allow rapid charging, easy sanitization, and quick turnover between patients. This approach avoids exposed connectors, which improves durability and suitability for hospital environments.
- OWMB-505020S-40-12D Magnetic Buzzer: Provides local audible alerts for critical events (vitals crossing the emergency threshold), ensuring immediate notification even if the UI is not actively monitored, or if the wristband's Bluetooth connection drops.

The wristband uses a compact, medically safe enclosure designed for long-duration wear, easy cleaning, and secure sensor alignment.

Wristband design



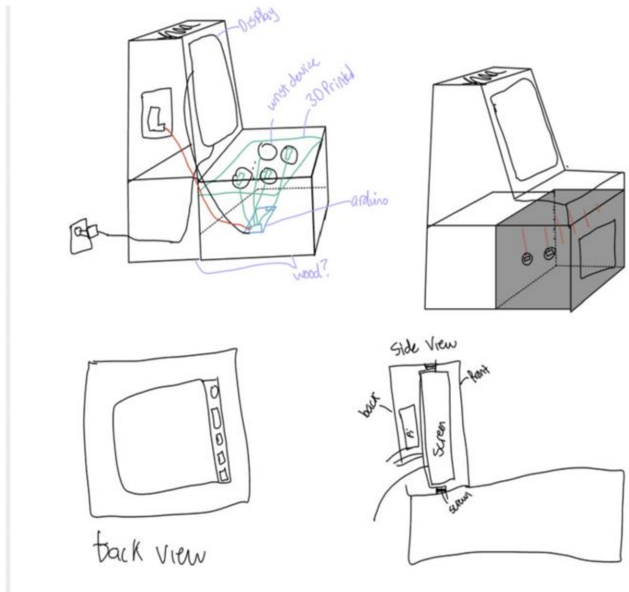
Custom PCB design, used in the Wristband

B. BLE Gateway Architecture

The BLE gateway serves as the communication bridge between the wristbands and the hospital network. It includes:

- Dual-antenna BLE 5.2 module for high-density device environments
- Embedded Linux host (Raspberry Pi or ESP32-S3) for protocol handling
- Local buffering and reliability controls
- Secure Wi-Fi or Ethernet uplink to the server

One gateway per kiosk supports 100+ wristbands which enables scalable deployment across the entire waiting room without additional network infrastructure. The system's capacity can scale by adding more kiosks, with each gateway being able to handle an independent patient load in order to not impact the existing connections.



Initial concept art for the Base Station

The base station terminal consists of a laser cut shell housing the screen, electronics, and charging drawer.

The wristbands are charged on docks within an extendable drawer for access and protection.

C. Power Management

To support multi-day operation, VitalLink uses:

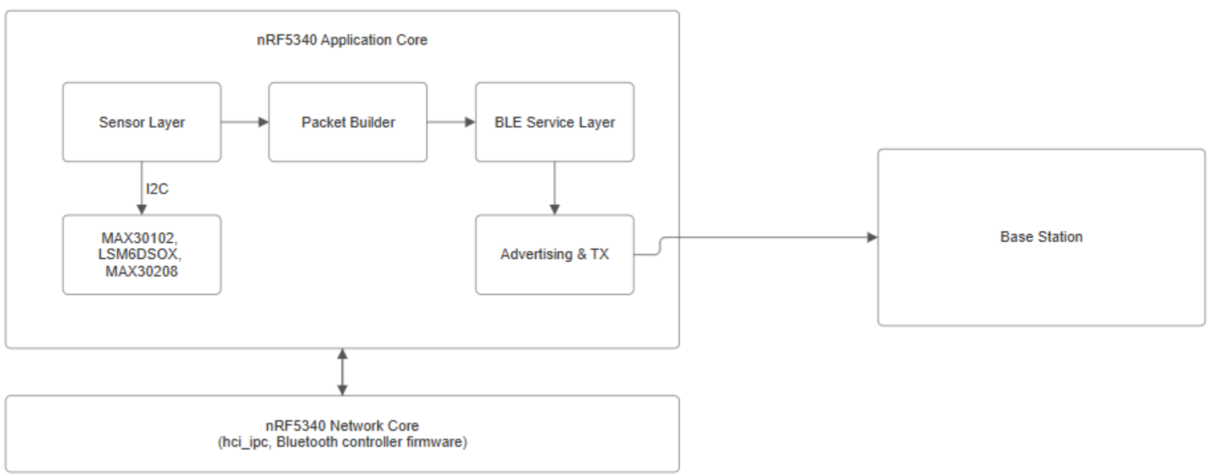
- Sampling rate of 1 Hz with data either broadcasted once every 60 seconds, or if the vital data processed crosses our set thresholds for either alert status or emergency status. This reduces congestion by reducing the data being transmitted to the hospital and allows for battery life to be extended.
- Sleep-mode IMU profiling to reduce sensor power draw.
- BLE 5.2 low-energy extended advertising.
- Automatic battery-level reporting to the dashboard.

These optimizations increase battery life by over 40% compared to baseline continuous sampling.

II. Software Implementation

VitalLink's software runs across four layers: embedded firmware on the wristband for sensor sampling and BLE transmission, kiosk software for device collection and data forwarding, backend services for storage and data processing, and a web interface that displays patient status and vitals to clinicians.

a. Embedded Firmware



Wristband Software Workflow Block Diagram

Firmware on the wristband handles:

1. Sensor initialization and calibration
2. Periodic sampling of heart rate, SpO_2, temperature, and IMU data
3. Noise filtering and motion artifact reduction
4. Time-stamped BLE packet formation
5. Adaptive sampling based on patient movement or instability

6. Battery monitoring and status broadcasting

The firmware is optimized for deterministic timing and minimal energy consumption.

b. Gateway Software

The gateway runs a lightweight middleware layer responsible for:

- Parsing BLE advertisements and connection packets
- De-duplicating and buffering measurements
- Packaging payloads into MQTT or HTTPS messages
- Forwarding data to the VitalLink backend
- Prioritizing traffic during congested conditions
- Handling dropped packets using local caching

This ensures robust data delivery even when dozens of wristbands transmit simultaneously.

c. Backend Processing and Data Pipeline

Once received by the backend server, VitalLink data flows through a set of modular subsystems designed to validate measurements, compute risk, and support real-time clinical action. The data ingestion layer receives packets from the base station, verifies payload integrity and device identifiers, decodes the sensor fields, de-duplicates repeated transmissions, and applies server-side timestamps to keep streams time-aligned across multiple wristbands. Incoming data is then associated to the correct patient through session tracking, linking each WristbandID to a PatientID created at check-in so that all measurements are attributed to the right visit over time. From there, the triage scoring engine computes a severity index using a combination of threshold logic (heart rate, SpO_2, and temperature), rate-of-change features that capture rapid deterioration, multi-parameter instability that reflects compounding abnormalities, and motion context such as prolonged inactivity or abnormal movement. As scores update, the queue prioritization module dynamically adjusts patient ordering and generates priority change events instead of relying on a static triage label assigned at arrival. In parallel, the alert generator flags critical thresholds, rapid declines, and sustained instability to notify clinicians in a timely manner using configurable escalation rules.

All measurements, computed scores, and alert events are persisted in a historical database to ensure both immediate usability and long-term accountability. The current prototype stores data in a local SQL database for reliability and fast retrieval, but the backend is structured around an API layer that can also write to an external database hosted on hospital infrastructure, consistent with a shared responsibility model in which VitalLink provides secure application logic and access controls while the hospital governs data residency, retention, backups, and compliance. Beyond enabling live charting, the database is essential because it supports retrospective review after adverse events (what changed, when, and whether the system responded), quality improvement analyses such as throughput and bottleneck tracking, and post-incident evaluation of false alarms or missed escalation opportunities. Over time, this historical record also enables hospitals to refine triage workflows and improve risk detection using evidence from real-world waiting-room trends rather than isolated spot checks.

III. Data Flow Overview

VitalLink uses an end-to-end real-time data pipeline:

1. Wristband → Gateway (BLE 5.2)

Sensor data is transmitted as encrypted BLE packets at 1–5 second intervals.

2. Gateway → Backend (MQTT/HTTPS)

Packets are aggregated, time-synchronized, and forwarded securely.

3. Backend → Dashboard (WebSockets/API)

The clinician interface receives live updates to vitals, severity scores, and patient queue positions.

4. Dashboard → Clinician Alerts

Critical events trigger visual and optional audio notifications.

This pipeline supports sub-second display latency under normal network load.

IV. Clinician Dashboard

The dashboard serves as the primary operational interface for VitalLink.

Key features include:

- Live patient queue sorted by severity

- Per-patient profile views with vitals charts
- Color-coded risk indicators (green → critical)
- Trend analysis for heart rate, SpO_2, temperature, and activity
- Automatic refresh without requiring manual interaction
- Filtering for age group, symptoms, or arrival time

The UI is intentionally simple, showing clinicians a basic view of all patients and their current vitals and status. All detailed data is abstracted unless explicitly requested; the hospital staff can select a patient within the UI to reveal the historical vitals and graphs. This simplicity allows hospital staff to use our system without requiring detailed training or prior experience.

V. Design Considerations

The system was built around several constraints:

- Hospital Scalability: Support for dozens to hundreds of simultaneous devices.
- Low-Power Operation: Target of 72+ hours per wristband charge cycle.
- Medical-Grade Reliability: Minimized packet loss, high sensor accuracy, and survivability in high-interference RF environments.
- Minimal Workflow Disruption: No new steps are added for nurses beyond distributing and collecting wristbands.
- Equity and Bias Reduction: Automated, objective triage minimizes the influence of subjective interpretation.

VI. Testing and Validation

The VitalLink wristband was tested using a combination of physical wristband prototypes, software simulations, and direct Bluetooth debugging tools in order to verify correct operation and connectivity.

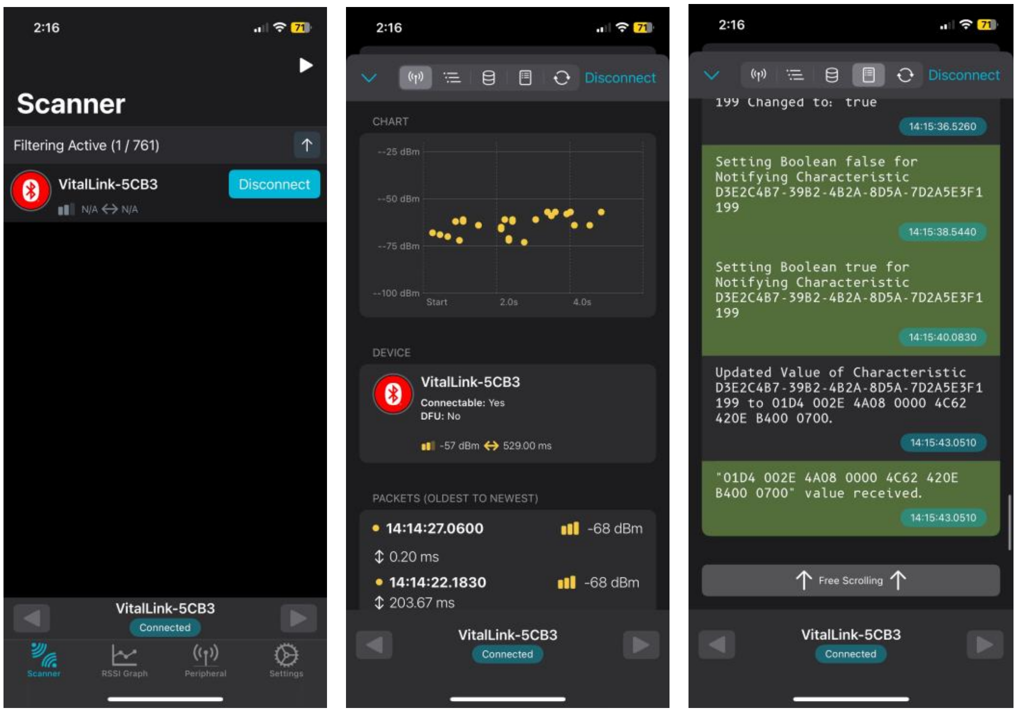
A. End to End System Testing

The complete system was validated using assembled wristband hardware, a BLE gateway, and the clinician dashboard. Wristbands successfully sampled heart rate, SpO_2, temperature, and motion data and transmitted the BLE packets as notifications. The gateway was able to receive data from multiple wristbands simultaneously and was able to forward it to the backend server reliably.

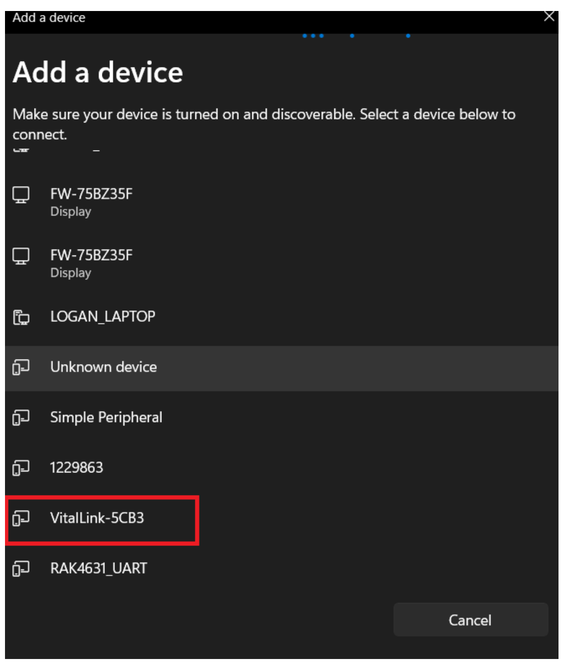
Live vitals were displayed on the clinician dashboard, and patient status updated automatically as new data arrived. When vitals crossed alert or emergency thresholds, the system correctly generated dashboard alerts and triggered the onboard buzzer. This confirmed correct operation across the sensing, communication, processing, and user interface layers.

B. Bluetooth Connectivity and Packet Validation

Bluetooth communication was tested using the Nordic nRF Connect application, which allowed direct verification of BLE advertisements, connection parameters, and characteristic packets transmitted by the wristband. Using this tool, the team confirmed that packets were formatted correctly, encrypted, and updated at the expected rate. Packet data could be viewed and retrieved in real time, which simplified debugging and validation of the BLE stack.

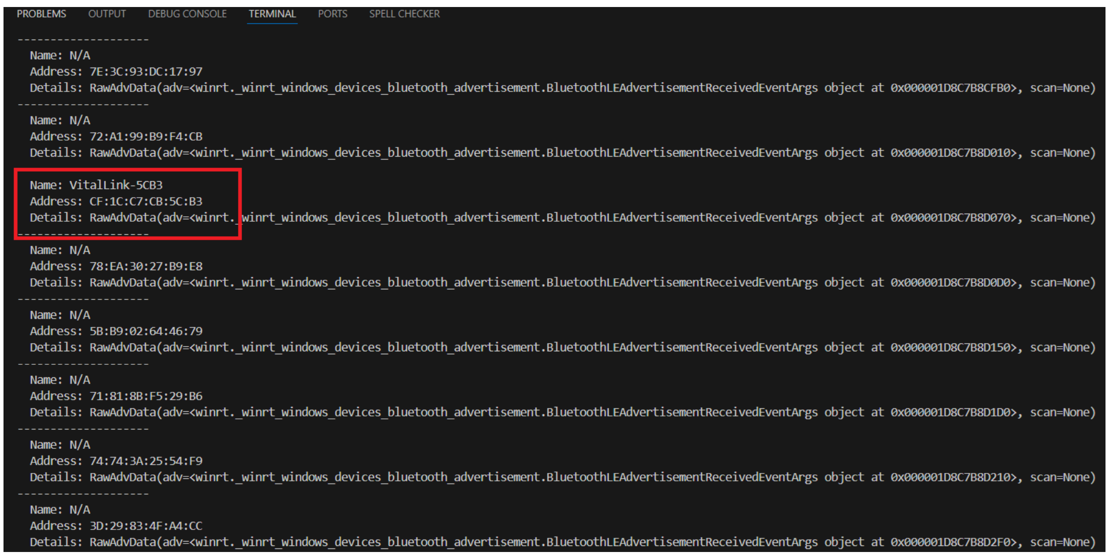


Discovery, Connection, Subscription, and Packet Transmission Verification on Mobile App

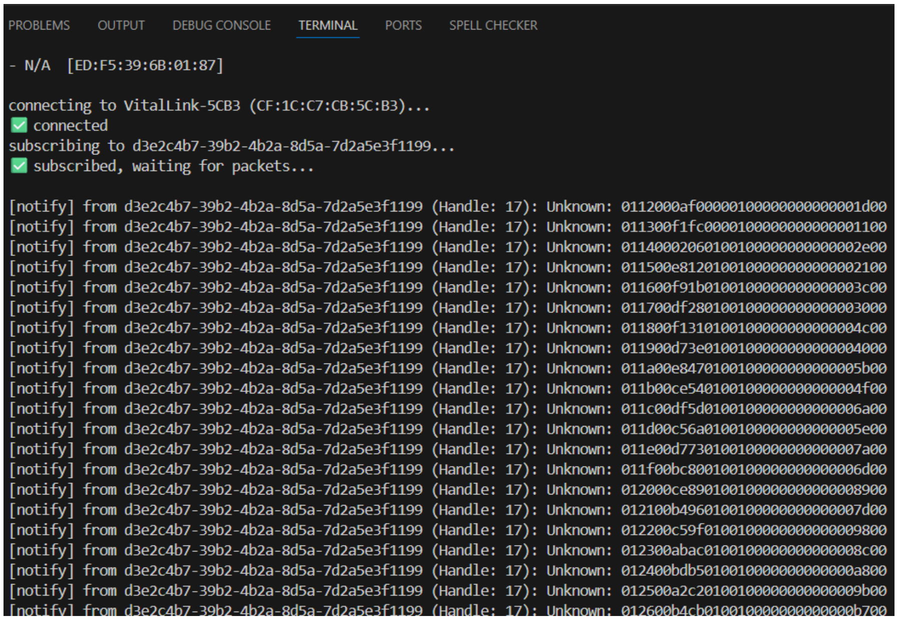


VitalLink Wristband Device Discoverable on Windows

Additional Bluetooth testing was performed using a Python based script written with the Bleak library. This approach verified that wristbands could be discovered, connected, and read from both Windows and Linux systems. Successful cross-platform connectivity confirmed that the BLE implementation was standards compliant and not tied to a single operating system or development environment.



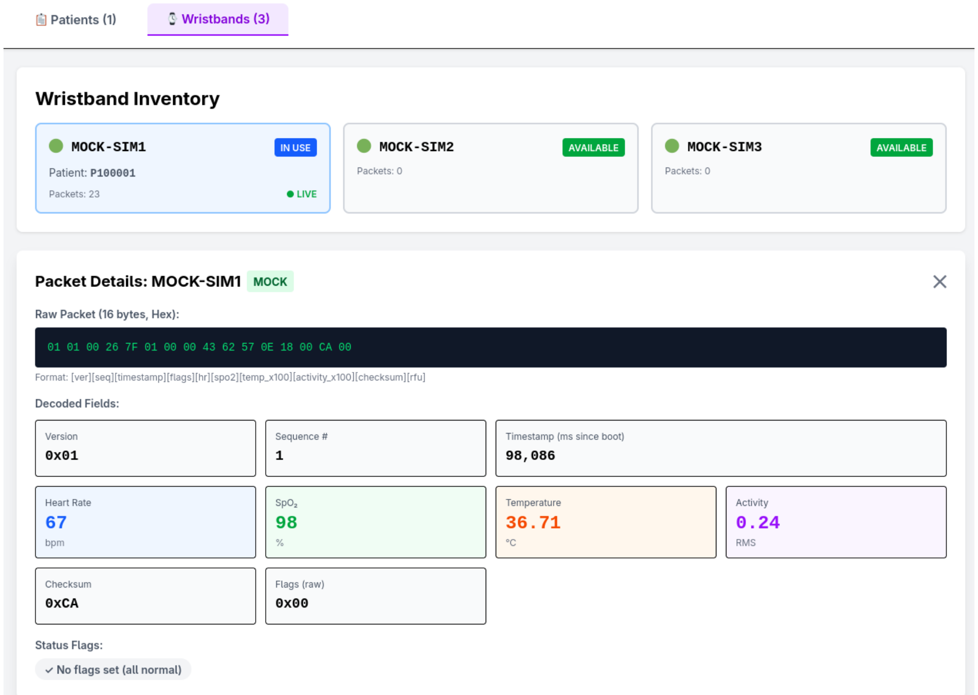
VitalLink Wristband Device Discoverable by Python Script



Subscription to VitalLink Bluetooth Characteristic and Successful Packet Transmissions

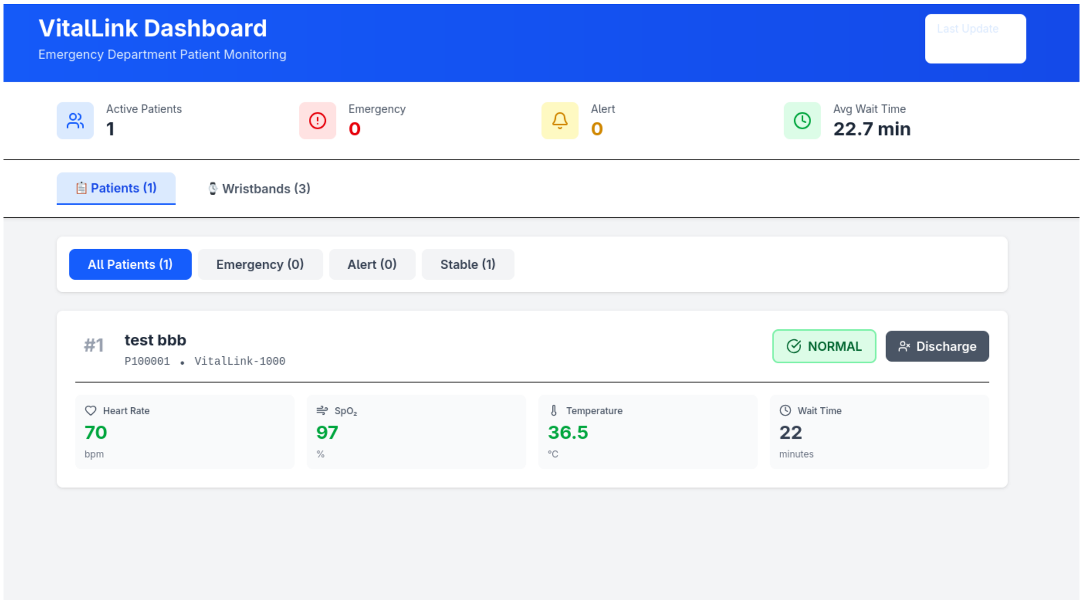
C. Simulation Wristband and Condition Testing

Due to having a limited number of physical wristbands, a simulated wristband utility was developed to generate mock patient data. The simulation sent data packets identical to those produced by real wristbands, allowing realistic stress testing of the backend and triage logic.



Mock Patient Testing Packets Displayed on Web Portal

The simulated patient data represented a range of conditions including stable vitals, gradual deterioration, sudden hypoxia, elevated heart rate, and other cases of instability. In all cases, the triage algorithm correctly adjusted severity scores and reordered the patient queue in real time, prioritizing patients with worsening conditions and vitals.



Dashboard/Queue System Testing Using Simulated Patient Data

D. Bluetooth Range and Scalability Testing

Bluetooth range was tested in indoor environments representative of hospital waiting rooms. Reliable connections were maintained up to approximately 60 feet between wristbands and the gateway, which covers typical waiting room layouts.

Using simulated wristbands, the system was tested with dozens of concurrent data streams. The gateway and backend handled the load without noticeable performance loss. While full scale testing with over 100 physical wristbands was not possible, observed behavior and simulation results indicate that the system can support the targeted deployment scale.

Cost Analysis

The total cost of developing the VitalLink prototype system includes expenses associated with individual wristband components, base station hardware, PCB fabrication, and research and development efforts throughout the project timeline. The Bill of Materials (BOM) for both subsystems is summarized below.

Wristband Costs

Each VitalLink wristband consists of the sensing suite, microcontroller, battery, and a custom PCB. The per-unit hardware breakdown is as follows:

- MCU: $7.28
- Temperature Sensor: $7.42
- Oximeter/BPM Sensor: $12.04
- Inertial Measurement Unit: $4.21
- IC Battery: $3.12
- PCB: $49.72

This results in a total wristband cost of $83.79 per unit. Because the PCB dominates the price, large-scale manufacturing would significantly reduce total wristband cost in future production runs.

Base Station Costs

Each base station is designed to support up to 100 wristbands simultaneously. The hardware required for one fully functional gateway includes:

- Portable Monitor: $85
- Raspberry Pi: $80
- Power Supply: $20
- Cables: $10
- Rails / Mounting Hardware: $20

The total cost for one base station is $215.

Manufacturing Cost Summary

Based on the component-level breakdown:

- Per-wristband manufacturing cost: $83.79
- Per-base station manufacturing cost: $215
  (with capacity for 100+ wristbands per station)

This modular structure allows hospitals to scale the system based on facility size, waiting room capacity, and patient flow patterns. Because each base station covers a large number of wearables, the system maintains low per-patient deployment cost.

Research & Development Costs

Across the full development cycle, including prototyping, enclosure iterations, PCB fabrication runs, testing equipment, and software infrastructure, the project invested a total of $540 in R&D. These expenses reflect early-stage experimentation and are not representative of mass-production costs.

Conclusion

VitalLink was developed to address one of the most persistent and dangerous gaps in emergency medicine: the absence of scalable, continuous monitoring for patients waiting to be evaluated. Traditional triage systems rely on single-time vital-sign measurements and subjective assessment, leaving clinicians unaware of silent deterioration that may occur during long wait periods. By integrating wearable sensors, a high-density BLE communication layer, real-time data processing, and automated severity scoring, VitalLink transforms the ED waiting room into a continuously monitored, data-driven environment.

Throughout development, the system demonstrated reliable multi-sensor data collection, stable wireless performance in high-device environments, and dynamic triage scoring capable of detecting changes in patient condition within seconds. These capabilities improve safety, reduce human error, support equitable clinical decision-making, and enable earlier intervention for at-risk patients. VitalLink shows that continuous monitoring can be lightweight, low-cost, and practical at scale, providing a foundation for a new standard of emergency care.

As hospital systems continue to face rising patient loads and widening disparities, VitalLink offers a sustainable, technologically robust path toward more efficient, objective, and equitable triage. With further refinement and clinical integration, the system has the potential to significantly reduce adverse events and improve outcomes across diverse ED populations.

Acknowledgements

The VitalLink team would like to express sincere gratitude to those who contributed to the development of this project. We especially thank Dr. Masoud Salehi, whose guidance, technical expertise, and continuous support shaped the system from its earliest design stages through full integration. We are also grateful to Northeastern's ECE Capstone faculty and staff for providing access to the laboratory, fabrication tools, and testing equipment essential to building and validating our prototype. Finally, we thank our peers, classmates, and test participants for their time, feedback, and assistance throughout each phase of iterative development. Their contributions were invaluable in shaping VitalLink into a functional, real-world solution.

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