

ECEN 403 – Senior Design

Benchmarking Report

FireGuard: Smart Fire Alarm with Occupant Detection

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1. Introduction

1.1 Problem Statement

A structural fire poses an immediate concern of life and safety to people around the world [15]. In 2024 alone, fires in the United States resulted in civilian deaths of 3,920 people and injuries to 11,780, according to the National Fire Protection Association (NFPA) [15]. When fire crews arrive at an emergency scene, the incident commander has to work out whether anyone is still inside the building and exactly where they are [2][4]. A conventional fire alarm works in one direction only: it warns that there is a fire [1][3][11]. It does not track whether people are inside or where they are in real time [3]. As a result, every room has to be treated as possibly occupied, and search-and-rescue teams end up checking rooms one by one in low-visibility, high-heat conditions [2][6]. This blind spot delays victim extraction, adds to civilian deaths and keeps firefighters exposed to toxic smoke, flashovers and structural collapse for longer than necessary [2][15].

1.2 Proposed Engineering Design Solution

To close this gap, Team 3 is developing FireGuard, a smart Fire Alarm System (FAS) that pairs millimeter-wave (mmWave) radar sensing with a dynamic user interface (UI) for emergency responders, building on earlier work in smart fire detection and occupancy sensing [3-6][8][10][11][16]. The system uses off-the-shelf smoke-detection hardware (Ei Electronics Ei3016 [19]), an isolating relay interface (Ei128RBU relay base [20]), Texas Instruments overhead mmWave radar sensors (IWR6843ISK-ODS [5-7][16]), mounted on the TI MMWAVEICBOOST carrier board [17] and an Android application running on a tablet (Samsung Galaxy Tab A11 [18]).

The mmWave radar sensors are intended to remain powered OFF in standby, so nothing is emitted during normal operation while no alarm is active [5][16]. When a fire is detected, the smoke alarm energizes the relay, which switches the mmWave sensors from OFF to ON [19][20]. The mmWave radar sensors are designed to use 3D point-cloud processing to detect moving and stationary people, even in smoke or darkness. The detection performance will be evaluated during prototype testing [5–7]. The occupancy data (Room ID, Floor, Occupancy status) is sent wirelessly to an Android dashboard, which puts the fire-origin room and any occupied rooms at the top so first responders know where to go as soon as they arrive [3][8] [10][12][13][18].

1.3 Relevant Standards and Design Constraints

The FireGuard design process follows strict engineering requirements and restrictions:

- **Fire Safety Standard:** Hardwired alarm interconnection and fail-safe power supply requirements, as set out in NFPA 72 (National Fire Alarm and Signaling Code) [13].

- **Wireless Communication Standard:** IEEE 802.11 (Wi-Fi) protocols for secure local delivery of data packets [8][10].
- **Embedded Sensing Standard:** Texas Instruments mmWave radar processing tools and 3D point-cloud capabilities will be used to support occupant detection [16][17].
- **Operational Constraint:** Radar emissions must be avoided during normal standby to save power and protect privacy [5][16].
- **Environmental Constraint:** The system is designed to support occupant detection in smoke and darkness. Its performance under simulated smoke and other environmental conditions will be evaluated during prototype testing [5][6].
- **Latency Constraint:** The full data path, from the fire trigger to the update on the dashboard, must take less than 2 seconds. This target will be evaluated during prototype testing

2. Existing Solutions

2.1 Commercial Solution 1: Traditional Hardwired Fire Alarm Systems

The first commercial solution is the traditional hardwired fire alarm system. Hardwired photoelectric or ionization smoke alarms, such as the Ei Electronics Ei3016, are the standard fire-alarm technology in most residential and commercial buildings [1][11][19]. Once smoke particles enter the sensing chamber, an 85 dB alarm sounds and the interconnect wiring sets off the other alarms in the dwelling [19].

- **Advantages:** Low cost, reliable fire detection and simple hardwired installation [1][19].
- **Disadvantages:** Traditional fire alarm systems do not ordinarily provide information about occupant presence or room-level location to emergency responders [1][19].
- **Constraints & Standards:** Runs on 230 V AC mains power with a 10-year sealed lithium backup battery [19].

2.2 Commercial Solution 2: Smart IoT Wireless Fire Alarm Systems

In commercial smart fire alarm systems, IoT sensor nodes using ZigBee or Wi-Fi send push notifications to a smartphone or building management system when smoke is detected [3] [8] 10][14]. These systems also allow remote monitoring and keep a status log [8].

- **Advantages:** Instant remote alerts to smartphones and quick checking of false alarms [3][8].
- **Disadvantages:** Only reports fire events; does not detect people, their location or how many are in the affected area [3][8].
- **Constraints & Standards:** Needs a constant home Wi-Fi connection and access to cloud servers [8][10].

2.3 Advanced/Academic Solution 3: Optical Camera AI Surveillance Systems

In high-security commercial systems and in academic research, ceiling-mounted RGB or thermal cameras run computer vision models such as YOLOv8 to detect people and flames indoors [2][9].

- **Advantages:** High accuracy when the camera has a clear field of view [2].
- **Disadvantages:** Optical cameras fail in heavy smoke or darkness, and placing cameras in private bedrooms raises serious privacy concerns [2][5].
- **Constraints & Standards:** Needs high-bandwidth video streaming and expensive edge GPU hardware [2][9].

2.4 Comparative Summary of Existing Technical Gaps

Fire alarms are mainly intended for detecting fires, whereas camera and radar systems use different techniques to monitor occupants. The proposed FireGuard system integrates fire alarm activation, camera-free mmWave radar occupant detection and a responder-focused interface. Its ability to provide reliable occupancy information under emergency conditions will be evaluated through prototype testing [1–7].mmWave radar occupant detection and a responder-focused interface. Its ability to provide reliable occupancy information under emergency conditions will be evaluated through prototype testing [1–7].

3. Benchmarking Criteria

For a thorough comparative benchmarking study, seven different evaluation metrics were set, which directly correspond to technical, societal, environmental and economic aspects:

3.1 Functional & Performance Metrics

- **1. Occupant Detection Capability:** The ability to detect that a person is inside the building during an emergency [6][7].
- **2. Spatial Localization Accuracy:** How accurately the system identifies the room and floor of trapped occupants [6][7].
- **3. Smoke & Environmental Immunity:** Reliable performance in smoke, dust, steam or zero ambient light [2][5].

3.2 Public Health, Safety, and Welfare Impact

- **4. Public Safety & Rescue Enhancement:** How much the system cuts search-and-rescue time and lowers the risk of death and injury to civilians and firefighters [2][15].
- **5. Privacy Preservation:** Protection of occupants' privacy during everyday, non-emergency operation [5][16].

3.3 Global, Cultural, Social, Environmental, and Economic Factors

- **6. Social & Regulatory Alignment:** Alignment with the Human and Social pillars of Qatar National Vision 2030 and with international life safety codes.
- **7. Economic Feasibility & Cost:** Total bill of materials (BOM) cost and how practical it is for homes and businesses to adopt [10][19].

4. Benchmarking Table

The table below shows the proposed FireGuard solution compared to the "market" solutions that meets the benchmarking criteria listed above:

Benchmarking Criteria	**Traditional Fire Alarm [1, 19]**	**Smart IoT Wireless Alarm [3, 8]**	**Optical Camera AI [2, 9]**	**FireGuard Solution [5-7, 16]**
Occupant Detection Capability	None (Smoke/Heat only)	None (Smoke/Heat only)	High in clear conditions; fails in smoke	Designed to detect moving and stationary people using 3D mmWave radar processing
Spatial Localization Accuracy	Building-wide alarm tone only	Zone notification on app	High precision in clear line of sight	Room-Level and floor-level occupancy identification
Smoke & Environmental Immunity	N/A (Detects smoke, no sensing)	N/A (Detects smoke, no sensing)	Low (Fails completely in dense smoke/dark)	Designed to operate in smoke and darkness
Public Safety & Rescue Impact	Low (Responders search blindly)	Moderate (Confirms fire event location)	Moderate (Fails during dense active fires)	Potential to improve rescue prioritization
Privacy Preservation	Maximum (No sensors/cameras)	Maximum (No visual sensors)	Low (Video recording raises privacy concern)	Camera-free occupant detection
Social & Regulatory Alignment	Meets basic building codes	Meets basic IoT standards	Faces social/cultural privacy pushback	Aligned with Qatar Vision 2030 & NFPA 72
Economic Feasibility & Cost	Very Low Cost (~270 QAR)	Low-Moderate Cost (~300 QAR)	High Cost (>2,500 QAR + GPU hardware)	Feasible Capstone Cost (~3,541 QAR total)

5. Benchmarking Study Analysis and Summary

5.1 Key Findings & Comparative Advantages

Of the solutions discussed in this report, FireGuard is intended to provide first responders with room-by-room occupancy information. If the prototype is successfully validated, this capability could assist responders in prioritizing their searches in an emergency.Of the solutions discussed in this report, FireGuard is intended to provide first responders with room-by-room occupancy information. If the prototype is successfully validated, this capability could assist responders in prioritizing their searches in an emergency.

The proposed mmWave radar sensing approach aims to support occupant detection in smoke and darkness without capturing conventional camera images [2][5][6]. During prototype testing, detection performance under these conditions, especially for stationary occupants, will be evaluated.

5.2 Design Modifications & Architectural Iterations

With a review of the benchmarking results and initial engineering assessments, the initial FireGuard design was modified into two important changes:

- **1. Relayed Standby Power Control:** A physical relay trigger circuit was added to protect privacy outside emergencies and to keep energy use low [20]. The mmWave radar nodes are designed to remain powered OFF in standby and to turn ON only when the fire alarm is activated [16][19][20].
- **2. UI Dynamic Priority Sorting:** The software was changed to sort rooms by priority so responders are not overloaded with information. The room where the fire started is shown at the top, and occupied neighbouring rooms are highlighted in red [12][13].

5.3 Summary of Future Work & Validation Steps

During ECEN 403, the team will complete the software data pipeline and Android UI dashboard [12][13]. The physical assembly, relay coupling, and experimental testing of the radar range under simulated smoke and obstacle conditions, all of which will provide a fully working prototype, will be finished in ECEN 404--Physical Hardware Assembly.

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