

Intelligent Deployment for Post-earthquake Response: Ray Tracing-assisted Connectivity for Indoor Rubble-trapped Victims

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Abstract—In post-disaster environments, telecommunication infrastructure is often disrupted due to damage in power and communication lines, resulting in reduced wireless connectivity. This study investigates an External Rescue Publisher (ERP) system to mitigate communication disconnectivity in a simulated post-earthquake indoor environment. A ray-tracing-based simulation using a computer-aided design model was conducted in a typical office setting comprising 30 room scenarios (15 corner, 15 non-corner) across three Philippine Institute of Volcanology and Seismology (PHIVOLCS) Earthquake Intensity Levels (6, 7, and 8) and three subscriber-to-publisher cardinalities (1:1, 1:3, 1:5), yielding 90 simulation runs. Under the baseline in-room ceiling publisher, evaluated across 150 unique subscriber positions at 1:5 cardinality, only 114 nodes (76.0%) satisfied the -91 dBm receiver sensitivity threshold. In contrast, 36 nodes (24.0%) fell below it, with failed nodes exhibiting a median received power of -100.6 dBm against an all-node mean of -80.8 dBm. Failure rates increased with debris severity, from 18% at Intensity Level 6 to 34% at Level 8, and were marginally higher in corner rooms (25%) than in non-corner rooms (23%). Repositioning the ERP outside the room restored connectivity in 57% of affected rooms at nominal transmit power alone, with the remainder requiring incremental power increases of 10–30 dBm. Overall, ERP intervention restored all 36 previously disconnected nodes to at least -91 dBm, a 100% recovery rate, with a median power gain of 21.4 dBm. Power Delay Profile and Power Angular Profile analysis further showed that below-threshold subscribers consistently exhibited smaller delay and angular spreads, indicating fewer resolvable multipath components.

Keywords—channel models, earthquake, indoor communication, indoor environment, propagation losses, quality of service, ray tracing, solid modeling, wireless communications

I. INTRODUCTION

A. Background of the Study

These days, a lot of electronic devices use Bluetooth, Wi-Fi, or both to transfer data between nodes. According to Estella and Löffelholz [1], the expected number of smartphone users in 2021 in the Philippines was 90 million, out of a total population of about 110 million in 2020 [2]. Wireless communication technologies enable hundreds of devices to communicate with one another. The integration of mobile devices into Wi-Fi or Bluetooth networks enables an Internet-free, multiplatform communication system that could play an essential role in emergency communications following a disaster.

Past events have proven that earthquakes can affect communication and power lines, thereby limiting the ability to contact emergency services [3]. In response to this challenge, the emergence of longer-lasting phone batteries allows the network formed by smartphones and publisher nodes to remain functional long enough after a power outage for rescuers to locate survivors trapped under rubble. However, this debris, called Interacting Objects (IO) in the study, can interfere with device-to-device connections. Thus, poor interaction between subscriber and publisher nodes could hinder effective communication between rescuers and trapped subscribers [4].

The study is limited to a single-room indoor environment that employs a one-to-many communication architecture, where a single publisher node, referred to as the External Rescue Publisher (ERP), communicates with multiple subscriber nodes. Ray tracing-based simulations using Altair FEKO and MATLAB are utilized to determine the optimal placement of the ERP for subscriber rescue under post-earthquake scenarios. The simulated room environments are modeled based on debris intensity corresponding to the Philippine Institute of Volcanology and Seismology (PHIVOLCS) Intensity Levels, with randomized object layouts and subscriber positions beneath fallen debris to better represent realistic earthquake conditions. While the study is confined to a single-room setting, this limitation, however, provides a controlled evaluation of the effects of debris density, signal attenuation, and ERP placement on wireless communication performance without the added complexity of multiple rooms, floors, or building layouts. Consequently, the study establishes a baseline for assessing the proposed rescue communication system in a Philippine post-earthquake context while providing a foundation for future research involving larger indoor environments, multi-room structures, or complete building scenarios.

Despite the growing body of research on mobile ad hoc networks and infrastructure-less communication systems for disaster response, existing studies have primarily focused on network architectures, routing protocols, and message applications rather than the physical conditions under which these wireless networks must operate. There remains limited investigation into how common post-earthquake debris materials, such as concrete, wood, and glass, affect smartphone-based device-to-device communications. Previous works also tend to evaluate these wireless protocols

independently, leaving a gap in the comparative understanding of their performance under debris-obstructed environments. Furthermore, while publisher-subscriber communication models have gained popularity for decentralized information exchange, their effectiveness in post-disaster scenarios with signal-attenuating obstacles has not been extensively studied. Existing literature has barely examined the combined influence of multiple interacting objects on critical wireless performance metrics. Addressing these gaps, the present study investigates the effects of common earthquake debris materials on publisher-subscriber communications, with the objective of identifying approaches that can improve the reliability and resilience of smartphone-assisted emergency communication networks during post-disaster scenarios.

This study aims to improve wireless network connectivity by strengthening the links between subscriber nodes and their primary publisher nodes, thereby enabling device-to-device communication without reliance on the Internet or cellular infrastructure. The proposal addresses device disconnection following an earthquake, which arises from structural damage, disrupted wireless protocol gateways, and the interaction of debris with transmitted and received wireless signals. Ultimately, the authors envision that the proposed solutions could be implemented to improve post-disaster connectivity in the Philippines, contributing to more effective emergency communication services.

B. Prior Studies

A study by Isobe [5] discussed the motion behavior of furniture during earthquakes through simulation and experimentation. Even if the building was completely undamaged, a carelessly secured table in an earthquake of high magnitude could endanger human life. The tests and numerical analysis were conducted using a set of furniture. There were five items, ranging in weight from a large cabinet weighing around 44 kg to a light office chair with casters weighing about 6 kg. Each item's dimensions, center of gravity locations, and contact characteristics were considered. Various contact phenomena of the furniture were simulated in the simulation, considering the frictional contact between objects was evaluated using a sophisticated penalty method. In the experimentation, six infrared cameras were placed around the shake table as part of a motion capture system to measure each object's motions. Isobe obtained four different furniture states at the end of varying input waves, as seen in Fig. 1.

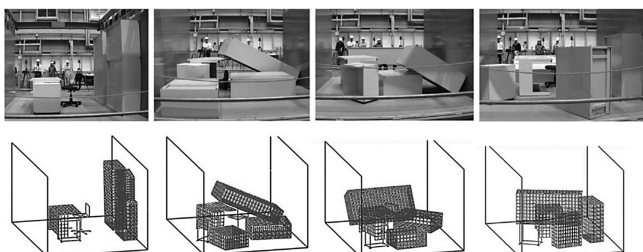


Fig. 1. Condition of the furniture after various input waves.

The same author, Isobe [6], also provided results for steel-framed buildings subjected to collapse. In the study, the relationship between the structural columns and the vertical capacity of the building was measured on a scale of

progressive collapse. Using the ASI-Gauss Code to measure the scale of the destruction, the experiment applied the sum of the potential energy values of the building components. The study then determined that a higher risk of structural failure depends on the high number of the critical element index, a measure of the relationship, as mentioned earlier.

Isobe also analyzed an actual collapse of a building, which was the Canterbury Television (CTV) building that collapsed during the aftershock of an earthquake in Christchurch, New Zealand, with a magnitude of 6.3 [7]. One of the columns at the 4th level of the building lost its capacity, causing an eastward tilt in the top stories, and the entire building vibrated in a twisting mode. Due to their inability to support the newly distributed floor loads, the other columns slowly collapsed. The study used a deteriorating trilinear model for the constitutive equation to analyze the collapse. According to the study, the twist mode vibration around the north wall complex before the failure was mainly caused by a lack of southerly beams and an uneven distribution of anti-seismic walls. The columns may have deteriorated further as a result.

The debris and structural damage resulting from earthquakes have also been shown to affect wireless signal propagation, as explored in several studies. In a study by Menon *et al.* [8], various communication technologies for an aerial IoT system design to localize victims under collapsed structures were evaluated. These technologies included Wi-Fi, LoRa, ZigBee, and Bluetooth. The propagation effects for these communications technologies were analyzed as they pass through different materials such as wood, glass, and concrete in a simulated collapsed infrastructure environment. The results of this study showed that each communication technology responded differently depending on the propagation medium, with Wi-Fi performing best under glass and worse under wood. In contrast, Bluetooth showed the weakest overall detection capability. It was concluded that a combined deployment of multiple communication modules would be necessary for effective victim localization.

In a related effort, Jiang [9] investigated the Wi-Fi signal propagation model in a post-earthquake environment to locate buried victims through wireless module positioning. The propagation characteristics of 2.3–2.5 GHz signals were measured using a frequency domain sweep method and were analyzed in MATLAB to obtain attenuation data, which included free-space path loss and debris material penetration loss. The power delay profile produced was then used to describe the large-scale parameters of the channel. In addition, the Root-Mean-Square (RMS) delay spread was statistically fitted against multiple distributions. From these results, a wireless channel model for the post-earthquake environment was derived based on the Motley-Keenan (MK) model, which calculates path loss by considering the attenuation contributed by each layer of debris material the signal passes through. This wireless channel model was shown to produce lower positioning error compared to a standard logarithmic distance model.

Macaia *et al.* [10] also presented a complete framework for indoor wireless propagation modeling through ray-tracing in Wireless Insite. In the framework, a CAD tool was used to construct a three-dimensional layout of an indoor office floor with walls, doors, windows, and furniture of varying materials such as wood and metal. After drafting the indoor

environments, transmitter and receiver nodes were placed, and the simulation was run to obtain channel model parameters, including the power delay profile in MATLAB. Similar to previously mentioned studies, Macaia *et al.*'s [10] work demonstrated the effect of furniture material on received signal strength, noting that metallic surfaces produced stronger reflected paths compared to wooden furniture. Their results showed that the initial transmitter node placement was not sufficient to reach all receiver nodes on the floor.

In the context of restoring communication after disasters, Gao and Wang [11] proposed a distributed rapid-deployment method that uses Unmanned Aerial Vehicles (UAVs) as aerial base stations to restore communication networks in disaster-stricken areas. Their approach splices the three-dimensional deployment problem into vertical and horizontal components. It optimizes node placement to cover all target points while maintaining connectivity and maximizing coverage. This work closely parallels the current study, as both reposition a transmitting node to re-establish connectivity for users left without service after a disaster.

Similarly, McRae *et al.* [12] investigated the use of a repeater-equipped aerial drone to restore and maintain radio communication during search-and-rescue operations. After a confirmed loss of contact, the drone was flown above the incident command post to re-establish links between rescuers and command, demonstrating that a mobile relay can recover communication when line-of-sight is obstructed. This approach provides an outdoor analogy to the indoor External Rescue Publisher.

Martin *et al.* [13] developed a MATLAB-based Device-to-Device (D2D) discovery simulator for 3GPP and Public Safety Networks (PSNs). The tool models different path-loss scenarios to study how mobile devices discover one another when base stations are non-functional, thereby enabling communication between victims trapped under wreckage and rescue teams without network infrastructure.

In a related effort, Yin *et al.* [14] proposed a throughput-aware D2D multicasting strategy for 5G public safety networks, allowing nearby users to communicate directly without a base station. Using a Hungarian-algorithm-based channel allocation scheme, their approach extended network coverage and improved resource utilization for emergency communications, reinforcing the feasibility of the infrastructure-less device-to-device links.

Tai and Yu [15] presented a smartphone-based system that transforms Bluetooth beacons into low-power locating tools for trapped victims. Exploiting the long battery life of smartphones, the signals continue transmitting so that rescuers can localize victims covered by fallen debris, such as wood or tiles, within approximately two meters. The work illustrates how surviving subscriber devices can remain discoverable under rubble.

Alvarez-Merino *et al.* [16] proposed a victim detection and localization method that fuses Wi-Fi Fine Time Measurement (FTM) and Ultra-Wideband (UWB) technologies mounted on drones to locate individuals buried under rubble and to complement partially damaged infrastructure. Their findings on radio penetration and localization accuracy under debris support the relevance of characterizing signal behavior around interacting objects.

Focusing on propagation modeling, Tarapiah *et al.* [17] developed ray-tracing-based site-specific propagation models at 2.4 and 5 GHz using a three-dimensional shoot-and-bounce ray method in Wireless InSite, validating predicted received signal strength against measurements in an indoor environment. Their methodology mirrors the ray-tracing approach adopted in the study for characterizing indoor post-earthquake propagation.

Complementing the propagation studies, Liu *et al.* [18] experimentally measured and modeled the penetration loss of common building materials, including wood, glass, foam, and concrete, across the FR1 and FR3 bands using a vector network analyzer. Their analysis of the frequency and thickness dependence of penetration loss provides material attenuation parameters relevant to modeling the interacting objects considered in simulation designs.

Chang *et al.* [19] examined reliable publish/subscribe communication for constrained Internet-of-Things devices by proposing a gateway-assisted retransmission mechanism for Message Queuing Telemetry Transport for Sensor Networks (MQTT-SN). Their work addresses message-delivery reliability under lossy conditions, which underpins the publisher-subscriber communication paradigm employed in the present study.

Finally, Zhang *et al.* [20] designed a real-time IoT-based public safety alert and emergency response system that relies on the Message Queuing Telemetry Transport (MQTT) publish-subscribe protocol for low-latency communication among heterogeneous sensors and responders. Their architecture demonstrates the applicability of the publisher-subscriber model to emergency scenarios.

C. Objectives

1) General Objective (GO)

To improve connectivity success among publisher-subscriber nodes in simulated indoor rubble-trapped post-earthquake scenarios, targeting a recovery rate of at least 50% of previously disconnected scenarios.

2) Specific Objectives (SOs)

To achieve the GO, the following SOs are the targets of this work.

- SO1: (i) To model a typical office indoor setting at low, medium, and high subscriber-to-publisher cardinalities using a computer-aided design tool, and (ii) to arrange the wireless network nodes within it;
- SO2: To simulate wave scatterers in post-earthquake snapshots by Intensity Level 6, Intensity Level 7, and Intensity Level 8 descriptions of PHIVOLCS;
- SO3: To position publisher nodes to reach at least -91 dBm.

D. Assumptions, Scope, and Delimitations

1) Assumptions

- (1) Given a wireless communications network, full connectivity among publisher and subscriber nodes ensures seamless indoor communication, even if cellular or Internet is absent.
- (2) It is assumed that there is no cellular or Internet signal.
- (3) It is assumed that the number of publisher and subscriber nodes to be tested are the nodes that survived the earthquake.

- (4) The placement of wireless communications network nodes is accessible to the users.
- (5) At least one publisher can provide access to the site.
- (6) Subscriber height is what would be typical under rubble.
- (7) It is assumed that the trapped individual retains a functional and usable phone.

2) Scope

- (1) The simulation of indoor rubble-trapped post-earthquake scenarios and the test of disconnectivity reduction through node positioning based on wireless communications network coverage measurements were simulated.
- (1) The simulation includes unified wireless communications publishing nodes with several wireless communications subscriber nodes in an office room with multiple interacting objects.
- (2) The wireless communications network nodes simulated would be in a typical indoor setting.
- (3) The study measures wireless communications network coverage through disconnected and connected scenarios.
- (4) The office room will be limited to one level under the penthouse floor of a high-rise building.

3) Delimitations

- (1) The simulation will only consider a single-room indoor scenario and will not include multi-room scenarios.
- (2) The study is wireless standard agnostic.
- (3) There will be no hardware implementation; the study will be done through electromagnetic ray tracing-based simulation.
- (4) Scenarios due to pancake-type progressive collapse are excluded.

II. METHODOLOGY

A. Tools Overview

The post-earthquake simulated scenarios and tools used in the project were accessible through a personal computer. The tools utilized were Altair WinProp ProMan, Altair WinProp WallMan, and MATLAB.

The Altair WinProp ProMan application was utilized with a student version license. The ProMan application predicts path loss between the transmitter and receiver. It helps network planning through different wireless standards and the implementation of multiple receivers (mobile stations) and transmitters (base stations). Models for propagation in rural, urban, and indoor settings are accessible, along with the distinct CNP mode tailored for hybrid situations. Both terrestrial and satellite transmitters can be considered [21].

Like ProMan, WallMan was utilized with a student version license. This software primarily aims to create indoor scenarios affected by a specific PHIVOLCS earthquake level. WallMan has a built-in materials catalog with typical materials that affect frequencies and path losses in radio propagation.

MATLAB is an extensively used high-level programming language and computing environment for technical computing, data analysis, and visualization [22]. Its robust graphics capabilities allow users to analyze and visualize data using multiple methods. The software supports several data types, such as numeric, character, and structure arrays. Its user-friendly interface makes it easy for users to work with

data and code efficiently. The authors used MATLAB for parsing and analyzing the data collected from WinProp.

B. Implementation

1) Altair WinProp WallMan database design

The study included a total of 30 different scenarios after an earthquake. Among the 30 scenarios are 15 Corner rooms and 15 Non-Corner rooms. The critical difference between a Corner and a Non-Corner room is exterior access, a feature typically present in Corner rooms. In a multi-subdivision building, a Corner room typically has two adjacent sides exposed to the outside, made of glass. In contrast, a Non-Corner room can only have, at most, one side exposed to the outside in a building setting. The thickness of materials affects wave propagation [23]. Thus, it was essential to create 30 scenarios across three different intensity levels with other materials to simulate unique and randomized wave propagation behaviors.

In preparation for the computer-aided-drawn models of these rooms, the National Building Code of the Philippines, or RA 6541, Presidential Decree 1096 (rev. 2005) [24], was used as a reference by the researchers, alongside further consultation with architecture and structural engineering experts. The office room database used the existing, predefined materials in the materials catalog provided by Altair in WinProp WallMan. Fig. 2 shows example rooms drawn in WallMan.

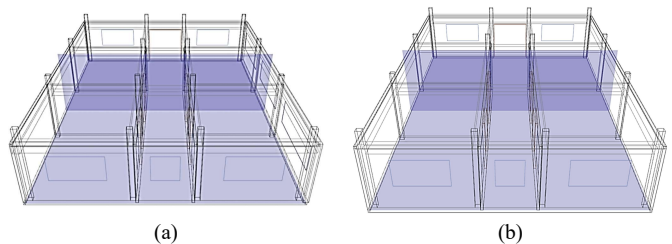


Fig. 2. WallMan room database of (a) Corner and (b) Non-corner rooms.

In addition to the database specifications, furniture using the materials catalog was added to simulate interacting objects: wooden and metal shelves, wooden chairs, wooden tables, and fallen debris made of concrete. Based on the PHIVOLCS Earthquake Intensity Scale (PEIS) and existing literature relating to the effect of earthquakes on buildings, specifically on higher stories, the post-disaster scenarios were drawn by the researchers in consultation with civil engineering experts on the prediction of post-earthquake damage. Additionally, the experts' advice on beam and column placement helped design what a room might typically look like after specific PEIS level intensities. Prior studies on indoor wave propagation have not modeled beams and columns as interacting objects, a gap this study addresses by incorporating structural beams and columns composed of signal-interacting materials. It should be noted, however, that earthquake outcomes reported in the literature do not precisely predict the outcomes of future disasters. As such, the scenarios modeled in this study are based on existing references on how an earthquake may affect debris and object shift. For the Philippine context, the PEIS was mainly referenced in this study. Some studies on the simulation and emulation of earthquakes were also considered when

designing the database and interacting objects.

2) Interacting objects

One of the primary considerations of the researchers in designing the placement of the IO is to increase the rate of disconnectivity between the publisher and the subscribers. As such, many Interacting Objects were placed in the database to increase the probability of Non-Line of Sight (NLOS) interactions between the publisher node and subscriber nodes. Through this, rays would be expected to go through reflection, refraction, diffraction, and scattering. The introduction of Interacting Objects and their displacement in a post-disaster scenario simulates the challenges in communications after an earthquake.

In a typical office setup, furniture is assumed to be placed near walls and upright, clearing the way for people's mobility. With proper regard to the PEIS, earthquake emulation results, furniture dimensions, and database design, the reference height for the new IO placed in the database was at $z = 0.2$ m. This height prevents objects from coinciding with the thickness of the floor, which spans from $z = 0$ m to $z = 0.1999$ m. The CAD program Altair WinProp WallMan would return an error if an object is placed "inside" the floor. This error served as a guide in the placement of furniture. Likewise, to simulate the toppling effect of furniture, for instance, a shelf falling on top of a table, the orthogonal objects were rotated along their x - and y -axes until each object rested naturally on the other, with no corners protruding through the walls, floor, ceiling, or adjacent furniture. Fig. 3 is an example of how toppled pieces of furniture were drawn with WallMan in post-quake scenarios.

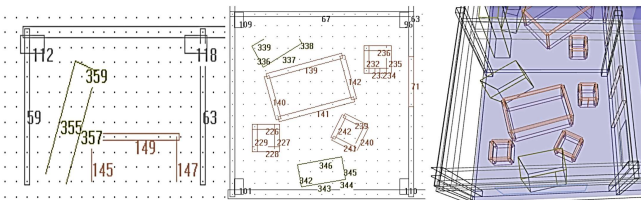


Fig. 3. X-Z, X-Y, and 3D point-of-view of toppled furniture.

3) Publisher, subscriber, and external rescue publisher placement

The publisher node for initial simulations is an access point located at $x = -3.00$ m, $y = 60.00$ m, $z = 2.24$ m to simulate a transmitter's typical ceiling placement in an office. It is situated near the main door entrance. The locations of subscribers that failed to reach the threshold were considered in the rerun of simulations after positioning the External Rescue Publisher.

Meanwhile, the subscriber nodes in a post-disaster scenario are assumed to be under Interacting Objects after an earthquake. After drawing post-scenario databases, the subscribers are placed near or under an IO to simulate people trapped under rubble. While x and y coordinates vary, the height for subscriber nodes used in the simulations is $z = 0.2$ m, considering the thickness of the concrete floor.

4) Altair WinProp ProMan simulation parameters

After the indoor databases were drafted in WallMan, Altair WinProp ProMan was used for radio wave propagation simulation. A total of 90 scenarios were run and simulated in

ProMan to monitor radio wave behavior in a post-earthquake scenario, with different transmitter-to-subscriber cardinalities. The following simulation parameters—with established rationale—were used in the collection of data.

One of the study's goals was to study the behavior of radio waves in a post-earthquake scenario. The Area of Simulation setting was set to Multiple Points (publisher to subscriber nodes) as opposed to the generation of a heatmap for the entire indoor database, a) to reduce simulation time; and b) to generate propagation rays which are helpful in visualizing the paths radio waves take in different scenarios. Additionally, the Resolution of prediction results was set to 0.25 m for improved accuracy, finer space discretization, and better representation of complex geometries in the simulation area. As part of the assumptions in the scenario, the subscriber nodes must be set 0.2 m above the ground, considering the 20 cm floor thickness of the indoor database, and avoid object clipping between the subscriber node and the 3D floor plane. To study the results at the mobile stations, certain settings were enabled, including propagation paths, per Stream and Sub-Channel Power Results, Delay Spread, Angular Spread, and Angular Mean, all of which were recorded and analyzed in MATLAB. At mobile stations, omnidirectional antennas are used to transmit and receive rays from all directions, enabling the coherent superposition of rays and the combination of per-ray information. 20 MHz was also the channel bandwidth used to represent typical bandwidth among communications devices.

At the publisher node, frequency was set to 2.4 GHz with power at 0 dBm Effective Isotropic Radiated Power (EIRP), 0 dBi isotropic antenna, typically used in many modern transmitting devices. Air interface limitations, such as Wi-Fi, Bluetooth, Zigbee, among others, were not considered, as the study is aimed at ray propagation rather than channel-specific analyses.

To simulate the effect of interacting objects in radio wave propagation, database material properties were considered. Materials such as wood, glass, and concrete had pre-defined values in Altair WinProp ProMan, and each interacting object had different materials set for its geometry.

For the ray optical propagation model, Standard Ray Tracing (SRT; 3D Ray Tracing) was used to provide more accurate results due to a more rigorous computation model. Minimum requirements were set for SRT, accounting for increased indoor objects as propagation obstacles in post-earthquake scenarios, while still simulating connectivity challenges in post-disaster indoor propagation. The requirements include a) Max. Transmissions = 2; b) Max. Reflections = 2; c) Max. Diffractions = 2; d) Max Reflections AND Diffractions = 4; e) Add. Diffractions: Ignored; f) Add. Transmissions: Ignored; g) Min. Length of wedges: 0.01 m (default), and h) Max. Inner angle of wedges = 180 deg (default).

Following the parameters would produce results that characterized the behavior of each subscriber node present in the room. As such, the received power at the subscriber can be determined, allowing the classification of subscribers that fall below and above the threshold accordingly.

5) MATLAB data processing

Extracted data from the Altair WinProp ProMan

simulations were then imported into MATLAB for processing and visualization. Data imported into MATLAB include Field Strength, Delay, Angle of Arrival (AoA)-Azimuth, Angle of Arrival-Elevation, Angle of Departure (AoD)-Azimuth, and Angle of Departure-Elevation in all 90 simulations. To visualize the subscriber nodes' behavior, normalized Power-Delay (PDP) and Power-Angular (PAP) profiles were utilized to observe the subscriber nodes' behavior when they failed to meet the threshold concerning the other successful subscribers in the room, depending on the simulated cardinality. This visualization was accomplished by plotting the relative power of the rays of each subscriber versus the ray's corresponding Delay, AoA-Azimuth, AoA-Elevation, AoD-Azimuth, and AoD-Elevation. The field strength results were measured in dBuV/m. So, they had to be converted to relative power, accordingly. Meanwhile, delays in nanoseconds and angles of arrival and angles of departure in radians were used to solve the delay and angular spreads of the scenarios and to explicitly observe the behavior of subscribers, whose results fall below and above the set thresholds.

The delay and angular spreads are crucial to understanding multipath propagation in an indoor post-earthquake scenario. The delay spread quantifies the time range the ray has taken to reach the subscriber with interacting objects, resulting in reflection and scattering. In contrast, the angular spread determines the different angle spreads the rays depart from the publisher node and arrive at the subscriber node.

III. RESULTS AND DISCUSSIONS

A. Level 6 Corner and Non-corner Rooms

Fig. 4 illustrates the representative office layout for Level 6 Corner and Non-Corner room scenarios generated using Altair WinProp WallMan. Based on the PHIVOLCS Earthquake Intensity Scale, Level 6 conditions are characterized by furniture and large objects that experience significant shaking without complete overturning. Accordingly, the simulated environment incorporates chairs, tables, and shelves placed in varied orientations and positions to represent realistic post-earthquake displacement within an indoor setting.

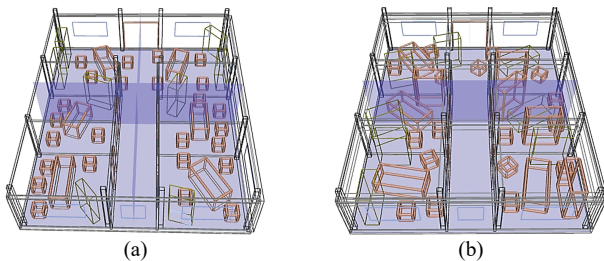


Fig. 4. Typical office setting of Level 6: (a) Corner room and (b) Non-Corner room.

Fig. 5 illustrates a Level 6 Corner and Non-Corner Room layout, demonstrating the placement of receiver nodes underneath tables. Seismic events of Level 6 Intensity are characterized by strong ground motion that may cause noticeable displacement of furniture and interior objects. As a result, the simulation includes receiver placement in protected areas beneath tables to mimic common post-earthquake actions, particularly the “duck-cover-and-hold”.

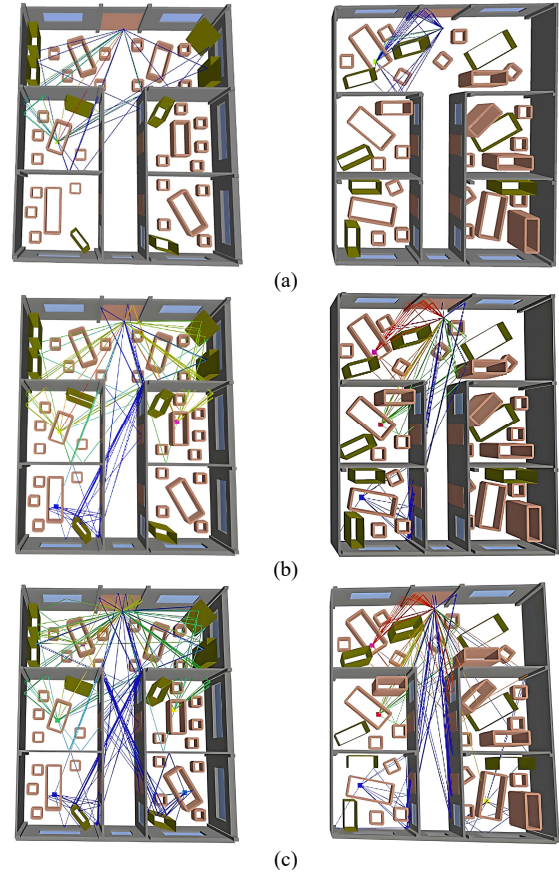


Fig. 5. Level 6 ray-tracing results for corner and non-corner rooms at cardinality ratios of 1:1, 1:3, and 1:5. (a) 1:1; (b) 1:3; (c) 1:5. In each panel, left: Corner room; right: Non-Corner room.

Analysis of the simulation indicates that metal furniture elements, particularly those with a thickness of approximately 5 mm, significantly influence received signal strength due to their high reflectivity and strong obstruction characteristics. In addition, diffraction around sharp edges of metal cabinets contributes to the formation of secondary propagation paths, which further affects the spatial distribution of received power within the room.

B. Level 7 Corner and Non-corner Rooms

Fig. 6 shows the Level 7 Corner Room configuration generated using Altair WinProp WallMan. Based on the PHIVOLCS Earthquake Intensity Scale, Level 7 conditions are characterized by strong ground motion that causes furniture and large objects to move, overturn, or topple. Accordingly, the simulated environment incorporates displaced and rotated furniture elements, including shelves, tables, and chairs, to represent realistic post-earthquake indoor conditions.

Fig. 7 presents the Level 7 Corner Room configuration, highlighting the propagation characteristics observed under increased environmental complexity. In line with the PHIVOLCS Earthquake Intensity Scale, Level 7 Intensity earthquakes entail scenarios in which heavy objects and furniture have the potential to topple. Some well-constructed structures might experience minor damage, occasionally leading to the emergence of cracks in concrete hollow block walls.

The transmitted signals exhibit multiple interaction mechanisms, including reflection from glass surfaces, diffraction around furniture edges, and attenuation through

structural elements. Results further indicate that increased node cardinality leads to a higher density of transmitted rays within the environment, which in turn increases the likelihood of multipath formation and spatial interference.

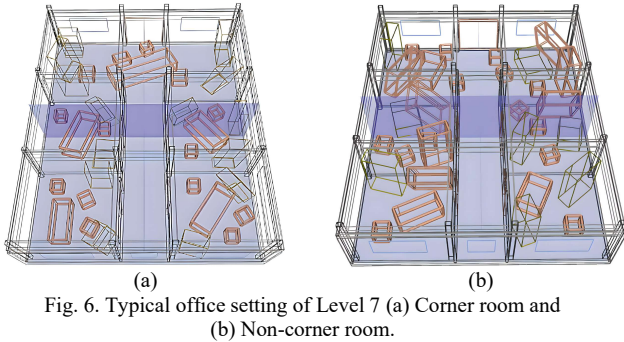


Fig. 6. Typical office setting of Level 7 (a) Corner room and (b) Non-corner room.

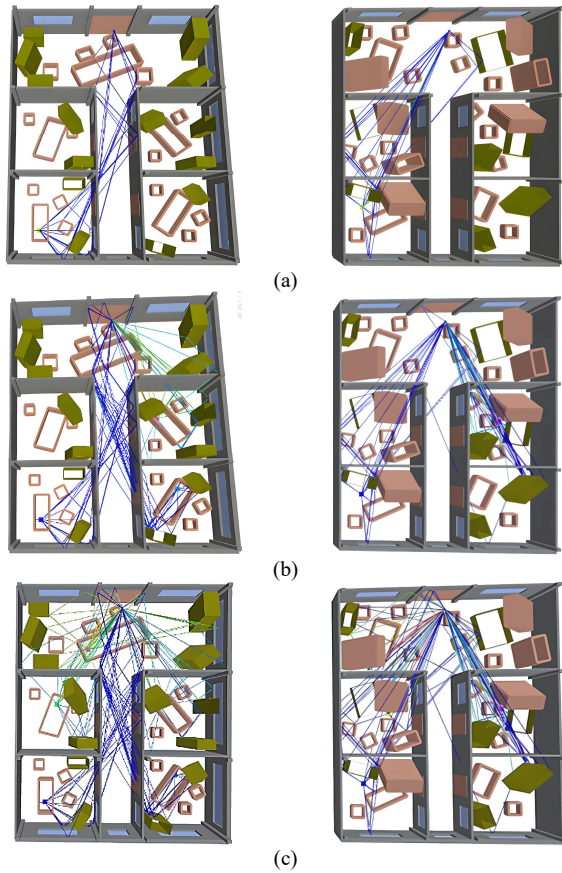


Fig. 7. Level 7 ray-tracing results for corner and non-corner rooms at cardinality ratios of 1:1, 1:3, and 1:5. (a) 1:1; (b) 1:3; (c) 1:5. In each panel, left: Corner room; right: Non-corner room.

C. Level 8 Corner and Non-corner Rooms

Fig. 8 illustrates a standard office setup within a Level 8 Corner and Non-Corner Room. Per the PHIVOLCS Earthquake Intensity Scale, it is important to note that seismic events reaching an intensity of Level 8 can result in significant displacement and toppling of furniture and large objects. Drawing from this understanding, the simulation of the Level 8 Rooms was meticulously designed to portray the realistic aftermath of such an intense earthquake scenario. This depiction involved simulating shelves that had fallen over; tables and chairs relocated to different positions and rotated at various angles, and a collapsed ceiling, causing debris to fall on top of the subscriber nodes.

Fig. 9 presents a visual representation of a Level 8 room

layout, primarily focusing on the strategic placement of receivers beneath either a table or a chair, near an entirely toppled metal cabinet. The positioning of the receivers underscores the critical need for rapid protective action, as individuals often have only seconds to seek shelter, and sometimes, there is no opportunity for protection.

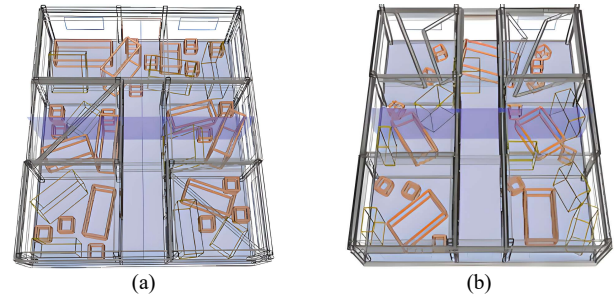


Fig. 8. Typical office setting of Level 8: (a) Corner Room and (b) Non-corner room.

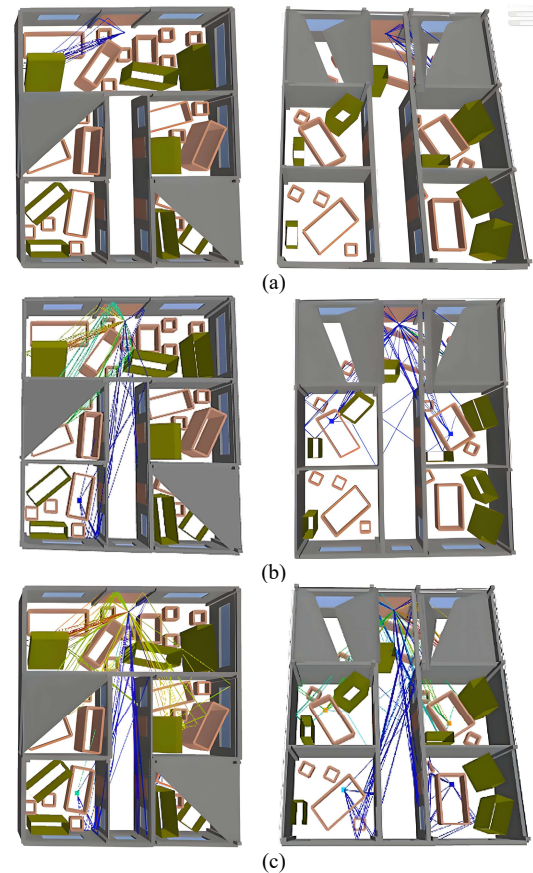


Fig. 9. Level 8 ray-tracing results for corner and non-corner rooms at cardinality ratios of 1:1, 1:3, and 1:5. (a) 1:1; (b) 1:3; (c) 1:5. In each panel, left: Corner room; right: Non-corner room.

Furthermore, the rays emitted by the transmitter undergo various interactions, including interactions with fallen ceiling debris, as they propagate within the scenario. These interactions include diffraction when encountering toppled furniture, reflection when encountering glass surfaces, and refraction as they pass through cracked walls and specific furniture pieces. It is critical to note that the number of transmitted waves increases proportionally with cardinality. Conversely, the strength of the received signal diminishes significantly as the distance between the transmitter and receiver grows, considering the presence of fallen ceiling debris.

Table 1. Summary of before external rescue publisher positioning intervention post-earthquake scenario

PHIVOLCS Earthquake Intensity Scale	PEIS6						PEIS7						PEIS8					
Room Type	Corner Room			Non-Corner Room			Corner Room			Non-Corner Room			Corner Room			Non-Corner Room		
Cardinality	①	③	⑤	①	③	⑤	①	③	⑤	①	③	⑤	①	③	⑤	①	③	⑤
Total Indoor Scenario Count	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Indoor Scenario Count Above the Threshold	5	2	1	5	3	3	4	1	1	4	4	2	4	1	0	5	3	0
Indoor Scenario Count Below the Threshold	0	3	4	0	2	2	1	4	4	1	1	3	1	4	5	0	2	5
Subscriber Count in the Indoor Scenario Below the Threshold	0	3	6	0	2	3	1	5	6	1	1	4	1	4	7	0	2	10
Subscriber Average Received Power Below the Threshold [dBm]	n.a.	-106.4	-101.5	n.a.	-119.0	-114.8	-102.8	-99.2	-99.6	-94.3	-94.3	-93.6	-96.9	-105.8	-110.1	n.a.	-107.0	-115.9
Total Indoor Scenario Count Below the Threshold per Room Type	7			4			9			5			10			7		
Total Indoor Scenario Count Below the Threshold per PEIS	11						14						17					
Total Indoor Scenario Count Below the Threshold	42																	

D. Summary of Simulated Post-earthquake Scenarios Before the Positioning of the External Rescue Publisher Intervention

Table 1 shows the summary of the simulated post-earthquake scenarios before the positioning of the External Rescue Publisher intervention. The table summarizes the subscriber count at each cardinality and Intensity Level. It classifies them into subscribers below and above the -91 dBm threshold. Likewise, the table shows the average receiver power at each intensity level. The table shows that there are a total of 42 scenarios that are below the threshold.

Results in Table 1 show that the most severe degradation in communication performance occurs under PHIVOLCS Intensity Level 8 conditions, which exhibited the highest number of failed subscriber nodes. This result indicates that increased debris intensity directly correlates with a higher probability of communication failure due to greater signal obstruction and attenuation. In addition, the simulation results show that subscriber nodes fully obstructed by metal IOs experienced the most significant decline in signal quality. It was also observed that Corner room configurations exhibited reduced connectivity due to signal interaction with the glass windows. In such cases, signal propagation was affected by the diffraction around the glass surfaces.

To quantify baseline performance, the connectivity of the original in-room ceiling publisher was evaluated across the 150 unique subscriber positions defined by the 1:5 cardinality layouts. Under this baseline, 114 of 150 subscriber nodes (76.0%) satisfied the -91 dBm sensitivity threshold, while 36 nodes (24.0%) fell below it. Received power across all baseline nodes had a mean of -80.8 dBm and a median of -78.9 dBm (SD = 19.3 dB), with the failed subset exhibiting a median of -100.6 dBm. Table 2 summarizes the collected baseline before external rescue publisher positioning.

Table 2. Sensitivity of baseline failure rate to controlled factors

Factor	Configuration	Failure Rate	Mean Rx Power (dBm)
PHIVOLCS Intensity	Level 6	18%	-77.1
	Level 7	20%	-78.8
	Level 8	34%	-86.4
Room Type	Corner	25%	-78.7
	Non-Corner	23%	-82.8
Node Cardinality	1:1	10%	-75.9
	1:3	19%	-79.2
	1:5	24%	-80.8

Note: Intensity and room-type statistics are computed over the 150 unique 1:5 positions; cardinality statistics are computed per cardinality

E. Positioning of External Rescue Publisher

This section discusses the results of positioning an External Rescue Publisher (ERP) node to allow the failed subscriber nodes to reach the -91 dBm sensitivity threshold. It is assumed that there is no cellular connectivity. Accordingly, the ERP is positioned outside the room to represent the presence of external rescuers. At the same time, the initially placed in-room publisher is disregarded. The analysis focuses on subscriber nodes that fail to meet the -91 dBm threshold after initial evaluation. It is observed that these nodes are primarily located in the farthest regions of the room, particularly in the sub-rooms situated in the southern section. In a corner room configuration, the ERP is positioned at

accessible exterior walls with windows (Zones 1, 2, and 3), while in a non-corner room, the only accessible exterior boundary is the southern wall with windows.

Additionally, the transmitter power of the External Rescue Publisher was increased incrementally up to 30 dBm as a final optimization measure after repositioning of ERP remained insufficient in enabling the subscriber nodes to meet the receiver threshold. This adjustment serves as a link budget compensation, as increased transmit power improves received signal strength, thereby extending coverage and increasing the likelihood that obstructed subscriber nodes satisfy the -91 dBm requirement. However, increasing transmit power also raises overall radiated energy, which in practical deployments may result in higher interference levels, reduced energy efficiency, and potential regulatory limitations. In this study, these constraints are acknowledged; nevertheless, the approach remains valid as the analysis is conducted within a simulation-based emergency rescue framework aimed at evaluating the upper-bound feasibility of communication under severe post-earthquake propagation conditions rather than optimizing power efficiency.

Following ERP intervention, all 36 previously disconnected nodes were restored to at least -91 dBm, a 100% recovery rate. The received power of the failed-node population improved from a median of -100.6 dBm to -79.2 dBm, a median gain of 21.4 dBm. Relative to the no-intervention baseline of the original in-room publisher, which left 24.0% of subscriber nodes below threshold, the ERP restored connectivity for all previously disconnected nodes, providing a within-study quantitative baseline against which the intervention is measured. The contribution of ERP placement was further isolated from that of transmit-power adjustment: repositioning alone, at the nominal 0 dBm EIRP, was sufficient to restore connectivity in 13 of the 23 repositioned rooms (57%), while the remaining rooms required incremental power increases of 10–30 dBm. This outcome indicates that spatial placement resolves the majority of disconnections, with link-budget compensation addressing only the most heavily obstructed cases.

Fig. 10 presents the Empirical Cumulative Distribution Function (ECDF) plots of the RMS delay spread and the angular spreads (AoA and AoD, in azimuth and elevation) for subscribers above and below the -91 dBm threshold, with median values across all six level/room-type conditions summarized in Table 3. Below-threshold subscribers generally exhibit smaller delay and angular spreads than above-threshold subscribers, most consistently in RMS delay spread and AoA-azimuth, indicating that heavily obstructed nodes are reached by fewer resolvable multipath components, in the limiting case by a single dominant path. This distributional separation provides a statistical, rather than scenario-by-scenario, characterization of connectivity behavior and complements the received-power results.

1) Level 6 Corner and Non-Corner rooms with external rescue publisher

Fig. 11 illustrates the representative External Rescue Publisher placement scenarios for Level 6 Corner Room Scenario 1 and Non-Corner Scenario 1. The ray-tracing results indicate multiple propagation mechanisms, including line-of-sight transmission, reflection, diffraction, and

material penetration control that signal propagation. A significant portion of the transmitted energy propagates through window openings, allowing greater signal penetration towards the interior of the room. Upon entering the room, the electromagnetic waves undergo reflections from walls, furniture, and other interior surfaces. At the same

time, diffraction around edges and obstacles creates additional propagation paths that extend signal coverage to areas without a direct line of sight. These multipath components collectively contribute to the received signal strength at the subscriber nodes.

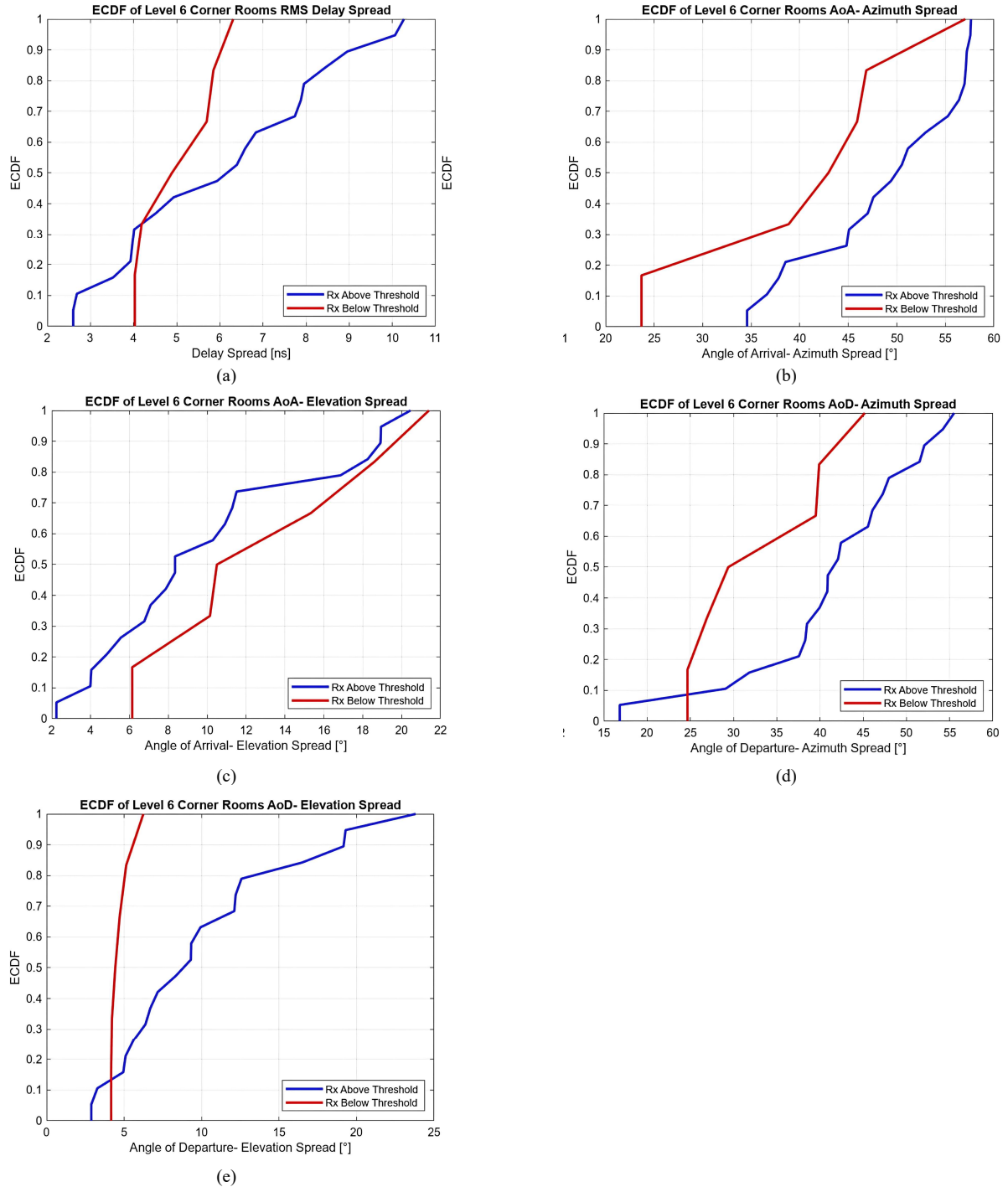


Fig. 10. ECDF plots of Level 6 Corner rooms: (a) Delay spread, (b) AoA-Azimuth spread, (c) AoA-Elevation spread, (d) AoD-Azimuth spread, and (e) AoD-Elevation spread.

Table 3. Median delay and angular spreads for above- vs. below-threshold subscribers

Metric (Above/Below)	L6-C	L6-NC	L7-C	L7-NC	L8-C	L8-NC
Delay spread [ns]	6.22/4.89	5.83/2.58	4.62/1.79	3.28/1.93	2.80/3.13	4.92/4.38
AoA-Azimuth [°]	50.18/42.95	50.79/5.67	50.32/36.09	50.67/27.90	47.44/47.23	51.17/42.19
AoA-Elevation [°]	8.34/10.50	12.02/10.04	13.62/13.09	11.53/5.28	14.50/13.52	14.09/4.23
AoD-Azimuth [°]	42.03/29.40	38.93/42.11	36.09/16.90	27.86/8.22	32.10/39.89	42.09/33.52
AoD-Elevation [°]	9.22/4.43	7.79/6.13	8.79/4.43	7.40/4.88	9.87/11.35	12.29/13.55



Fig. 11. Positioning of external rescue publisher in Level 6: (a) Corner room scenario 1; (b) Level 6 Non-Corner room scenario 5.

Furthermore, subscriber nodes located beneath wooden tables were still able to achieve the required -91 dBm threshold. This behavior can be attributed to the relatively low dielectric loss of wood at the operating frequency, allowing partial transmission of electromagnetic waves through the material with comparatively lower attenuation than denser interacting objects, such as metal debris.

Table 4 summarizes the power measured in dBm at each receiver for the scenarios with External Rescue Publisher nodes in Level 6 Corner and Non-Corner rooms. The power measured is taken directly from the simulated mobile stations' Altair WinProp ProMan simulation results. Overall, ERP placement substantially improved communication performance by increasing the received signal strength of subscriber nodes that initially failed to satisfy the -91 dBm receiver sensitivity threshold. This improvement demonstrates that positioning an external transmitter can effectively compensate for signal degradation caused by debris-induced attenuation and extended propagation distances.

Table 4. Summary of power at receivers in Level 6 with the external rescue publisher

Room Scenario	Tx (dBm)	Rx ₁ (dBm)	Rx ₂ (dBm)
Corner 1	0	-63.59	-
Corner 2	30	-82.08	33.87
Corner 3	0	-79.19	-79.7
Corner 5	0	-63.35	-
Non-Corner 1	0	-61.52	-
Non-Corner 5	10	-81.92	-79.26

While most Level 6 scenarios achieved the required threshold through ERP repositioning alone, several scenarios required an increase in transmit power. Specifically, Level 6 Corner Scenario 2 and Non-Corner Scenario 5 required transmit power adjustments to 30 dBm and 10 dBm, respectively. These scenarios were characterized by greater obstruction between the ERP and subscriber nodes, resulting in higher penetration and diffraction losses. Nevertheless, after the combined optimization of ERP placement and transmit power, all subscriber nodes successfully achieved the minimum receiver sensitivity of -91 dBm.

2) Level 7 Corner and Non-Corner rooms with external rescue publisher

Fig. 12 shows various scenarios of positioning External Rescue Publisher nodes within Level 7 Corner Room Scenario 1 and Non-Corner Scenario 4. The results indicate that optimal ERP placement is governed by the need to maximize the number of viable propagation paths to the subscriber nodes rather than simply minimizing the distance between transmitter and receivers. Positioning the ERP near the center of the sub-rooms enables the transmitted signal to

utilize multiple propagation mechanisms, including wall and window penetration, reflections from interior surfaces, and diffraction around structural obstacles. These multipath components collectively improve signal coverage by providing alternative transmission paths when the direct line-of-sight path is blocked by debris or room structures.

Furthermore, the simulations demonstrate that the propagation environment in Level 7 scenarios is dependent on the spatial arrangement of obstacles, requiring the ERP to be positioned where both direct and indirect propagation paths can be effectively utilized. This result suggests that, in heavily obstructed post-earthquake environments, ERP placement should prioritize locations that maximize multipath diversity rather than relying solely on proximity to subscriber nodes.

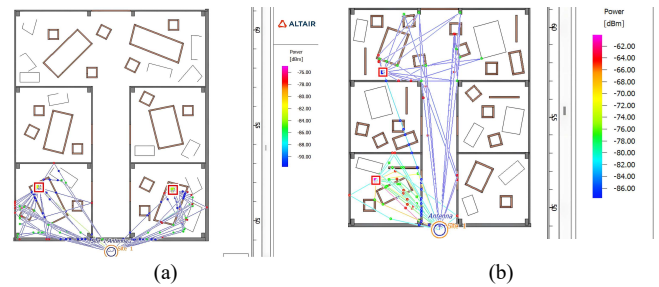


Fig. 12. Positioning of external rescue publisher in Level 7: (a) Corner room scenario 1; (b) Non-Corner room scenario 4.

Table 5 summarizes the received power measured at each subscriber node for the Level 7 Corner and Non-Corner room scenarios following ERP placement. Similar to the Level 6 results, the majority of the scenarios achieved the required -91 dBm receiver sensitivity threshold through ERP repositioning alone. However, Level 7 Corner Scenario 4 and Non-Corner Scenario 4 required additional transmit power increases to 10 dBm and 30 dBm, respectively, which indicated that the increased debris severity and obstruction in these layouts produced greater propagation losses that could not be compensated by transmitter repositioning alone. Despite the more challenging propagation environment associated with Level 7, the combined strategy of ERP placement and selective transmit power adjustment enabled all subscriber nodes to satisfy the required receiver threshold.

Table 5. Summary of power at receivers in Level 7 with the external rescue publisher

Room Scenario	Tx (dBm)	Rx ₁ (dBm)	Rx ₂ (dBm)
Corner 1	0	-82.89	-
Corner 2	0	-85.10	-80.18
Corner 3	0	-72.8	-
Corner 4	10	-83.69	-70.23
Non-Corner 2	0	-61.65	-
Non-Corner 4	30	-60.17	-87.63
Non-Corner 5	0	-53.04	-

3) Level 8 Corner and Non-corner rooms with external rescue publisher

Fig. 13 shows various scenarios of positioning External Rescue Publisher nodes for Level 8 Corner and Non-Corner scenarios under severe debris conditions. The results indicate that the presence of dense IOs constrains optimal ERP positioning, particularly metal structures such as shelves, which introduce significant signal blockage and shadowing.

In Corner Room Scenario 1, feasible ERP locations are limited, with Zone 5 providing the most effective coverage due to its ability to establish partial line-of-sight and diffracted propagation paths toward both subscriber nodes. The results further show that diffraction around structural elements plays a dominant role in enabling signal penetration into obstructed sub-rooms, highlighting its importance in highly cluttered environments.

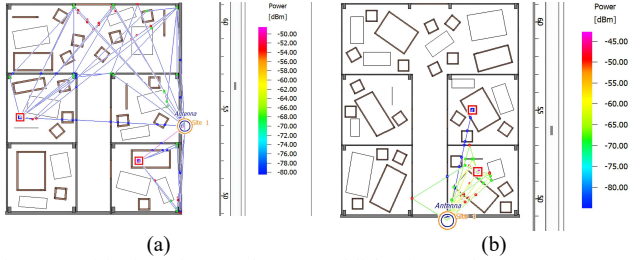


Fig. 13. Positioning of external rescue publisher in Level 8: (a) Corner room scenario 1; (b) Non-Corner room scenario 1.

In the Non-Corner configuration, ERP placement at Zone 2 provides better coverage by leveraging exterior wall openings. Signal propagation, in this case, was governed by a combination of wall penetration, reflection from interior surfaces, and diffraction around metal IOs, as seen in Fig. 13(a). Overall, the Level 8 results demonstrate that as debris severity increases, ERP effectiveness becomes increasingly dependent on identifying locations that maximize usable multipath components while minimizing interaction with high-loss materials such as metal IOs.

Table 6 summarizes the received power measured at each subscriber node for the Level 8 Corner and Non-Corner room scenarios following the positioning of the External Rescue Publisher (ERP). Compared to the lower intensity levels, Level 8 scenarios exhibited a larger number of cases requiring transmit power adjustment, with several Corner and Non-Corner configurations necessitating increases from 0 dBm to values ranging between 20 dBm and 30 dBm. This outcome indicates that the most severe debris conditions introduce substantially higher propagation losses. Despite these increased attenuation effects, all Level 8 scenarios ultimately achieved the -91 dBm receiver sensitivity threshold after ERP placement and selective transmit power enhancement. These results demonstrate that the proposed

approach remains effective under increasingly severe post-earthquake conditions while highlighting that transmit power adjustment is only necessary in scenarios where obstacle-induced attenuation significantly limits signal propagation.

Table 6. Summary of power at receivers in Level 8 with external rescue publisher

Room Scenario	Tx (dBm)	Rx ₁ (dBm)	Rx ₂ (dBm)
Corner 1	30	-80.50	-48.60
Corner 2	20	-81.33	-
Corner 3	30	-47.57	-90.43
Corner 4	0	-52.65	-
Corner 5	0	-69.90	-
Non-Corner 1	30	-84.97	-42.85
Non-Corner 2	30	-57.92	-83.67
Non-Corner 3	0	-32.95	-61.45
Non-Corner 4	0	-65.78	-88.53
Non-Corner 5	0	-78.45	-84.71

F. Comparison with Existing Post-disaster Communication Restoration Methods

Table 7 details the proposed External Rescue Publisher (ERP) approach against the principal families of post-disaster communication methods reported in the Prior Studies section. Unlike UAV-based aerial base stations [11, 12], which restore blanket coverage over wide outdoor areas, the ERP operates at an indoor, room-level scale and explicitly models the interaction of the rescue signal with debris materials such as concrete, wood, glass, and metal. Compared with infrastructure-less device-to-device and mesh public-safety networks [13, 14], which rely on a sufficient density of surviving peers to relay traffic, the ERP re-establishes connectivity from a single, deliberately placed external transmitter and does not depend on peer availability.

It is also distinct from victim-locating systems [15, 16], whose objective is to detect and position trapped devices rather than to restore a usable communication link to them. Finally, whereas several of these methods are validated through field trials, the present work contributes a ray-tracing-based optimization of transmitter placement and power against a -91 dBm receiver threshold, providing a controlled and reproducible basis for evaluating restoration feasibility under indoor post-earthquake conditions. A shared limitation is that the ERP results are simulation-based; field validation remains an avenue for future work, consistent with the empirical approaches in Refs. [12, 15, 16].

Table 7. Comparison of external rescue publisher positioning intervention with existing post-disaster communication restoration methods

Approaches	Environment	Primary Objective	Optimization and Validation
Proposed External Rescue Publisher (ERP) Intervention	Indoor, single-room, IO-obstructed	Restore link to disconnected subscribers	Ray-tracing-optimized external publisher placement and Tx power; simulation
UAV/aerial base stations [11, 12]	Outdoor, wide area	Restore blanket network coverage	UAV deployment/trajectory optimization; simulation [11], field test [12]
D2D/mesh public-safety networks [13, 14]	Cellular/peer, infrastructure-less	Direct peer-to-peer links among survivors	Discovery and resource-allocation algorithms; simulation
Victim-locating systems [15, 16]	Indoor/under-rubble	Locate trapped devices (not restore link)	RSSI/Wi-Fi FTM/UWB ranging; experiment

IV. CONCLUSIONS AND FUTURE DIRECTIONS

A. Conclusion

This study offers several contributions that may inform future post-disaster wireless communication systems.

Localized guidelines for earthquake damage description, grounded in the PHIVOLCS Earthquake Intensity Scale, were used to construct realistic ray tracing simulation scenarios. Building on this foundation, computer-aided design and ray tracing tools were used to model thirty post-earthquake scenarios, enabling a systematic study of

publisher and subscriber cardinality behavior. Parameter spreads were further analyzed to determine the probability of subscribers falling below or above defined thresholds, providing a probabilistic lens for assessing network reliability.

Beyond these simulation-based insights, publisher characteristics were translated into practical design considerations for post-earthquake antenna design. Similarly, a method was developed for determining fixed access-point placement in indoor office environments that minimizes multipath fading, accounting for the number and material composition of interacting objects. An approach was also demonstrated for positioning and adjusting the transmit power of the emergency publisher at subscriber height, reducing wave time-of-flight and improving signal delivery efficiency. Finally, the characterization of power-delay and power-angular profiles lays the groundwork for future multipath channel modeling in post-earthquake propagation.

Together, these findings advance the theoretical understanding of post-disaster wireless propagation while offering practical strategies to strengthen the resilience of emergency communication networks after seismic events.

B. Recommendation

The proposal addresses the disconnection between devices during post-earthquake scenarios due to rubble that can affect structures, wireless protocol gateways, and debris interaction with the received and transmitted wireless communication signals. The researchers recommend adding more transmitters and receivers and studying how this would affect the power and spread parameters of the subscriber nodes. Aside from this, the parameters of the publisher nodes could also be changed, such as their power, frequency, and antenna pattern. It is also recommended that the study be conducted in a different indoor setup.

C. Future Directions

Building on this study, several directions merit further investigation. Ray tracing may be extended to simulate wireless wave paths through intricate built structures, clarifying how different materials influence propagation. This technique may also assess network dependability and resilience, particularly for IoT or disaster response networks requiring continuous connectivity, and to predict multipath signal propagation in indoor settings.

Further work could refine network coverage by adjusting the placement and alignment of access points, routers, and nodes through ray tracing, thereby enhancing connectivity efficiency. Related to this, the impact of antenna placement and orientation on signal strength for subscriber and publisher nodes warrants closer examination, since optimized positioning can substantially affect performance. Ray tracing may likewise model signal penetration through structures, assessing how building materials and designs affect signal strength.

Finally, future research should situate room-level interventions such as the ERP within broader, systems-level emergency communication architectures. Recent work has proposed resilient IoT-based disaster-response networks integrating mobile base stations, LPWAN/IoT connectivity, aerial platforms, and satellite links into reconfigurable infrastructures capable of shifting between normal and emergency modes [25]. Future studies could examine how a

localized ERP deployment fits as an access-layer or edge component within such architectures, relative to KPIs like recovery time objective and system uptime, and emerging technologies such as UAV-assisted relays, edge computing, and AI-driven node placement optimization.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

R.A.R.A., M.G.C.B., M.F.G.E., and D.C.C.M. conducted the simulations, collected the results, and analyzed the data; L.M. provided idea generation, checked the analysis, helped draw major conclusions, and guided the group; all authors wrote the paper. All authors had approved the final version.

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