Emergency Management of Tomorrow Research: Landscape Assessment

A Summary Report of Peer-Reviewed Research in Emergency Management from 2018-2023

February 2024

Science and Technology

This report was prepared for the U.S. Department of Homeland Security under a Work-for-Others Agreement with the U.S. Department of Energy, contract DE-AC05-76RL01830, IA 70RSAT23KPM000025.

Pacific Northwest
NATIONAL LABORATORY

PNNL-35649

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Final Report

February 2024

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U.S. DEPARTMENT OF ENERGY

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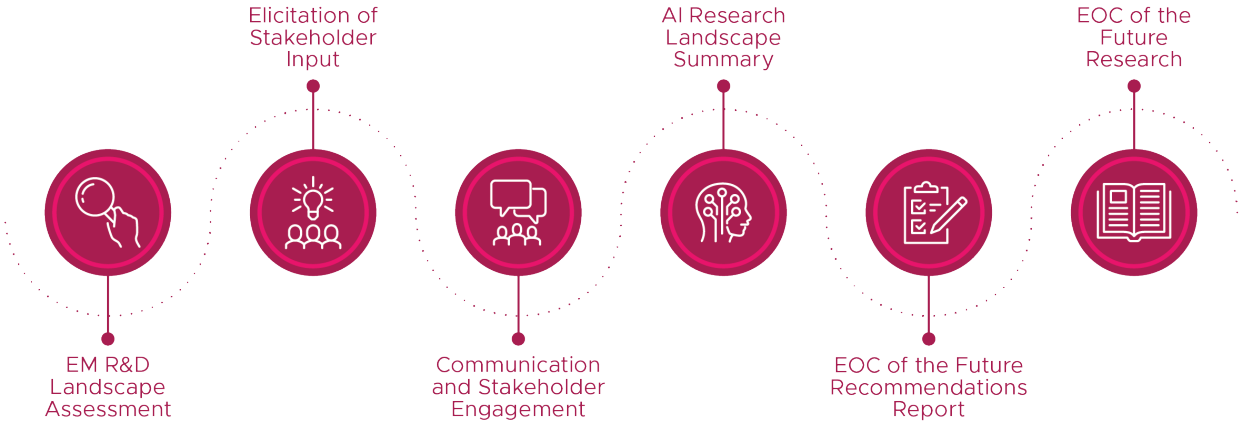
About the Emergency Management of Tomorrow Research

With support from the Department of Homeland Security (DHS) Science and Technology Directorate (S&T), Pacific Northwest National Laboratory (PNNL) is executing the Emergency Management of Tomorrow Research (EMOTR) Program to identify current EM research, elicit capability needs from EM practitioners, and identify where technology, such as artificial intelligence (AI), may benefit the future of EM and emergency operations centers. The project is delivering a phased and iterative approach to inform future research, development, and investments for the EM community.



Summary

As part of the EMOTR Program, sponsored by DHS S&T, PNNL conducted an EM Research and Development Landscape Assessment to assist in exploring future investment options.

As part of the assessment, PNNL conducted a literature review to identify existing research and relevant enabling technologies in various EM-related themes and stages of maturity. The literature review included publicly available research papers and open-source material from identified U.S. academic institutions, national laboratories, and other research centers. A broad technical literature search (2018 to present) resulted in nearly 36,000 records. This full set of records was narrowed to a smaller subset of over 1,600 by filtering on terms highly associated with applicable EM topics, as determined by PNNL subject matter experts.

PNNL used a suite of tools, including Scopus and Quid, to search for publications and analyze research trends. Key highlights from the assessment include:

- Subsets of highly correlated research, or research clusters, included social media data, COVID-19 pandemic, machine learning models, flood risk, and satellite images, to name a few.
- Top institutions based on publication volume within the search terms included George Mason University, Georgia Institute of Technology, the National Institute of Standards and Technology, Purdue University, and Texas A&M University.
- Potential overlap or opportunities for collaboration identified within the research areas included social media analytics, artificial intelligence and machine learning, community resilience, satellite technology, emergency response solutions to power grid issues, evacuation response, Smart City applications and informatics ecosystems, and critical infrastructure damage assessments.
- PNNL also identified capability gaps that lack an identified solution or sufficient research to bring a solution to market. These gaps include information management systems that support multi-jurisdictional responses during large-scale events and technical issues in the emergency operations center attributable to the operator at a similar rate as computer breakdown issues.

This report summarizes PNNL's overall approach, outcomes, and analysis of the results. A detailed annotated bibliography of publications identified in the literature review is available separate from this report. The spreadsheet includes README tab with user-friendly instructions for how to sort, filter, and search over 300 publications.

Acronyms and Abbreviations

AI	Artificial Intelligence
ANL	Argonne National Laboratory
BERT	Bidirectional Encoder Representations from Transformers
CIMS	Communication Information Management Systems
CNN	Convolutional Neural Network
CRC	Coastal Resilience Center
DHS	Department of Homeland Security
DOE	Department of Energy
EM	Emergency Management
EMOTR	Emergency Management of Tomorrow Research
EOC	Emergency Operations Center
FEMA	Federal Emergency Management Agency
GAO	U.S. Government Accountability Office
GA Tech	Georgia Institute of Technology
ICS	Incident Command System
INL	Idaho National Laboratory
IoT	Internet of Things
KG	Knowledge Graph
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
MIT	Massachusetts Institute of Technology
ML	Machine Learning
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
OSTI	Office of Science and Technical Information
PNNL	Pacific Northwest National Laboratory
PR	Project Responder
PSAP	Public Safety Answer Points
PSFM	Platform, System, Framework, Or Model
R&D	Research and Development
S&T	Science and Technology
TAMU	Texas A&M University
UAV	Unmanned Aerial Vehicles
UE	User Equipment
UW	University of Washington

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1.0 Introduction

As part of the Emergency Management of Tomorrow Research (EMOTR) Program, sponsored by the Department of Homeland Security (DHS) Science and Technology Directorate (S&T), Pacific Northwest National Laboratory (PNNL) conducted an Emergency Management (EM) Research and Development (R&D) Landscape Assessment to assist S&T in exploring future investment options. This assessment was completed by conducting a literature review that explored a series of emergency preparedness themes to identify existing research and relevant enabling technologies in various stages of maturity.

Through the literature review of publicly available research papers and open-source material, PNNL researchers identified U.S. academic institutions, national laboratories, and other research centers that identified potential solutions or recommendations for the myriad challenges facing emergency managers. This literature review captured a range of work in EM research subjects, from studies providing recommendations for further research to proposed technologies intended for immediate use in the field. New technologies identified in the research papers were also assessed for interoperability into current systems and potential barriers to implementation, including budget restrictions, insufficient training resources, and policy restrictions. Further, PNNL looked for overlapping research agendas, topics, and trends in advanced technologies that may be underutilized within EM and warrant future consideration for investment.

2.0 Methodology

PNNL designed the landscape assessment methodology to identify early- and mid-stage R&D being conducted at academic institutions, national laboratories, and other research institutions on EM-specific topics (primarily between 2018 and 2023). PNNL used a suite of publication databases, key search terms, and analytical tools to filter 36,000 journal articles and 1,600 patent publications to a manageable dataset of 300-plus peer-reviewed and open-source publications captured in a sortable spreadsheet available separate from this report (see Figure 1).

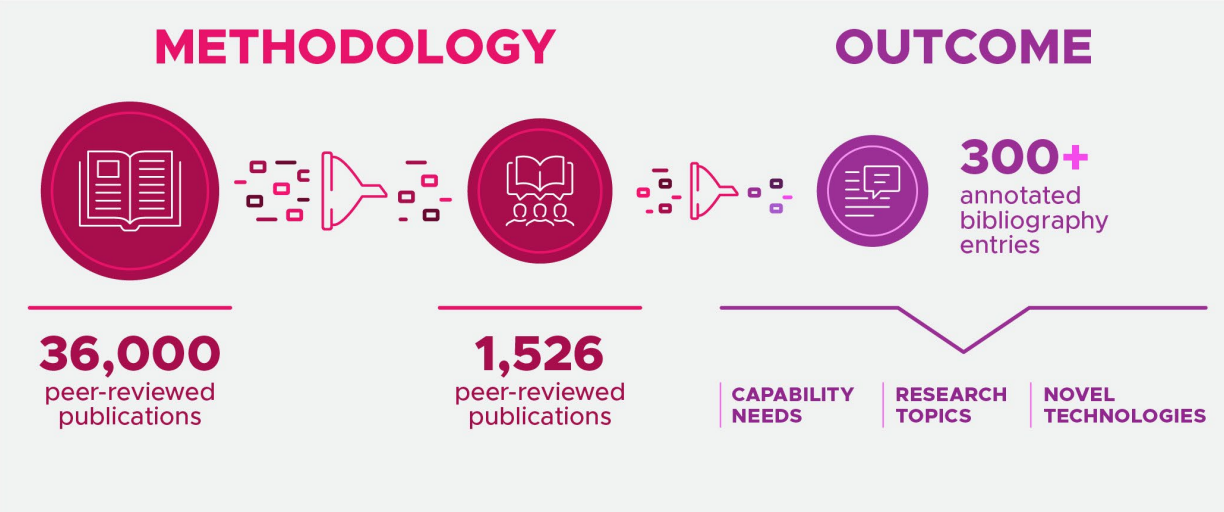

Figure 1. PNNL Landscape Assessment Overview

This section summarizes PNNL's structured approach to review existing EM R&D, identify and verify capability gaps and needs, and assess results for interoperability and impact. Sections 2.1-2.6 provide a high-level summary of the approach, including the databases, key search terms, and analytical tools used to initiate the assessment and filter publications and patents to a manageable and applicable dataset. A detailed methodology is available in Appendix A.

Altogether, the assessment identified promising early and mid-stage research on the application of emerging science and technology to the EM mission. Research efforts sought to answer the question: **What R&D is currently funded that addresses EM-related gaps?**

2.1 Sources

Sources used to collect data include databases to search publications, patents, and open sources (the Office of Science and Technical Information [OSTI], Laboratory-Directed R&D project lists, Google Scholar) for EM research.

2.2 Key Search Terms

Articles were selected based on applicability to specific key search terms that address capability gaps and needs in the EM mission areas (preparedness, mitigation, response, recovery). Key search terms are listed in Table 1.

The search terms selected were informed by PNNL's review of existing resources, such as the Project Responder (PR) reports, and previous work within the first responder and public safety communities and projects at PNNL, such as the First Responder Roadmap (Lesperance, A., et al., 2023). Key search terms were further down-selected to elicit technology-focused publications in EM, disaster management, and crisis management. The number of key search terms was limited to what could be reasonably covered within the timeframe of the assessment. In addition to research identified via PNNL's search tools, a data call was sent to the Department of Energy (DOE) national laboratories to include R&D projects that may not have open-source publications.

Table 1. Key Search Terms

Key Search Terms		
Climate change and extreme weather	Data sharing/data integration	Infrastructure vulnerability
Community resilience and equality	Disaster science	Resource management
Crisis information management system	Emergency management	Situational awareness
	Emergency operations center	Supply chain management
Crisis management	Incident command systems	Threat categories
Cybersecurity/cyber resilience	Information sharing	Workforce training

2.3 Tools

The key terms were used in Scopus[1] searches for peer-reviewed publications, PATSNAP[2] for patents, and other open sources (i.e., OSTI, Google Scholar) to identify and analyze applicable R&D efforts. The initial searches yielded approximately 36,000 journal articles and 1,600 patent publications. Additional sub-searches using Quid[3] further down-selected to the most relevant documents and records focused on key topic areas and associated concepts.

2.4 Limitations

Throughout the process, the publication data and parameters were refined to elicit a manageable and applicable dataset. Limitations and boundaries of the research includes the following:

- This review was limited to 2008-2023 and U.S. institutions as primary contributors, with the possibility to expand to incorporate new research and international with future funding.
- Publications were limited to topics with a technological focus to better target emerging technologies.
- The Scopus results were limited to peer-reviewed publications and information available on open-source databases and publicly available websites.
- PNNL analysts removed duplicative entries (such as repetition of technical papers and conference presentations) or entries where the term “emergency management” was not relevant or consistent to this project.
- When applicable, private sector partnerships and federal institutions were noted for ease of reference.
- The review focused on published peer-reviewed articles, which reflects only a small portion of research, and the results can be skewed or lagging indicators due to the age of the publication, public and policy interests, political climate and urgency, or funding trends. Therefore, this study sought to guide decision-making for further analyses and assessments and could not be comprehensive.
- Given the significant overlap with terms and mission areas of emergency preparedness, disaster management, crisis management, and so on, no firm demarcations exist between them.
- Efforts were directed toward covering as many applicable research topics and publications as possible; however, due to time and funding limitations, coverage may be limited in some areas.

2.5 Analysis

A high-level analysis and landscape characterization was conducted, including an assessment of the resulting research’s potential impact in terms of interoperability and implementation. The

[1] Scopus is a scientific database with abstracts and references from thousands of publishers, including scientific journals, books, and conference proceedings, covering research topics across scientific and technical disciplines.

[2] PATSNAP is an AI-powered patent analytics tool that uses machine learning to analyze patent data.

[3] Quid is an AI-powered commercial software tool for data analysis and visualization of indexed resources, consumer data, and market intelligence.

overall analysis is summarized in section 5.0. A detailed description of the impact assessment methodology is available in Appendix A.

2.6 Final Output

Findings were combined into an annotated bibliography in the form of a spreadsheet available separate from this report. The spreadsheet includes a separate README tab with user-friendly instructions for how to sort, filter, and search over 300 publications. The spreadsheet was organized per the following outline:

- Summary of the research or abstract
- EM capability gap addressed
- Source of funding
- Emerging technology associated with research
- Interoperability or multipurpose use assessment
- Impediments or barriers to implementation.

3.0 Key Findings

The following sections summarize key findings from the literature review, with a focus on the most common themes and areas of need, overlap, and opportunity identified across the research. This review, conducted over an approximately 4-month timeframe, explored EM research topics in publicly available, peer-reviewed documents published by academic institutions, research centers, and national laboratories between 2018 and 2023. The review sought to capture as many applicable research topics and publications as possible; however, due to time and funding limitations, coverage may be limited in some areas. The research captured in this review and the annotated bibliography is relevant at the time of publication and results could be updated or expanded pending future funding.

3.1 Possible Capability Gaps for Future Research Efforts

3.1.1 Limitations of Current Information Management Systems

Information management systems are used to improve the common operating picture and situational awareness among responders and responding agencies. Within the parameters of the review, PNNL researchers identified a common theme where consensus is clear between institutions: a need persists to improve existing information management systems, particularly during large-scale events with multi-jurisdictional responses that require the activation of mutual aid agreements. R&D to support information management system improvements must be scalable, flexible, easy to use, and interoperable with existing systems and between agencies. Studies from primarily academic institutions state the current information management systems used to coordinate large-scale events do not meet the needs of the responding communities.

The literature review highlighted detailed evaluations of existing information management systems, often proposing priorities for future research. This review did not extend to the private sector. Example research on this topic includes the following, not in order of prioritization:

- In a survey-informed study conducted by the University of Washington (UW), current communication information management systems (CIMS) lack the ability to support emergency managers during large-scale events (Scholl & Holdeman, 2023).
- Also from the UW, Ganji et al. (2019) describe obstacles in information sharing at a regional disaster exercise. They found that under the structured organizational framework of the Incident Command System (ICS), technology breakdowns manifest a problem rather than the cause for computational issues. The authors state “computer issues were as likely to be caused by unclear processes as technical issues.” This could include a lack of training and an infrequency of using designated systems.
- At Texas A&M University (TAMU), researchers developed an “integrative framework for performance analysis of disaster management system-of-systems” to support “integration between heterogeneous systems and entities involved in disaster management impacts coordination and operational efficiency” (Fan & Mostafavi, 2020).
- Researchers at the University of Delaware and Oklahoma State University investigated how established and trusted relationships may have a significant [positive] impact on the effectiveness of ICS implementation (Ray Change & Trainor, 2018).
- Duke University and North Carolina State University provided a thorough analysis of how the hierarchical structure of ICS does not reflect the actual response actions in a large-scale disaster impacting multiple jurisdictions (Nowell & Steelman, 2019).
- Research explored the potential for integrating satellite technology into existing wireless communication systems to support a common operating picture (Georgetown University: Wood & Frazier, 2022).

The following are identified tangible solutions in the research that may support segments of information sharing or have significant potential to supplement or complement current efforts:

- University of Missouri developed a “Hierarchical cloud-fog platform that provides augmented reality benefits with real-time human communication and geolocation services through the integration of a standardized [ICS] with smart devices” (Jiang et al., 2019).
- National Institute of Standards and Technology (NIST) evaluations of technologies that utilize 5G cellular networks while integrating data between devices (Liu et al., 2023).
- Cloud-like service using mobile edge computing for search and rescue operations (Bhunia, et al., 2022). Collaboration between TAMU and NIST.
- Suite of PNNL-developed tools that “utilize satellite imagery to generate timely damage assessments with revealing detail.” This includes the Risk Analysis Framework for Tropical Cyclones, Rapid Analytics for Disaster Response, and the Rapid Infrastructure Flood Tool (PNNL, 2019).
- PNNL crisis mapping using an informatics ecosystem by integrating Internet-of-Things (IoT) data, social media, and smartphone messages (Walker et al., 2018).
- University of Nebraska at Omaha developed the Real-Time Emergency Communications System for HAZMAT Incidents (REaCH), an IoT real-time interactive dashboard to monitor responder health and exposure data (Fruhling, Yoder & Jonnalagadda, 2023).

These research topics may address the integration of disparate information sources, such as IoT or social media. They may also address integrating data streams, such as available satellite data, first responder exposure data, and traffic data. However, the literature review results did

not yield a proposed single system to replace existing information management systems as an alternative solution. The identified gap is a lack of interoperability and scalability in existing information management systems with large-scale, multi-jurisdictional response. Further investigation could explore feasible solutions to improve interoperability and scalability in information management systems.

3.1.2 Information Technology Professionals Missing or Underrepresented in the Emergency Operations Center

Research indicated a lack of partnerships with the EM community and information technology and telecommunications professionals. This professional disparity may contribute to communication and data integration challenges in emergency operations centers (EOCs). As stated above, Ganji et al. (2019) found that the individual's uncertainty or lack of training in operating the computer system was as likely to lead to a technical issue as a computer issue.

Including IT professionals in crisis response actions and maintaining a seat in the EOC for training and program utilization support could lead to better overall response results (Romano & Albrecht, 2023; Stapleton et al., 2022).

3.2 Potentially Complementary or Overlapping Research

To support exploration of future investment opportunities in EM research, the following section summarizes institutions conducting research in similar, complementary, or supplemental EM topics.

3.2.1 Social Media Analytics

Several academic institutions and national laboratories are conducting R&D in social media analytics. Due to the topic's broad scope and institutions' specific priorities, not all research agendas are identical, but the intent is similar: researchers are examining ways to standardize ingestion from social media platforms and develop usable information for response efforts. Research was categorized into different capability need categories based on the scope (e.g., classification frameworks are categorized as data integration, and frameworks focused on geotagging social media posts for situational awareness are categorized as 3D geolocation). The gaps these research projects are attempting to resolve are different. Further research could explore whether the needs are sufficiently similar to spark collaboration of efforts.

Example overlapping research agendas identified in the literature review include the following:

- Both George Mason University (Purohit et al., 2018; Pandey et al., 2020) and Purdue University (Kumar et al., 2018) developed models to support efforts to classify and categorize social media information to promote effective responses to help requests during a disaster. George Mason University developed both the "CitizenHelper-Training" and "Social-EOC." See details on George Mason University research in section 4.3.2 and Purdue University research in section 4.3.5.
- Georgia Institute of Technology (GA Tech) and Oak Ridge National Laboratory (ORNL) are developing models for geotagging social media information to support response (Kar et al., 2019; Suprem & Pu, 2019; Salley et al., 2021). Overlap may exist between researchers at GA Tech and with ORNL.
- A Bidirectional Encoder Representations from Transformers (BERT) model is being used to support data integration and geotagging of social media posts at George Mason University,

TAMU, and the University of Texas at Austin (Chen et al., 2021; Fan, Wu, Mostafavi, 2020; Hembree et al., 2021; Powers et al., 2023).

3.2.2 Artificial Intelligence and Machine Learning Integration

Some parallel, supplemental, or complementary research exploring artificial intelligence (AI) and machine learning (ML) techniques that are part of potential solutions in different capability gaps includes the following:

- Research at GA Tech by Suprem et al. (2019) identifies end-to-end collaboration systems as part of a possible solution to support geotagging social media posts and improving situational awareness.
- TAMU and Old Dominion University are developing deep-learning damage assessment architecture based on satellite images (Kaur et al., 2023; Pour & Gheorghe, 2020).

For this landscape assessment, efforts were concentrated on 2022 and 2023 research within the AI/ML Scopus cluster topic. The broad technical literature search yielded ~200 articles in this cluster topic. Further analysis on AI/ML in EM applications will be provided in the AI landscape assessment to be delivered in a future EMOTR task.

3.2.3 Community Resilience

Institutions researching community resiliency provide insight into how improving preparedness and mitigation efforts will positively impact both the communities and EM agencies in the communities. Research in community resilience fits in multiple capability needs but had a common goal of increasing the general awareness of community resilience characteristics. Gaps identified in the research include social inequality in community resiliency planning, lack of defining characteristics for resilient communities, and the inability to use data streams to improve urban resiliency. Gaps are tackled with different techniques, and the identified needs between the research can also be very different. However, since the primary goal of increasing knowledge and awareness in community resilience is the same in much of the research, collaboration or awareness of research in community resilience will be crucial for researchers and operators alike.

Examples of identified overlapping, supplemental, or complementary research include:

- George Mason University (Purohit & Moore, 2018; Nguyen et al., 2021) and GA Tech (Wang & Taylor, 2019) are both investigating community resiliency characteristics and developing potential frameworks and repository databases to standardize characteristic traits.
- ORNL developed a spatial microsimulation model framework to provide social system representations while protecting individual privacy (Tuccillo et al., 2023).

Additional institutions are researching community resilience that currently do not have an associated technology or identified solution but may provide additional perspectives:

- The Virginia Commonwealth University and University of California at Irvine (Baker & Grant Ludwig, 2018) conducted research on public preparedness and the perception of public authorities at disaster preparedness institutions.
- The University of Michigan (Islam, Wahab & Benson, 2020) assessed the disaster-prone country of Bangladesh, finding the country began implementing a bottom-up approach with an emphasis on community participation. Similar research conducted as an international collaboration with the University of Manchester, the University of Texas at Austin, and the Ohio State University (Rumpa et al., 2023) also assessed Bangladesh. This study

investigated what was implemented as effective disaster risk reduction efforts, comparing damages from the 1988, 2004, and 2022 floods.

- Bowling Green State University conducted a study in 2020 on the potential impacts from completeness and effectiveness of local EM agency websites. Their findings suggested that the lack of uniformity could impact public knowledge in disaster response (Schmalzried et al., 2020).

Community resiliency can also incorporate coastal resiliency. The Coastal Resilience Center (CRC) is a DHS Center of Excellence led by the University of North Carolina at Chapel Hill and partners with many other coastal academic institutions. Through open-source information on the CRC website, active projects are researching how to support communities in disaster resiliency planning. It may be worth further investigation to identify overlapping or complementary research agendas at academic institutions not currently partnered with CRC. For example, the University of Central Florida investigated how Smart City applications, such as IoT and crisis informatics, increased “disaster resiliency” in coastal communities (Tonmoy, Hasan & Tomlinson, 2020). They do not have a current partnership with CRC.

3.2.4 Satellite Technology

The literature review results included research using different applications of satellite technology. Between 2018 and 2023, published research using satellite imagery and analytics has remained consistently prevalent in EM topics. Further investigation may help identify if research among institutions share commonalities or have the possibility of multipurpose applications.

Example research includes:

- At TAMU, researchers are developing deep-learning models where AI/ML supports damage assessments using satellite images (Kaur et al., 2023). Similar research using satellite images and ML techniques was conducted in 2020 at Old Dominion University (Pour & Gheorghe).
- At Georgetown University, researchers are investigating how satellite technology can be paired with emerging communication capabilities to develop a “common operating picture for all actors” (Wood & Frazier, 2022). This study provided evidence that satellite technology paired with other technologies provides a necessary redundancy for emergency communications.
- PNNL developed a suite of tools utilizing satellite imaging to support multi-formalism modeling for disaster forecasting, response, and promoting infrastructure resiliency (Coleman et al., 2019).

3.2.5 Emergency Response Solutions to Power Grid Issues

Research to support response efforts and reduce cascading impacts to the power grid maintained a common theme: quicker event recognition and severity determination to reduce potential impacts. The resulting research primarily focused on supporting utility operations rather than emergency managers. However, the ability to integrate this crucial information into EOCs or have a reliable way of communicating with emergency managers may warrant further investigation.

Examples from the range of identified research include:

- University of California, San Diego and San Diego State University (Bayani et al., 2023) researched power shut-offs to reduce wildfire ignitions.

- Argonne National Laboratory (ANL) (Xu et al., 2020) researched weather forecasting to anticipate power line hardening locations.
- ANL (Huang et al., 2018) examined cyber and physical network interrelations.
- GA Tech (Muralidhar et al., 2020) researched temporal segmentation framework to better understand power outage patterns.
- TAMU (Zang et al., 2020) explored using social media analytics to track social impacts of community disruptions.
- Massachusetts Institute of Technology (MIT) Lincoln Laboratory (Kratkiewicz, 2019) created a prototype for mapping power outages through IoT.
- The National Renewable Energy Laboratory (NREL) (Satkauskas et al., 2023) and ANL (Lei et al., 2018) are conducting independent research in emergency generation locations to support power losses during disasters.
- PNNL (Khatana et al., 2022) developed a horizon of viability engine to support power to critical infrastructure during catastrophic incidents.
- ORNL (Kar and Ethridge, 2019) researched geotagged social media information to track power outage and restoration patterns.
- PNNL (Quarm et al., 2022) researched proactive posturing of the power system components, informed by hurricane modeling.
- University of Maryland (Khanna, Panigrahi & Joshi, 2020) proposed a strategy to secure power system operations against cyber threats, specifically false data injections.

3.2.6 Improving Evacuation Responses

Understanding mobility decisions and time spent displaced during disasters are focal points at Purdue University. Research published by North Dakota State University and NIST may overlap or complement Purdue University research. Topics include:

- Research conducted at North Dakota State University explored a data-driven predictive framework that incorporates traffic uncertainty factors using ML approaches with spatiotemporal data sources (Afrin et al., 2023). Similar NIST research used a Bayesian Model Averaging model to address model uncertainty for influential factors in emergency traffic management (Zou et al., 2021).
- Research conducted at Purdue University used an evacuation simulator called A-RESCUE 2.0 to help support development of real-world connections (Gehlot et al., 2019).
- Purdue University evaluated social media information and the influence on mobility decisions following an evacuation (Yabe et al., 2021).
- Research at Purdue University also explored social media platforms used to support humanitarian aid efforts (Kumar et al., 2018).

3.2.7 Smart City Applications and Informatics Ecosystems

Smart cities are a concept of a city that uses a network of sensors and data collection devices (IoT) to efficiently operate or provide services. Smart cities use cybersecurity and AI/ML models to protect and learn about their systems and communities.

Example research identified in the literature review includes:

- Idaho State University: Employing ML and IoT for Earthquake Early Warning System in Smart Cities, (Abdalzaher et al., 2023).
- MIT Lincoln Lab: An Eye on the Storm: Tracking Power Outages via the IoT (Kratkiewicz, 2019).
- PNNL: Developing a Crisis Informatics Ecosystem for Smart Cities: Geosciences and Remote Sensing (Walker et al., 2018).
- PNNL: IoT System for Collecting Vital Signs and Geographic Location Data of Mobile Users (Yang et al., 2020).
- Northern Arizona University: Green IoT using unmanned aerial vehicles (UAVs) in B5G networks: A Review of Applications and Strategies (Alsamhi et al., 2021).
- University of North Texas: SBPG: Secure Better Portable Graphics for Trustworthy Media Communications in the IoT (Mohanty, Kougianos & Guturu, 2018).
- Previously identified in the community resilience section, the University of Central Florida connects Smart City technologies with the purpose of improving community resiliency.
- University of Nebraska Omaha: An IoT Dashboard Monitoring First Responders' Health and Environmental Data during HAZMAT Emergencies (Fruhling, Yoder & Jonnalagadda, 2023).

3.2.8 Critical Infrastructure Damage Assessment

Institutions developing critical infrastructure damage assessment methods may be focused on confronting gaps in different EM mission areas. Some focus on developing models to provide predictive analytics before disaster strikes. Others are attempting to solve the problem of integrating a vast amount of information in real time. Both are important and have potential for a feedback loop where improving situational awareness with predictive analytics improves real-time response. Further examination could explore whether collaborative opportunities and similar research goals exist between research in predictive analytics and during response efforts for critical infrastructure damage assessments.

Example research for predictive analytics or models to support efforts before emergencies occur includes:

- Purdue University is utilizing social media networks for resource disbursement efforts (Kumar, Yabe & Ukkusuri Lyles, 2018).
- ORNL is developing a model of models to assess and predict critical infrastructure impacts (Kar et al., 2020).
- ORNL's Urban-NET provides a networked graph of interdependent critical infrastructure systems to help detect cascading impacts.
- Models from George Mason University and TAMU are using social media data to determine infrastructure failure and restoration efforts (Chen et al., 2021; Zhang et al., 2020).
- PNNL is using a multi-formalism modeling platform used to improve situational awareness (Coleman et al., 2019).
- A multi-national laboratory collaboration in the North American Energy Resilience Model is developing state-of-the-art modeling tools to support decision-makers in energy infrastructure and interdependent systems evolving challenges.

Example research developed for response efforts during emergencies includes:

- Lawrence Berkeley National Laboratory (LBNL) is using robotics for infrastructure scanning during disasters to construct 3D images for classification (Wudunn et al., 2020; GA Tech: Yajima et al., 2021).
- ORNL is researching a temporal segmentation framework to capture major pattern changes during power outages (Muralidhar et al., 2020).
- PNNL is researching crisis mapping using an informatics ecosystem by integrating IoT data, social media, and smartphone messages (Walker et al., 2018).
- PNNL developed a suite of tools utilizing satellite imagery for timely damage assessment, including the Risk Analysis Framework for Tropical Cyclones, Rapid Analytics for Disaster Response, and the Rapid Infrastructure Flood Tool (PNNL, 2019).

4.0 Results

The following sections discuss overall findings, trends in the research and patent landscape, and activities at the forefront of technical and patent literature. The broad technical literature search (2018 to present) resulted in nearly 36,000 records. This was narrowed to a smaller subset of over 1,600 based on terms highly associated with EM such as first responders, EOCs, emergency call centers, emergency preparedness, firefighter, etc. Narrowing the dataset may have omitted terms that could be valuable for a broader analysis but were necessary for delivering a manageable dataset. Figure 2 shows a visual representation of this reduced set. The figures in this section demonstrate the Quid clustering of literature data reviewed in this assessment.

4.1 Network View

The network view shown in Figure 2 provides a visual aid for understanding the broad topic areas covered in the dataset. The proximity of the clusters also reveals general topic areas such as visual analytics, human-centered research, and data science.

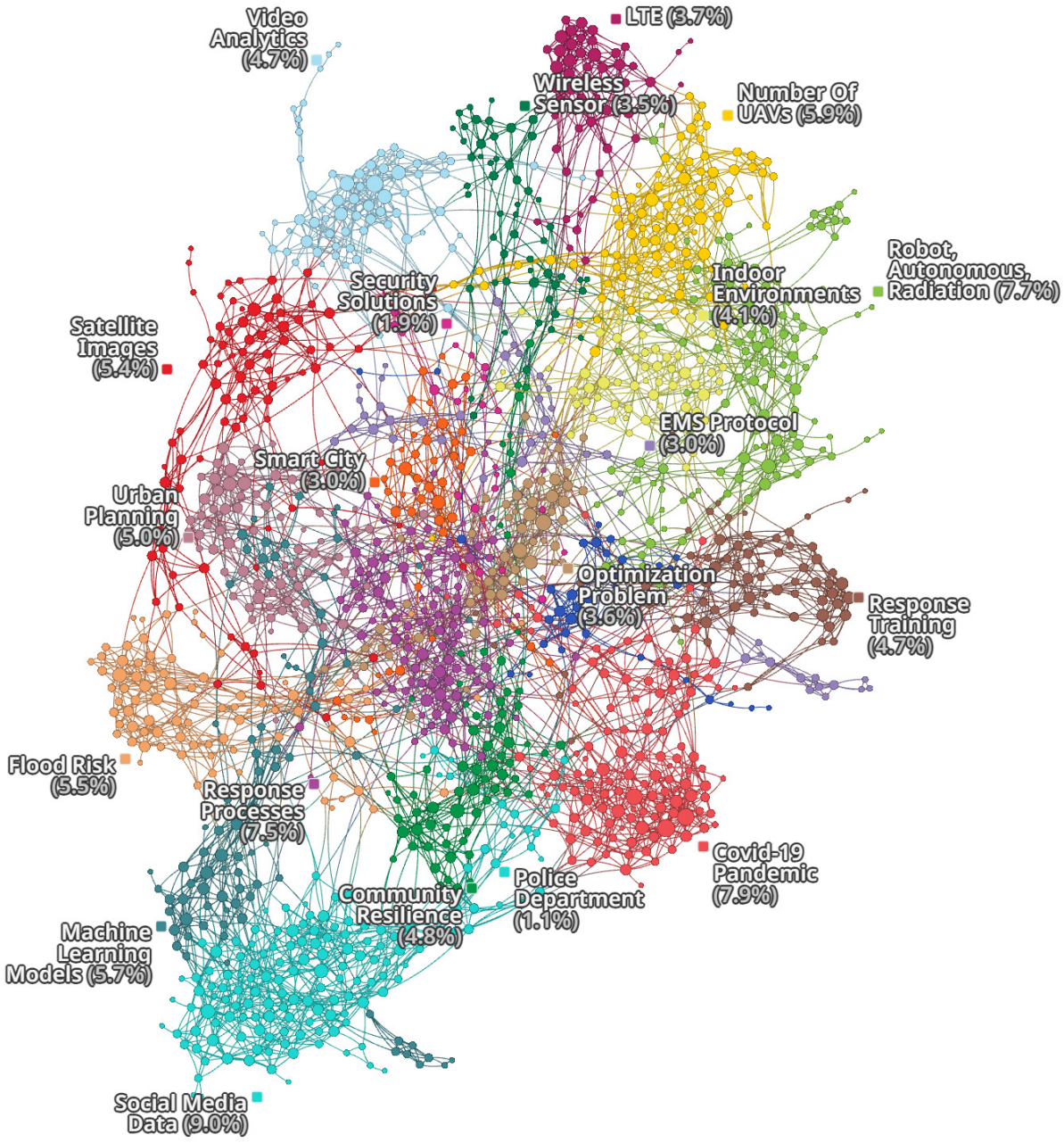

Figure 2. Network View

4.2 Bar Chart

The bar chart in Figure 3 shows the publication count per cluster. The Social Media Data and COVID-19 Pandemic clusters show the most activity. Other prominent topic areas include Robots, Response Processes, Machine Learning Models, Flood Risk, Satellite Images.

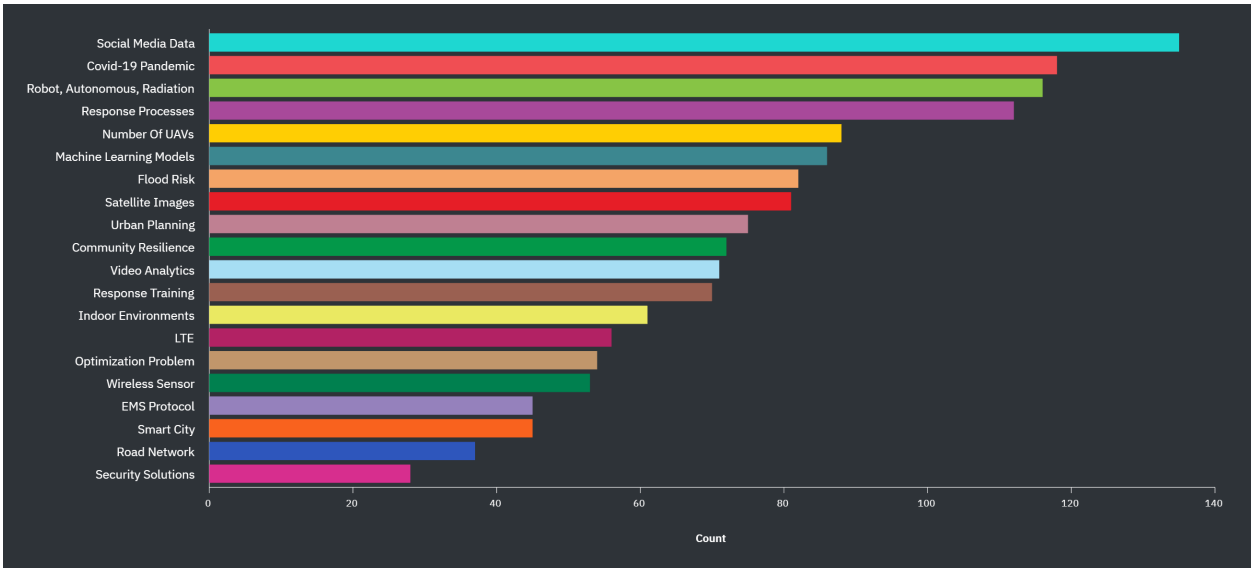

Figure 3. Bar Chart by Cluster

4.3 Top 5 Organizations Based on Publication Volume

The first down-selecting search results used included the top five organizations publishing in relevant topics based on publication volume. The Scopus search resulted in 1,526 peer-reviewed publications in the search string: “emergency operations centers,” “emergency call center,” “emergency preparedness,” “911 call center,” “fire fighter,” “first responder,” “emergency response,” “emergency management,” “disaster management,” “Public safety,” “disaster science.”

The search string is outlined below:

187 document results
(TITLE-ABS-KEY (“emergency operations centers “ OR “emergency call center” OR “emergency preparedness” OR “911 call center” OR “fire fighter” OR “first responder” OR “emergency response” OR “emergency management” OR “disaster management” OR “Public Safety” OR “disaster science”) AND AFFILCOUNTRY (“united states”) AND SUBJAREA (comp)) AND PUBYEAR > 2017 AND (LIMIT-TO (AF-ID , “Purdue University” 60009254) OR LIMIT-TO (AF-ID , “George Mason University” 60018319) OR LIMIT-TO (AF-ID , “Georgia Institute of Technology” 60019647) OR LIMIT-TO (AF-ID , “Texas A&M University” 60020547) OR LIMIT-TO (AF-ID , “National Institute of Standards and Technology” 60023053))

From these results, the top five organizations ranked by publication volume were identified and separated for a smaller set of data at 187 results. Institutions included George Mason University, GA Tech, NIST, Purdue University, and TAMU.

Figure 4 summarizes document volume by university or affiliation.

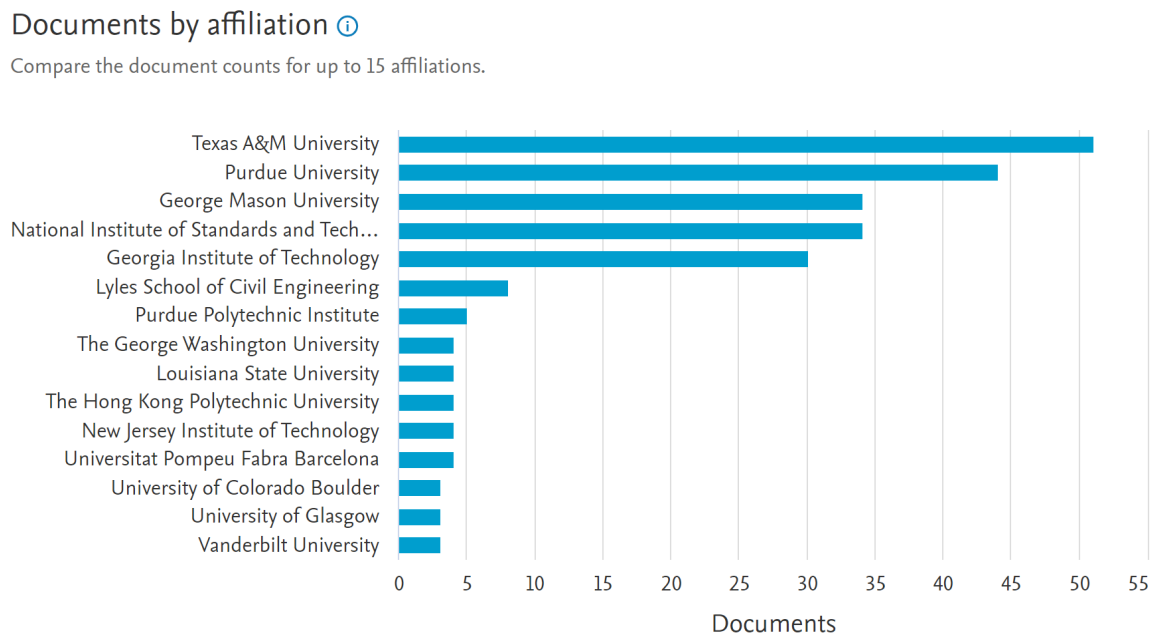

Figure 4. Publication Volume by Affiliation

From these results, the journal articles were reviewed and determined whether they had applicability for further analysis. Applicability was determined based on whether an associated emerging technology was included in the research, or the research specifically cited technology applications in EM functions. Primary research topics were determined based on publication volume. Secondary research topics include areas with more than one publication or discussion of a new technology in a topical area. The results per organization are summarized below.

4.3.1 Funding Information

Figure 5 summarizes the research results by funding sponsor, showing the National Science Foundation as the top funding source.

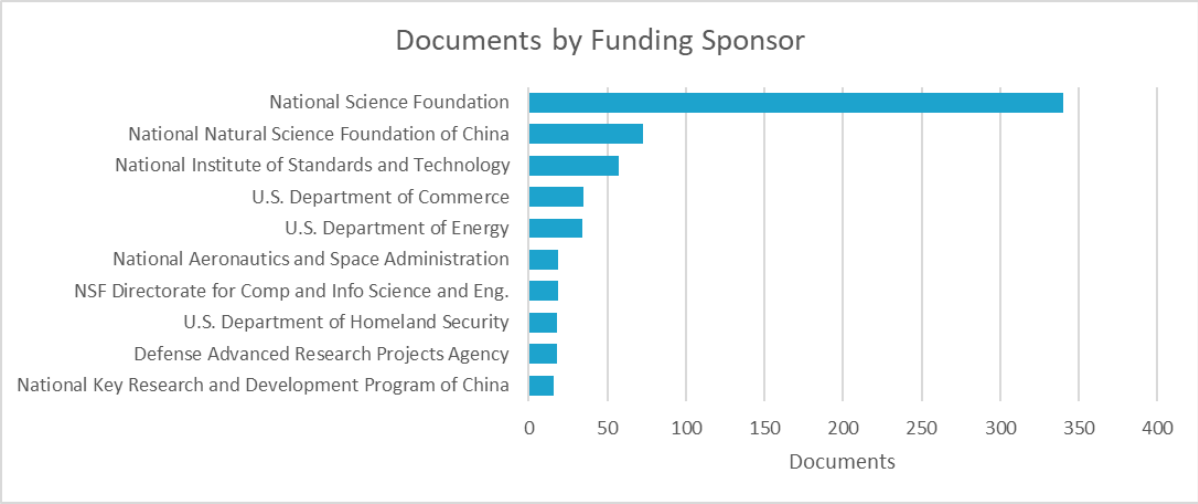

Figure 5. Documents by Funding Sponsor

4.3.2 George Mason University

Primary research topic: *Social media platforms and potential uses in emergency response.*

Technologies/Research Areas

Disaster Knowledge Graph (KG): DisasterKG, with deep learning-based KG embedded, may support timely access to information. (Purohit H.; Kanagasabai R.; Deshpande N., 2019)

Social-EOC: A formal model of serviceability that describes the elements of a serviceable message posted on social media expressing a request. Using the serviceability model, the authors describe a system for the discovery and ranking of highly serviceable requests and for re-ranking requests by semantic grouping to reduce redundancy and facilitate the browsing of responder requests. (Purohit, H.; Castillo C.; Pandey, R., 2018)

BERT model to track electricity-related posts: Mining social media for electricity-related social media analytics posts are extracted by the classifier developed from the (BERT). Public topics are modeled with unigrams, bigrams, and trigrams to incorporate the formulaic expressions of infrastructure conditions in social media analytics. (Chen, Y.; Yang, C.; Umana, A.; Ji, W., 2021)

Decoding linguistic ambiguity: Using a new model that can detect real emergency tweets with a high classification accuracy by using a transfer learning model BERT for emotion classification and behavior modeling approach to detect tweets in Twitter/X disaster datasets. In doing so, the authors hope to provide a great service in identifying relevant, real-time information to first responders. (Hembree, A.; Beggs, A.; Marshall, T.; Ceesay, E.N., 2021)

CitizenHelper-training: AI technologies have been explored in response operations and less in preparedness and mitigation [mission areas] of EM. To address this, an AI-infused system for multimodal analytics (IoT sensor streams and video recordings) to reduce overload and extract relevant data during emergencies. The system has been used during training exercises. (Pandey, R.; Bannan, B.; Purohit, H., 2020)

Responders-360 system architecture design for object detection: First responder training that includes “latency-aware Viewing and Query Service” with 360-degree object detection. The study used data collected from a firefighting institute, although considerations for the system architecture in EM [mission areas] can be explored. (Li, J., et al., 2023)

Resilience data repository: A general architecture for a resilience data repository that enables communities to adopt a general methodology for collecting, storing, managing, and sharing resilience-based information. (Nguyen, H.L.; Purohit, H.; Senarath, Y.; Akerkar, R., 2021)

The digital crow’s nest: A technology to assist emergency managers in preparedness and mitigation efforts, focusing on resilient community characteristics. Taking data from disaster case studies on relevant technology gaps and associated resiliency characteristics, the authors propose a “framework for proactive disaster informatics and resilience by open-source intelligence.” (Purohit, H.; Moore, K., 2018)

4.3.3 Georgia Institute of Technology

Primary research topic: *Human-agent teaming.*

Technologies/Research Areas

Improving human-agent team performance using real-time participant behaviors: Giving AI systems the ability to accurately model the human decision-making process in real time, enabling the creation of proactive decision support systems and improving overall human-agent teaming. (Walsh, S.E.; Feigh, K.M., 2022)

End-to-end collaborative drift adaptive system: Integrates corroborative and probabilistic sources to deliver real-time predictions. To address the drift phenomenon, real-world data exhibits continuous changes in data distribution, rendering ML models ineffective long-term. This system is adaptive to concept drift and performs continuous learning. (Suprem, A.; Pu, C., 2019)

Instance point cloud segmentation: Used to develop 3D point clouds in real time. A neural network, named Dynamic Graph PointNet (or DGPointNet), is trained to classify objects in the disaster environment while building up a semantic 3D map of the environment by mobile robots. (Yajima, Y.; Kim, S.; Chen, J.; Cho, Y.K., 2021)

Semi-supervised ML framework: Enhances the speed of emergency response by integrating natural language processing and spatiotemporal analytics, augmented by social media analytics with a community-driven application (Waze) to better identify precise geolocations of an emergency. (Salley, C.; Mohammadi, N.; Taylor, J.E., 2021)

4.3.4 National Institute for Standards and Technology

Primary research topic: *First responder communication – analysis of gaps and needs with available tools.*

Technologies/Research Areas

Public safety communication technology landscape with a focus on rural communities: The authors completed 63 semi-structured interviews and 2,698 surveys to explore the communication technology problems and identified the most persistent problems they reported. (Buchanan, K., Choong, Y.-Y.; Dawkins, S.; Prettyman, S.S., 2023)

Text REtrieval Conference Incident Stream: Developed standard approaches for classifying critical information from online sources during disasters and emergencies, particularly in the wake of COVID-19. This paper provides a description of 2020 and the introduction of a new COVID-19-specific evaluation task. (McCreadie, R.; Buntain C.; Soboroff I., 2021)

Resilient disaster communications network architecture: The resilient architecture design considers layers in information and networks that work together to support communication and data processing in disaster management. (Ramakrishnan, K.K.; Seferoglu, H.; Yuksel, M.; Chen, J.; Blalock, R.A., 2021)

Public safety communication technology landscape: NIST-led, multi-phase research studies on first responder communications. Includes 193 in-depth interviews and 7,182 surveys. (Dawkins, S.; Morrison, K.; Choong, Y.-Y.; Greene, K., 2021)

Proximity Services (ProSe): Support mission-critical voice applications in rural areas by enabling device-to-device communication. Through a Network Simulator 3 simulation, results

show ProSe to outperform Wi-Fi in coverage range and access time. (Garey, W.D.; Sun, Y.; Rouil, R.A., 2020)

Distributed resource allocation schemes: Investigation of resource allocation schemes for out-of-coverage device-to-device group communication. Designed three distributed resource allocation schemes and conducted extensive performance evaluations in a variety of scenarios. (Wang, J.; Rouil, R.A.; Cintron, F.J., 2019)

Text Retrieval Conference Incident Streams: Brings together academia and industry to develop techniques for extracting actionable insights from social media streams during emergencies. (Buntain, C.; McCreadie, R.; Soboroff, I., 2020)

EdgeKeeper: Provides a holistic coordination approach to mobile edge cloud, with naming, network management, application coordination, and security to distributed edge computing applications. It maintains an edge cluster among devices and intelligently stores its data on a group of replicas to guard against node failure and disconnections. Collaboration with TAMU A&M University. (Bhunia, S.; Stoleru, R.; Haroon, A.; Sagor, M.; Altaweel, A.; Chao, M.; Maurice, M.; Blalock, R., 2020)

4.3.5 Purdue University

Primary research topic: *Citizen science (i.e., citizen responders, social media analytics).*

Research describes accessing and utilizing social media information and citizen response behaviors for myriad emergency response actions.

Technologies/Research Areas

Data-driven framework for post-disaster decision-making: With increasing natural disasters, response and recovery actions need to be understood and somewhat predicated using models and frameworks. This includes behaviors on evacuation and returning after a disaster. Social ties impact mobility decisions. The authors propose a data-driven framework to help predict post-disaster decisions from social media information to better understand the dynamics and influence social media platforms have on response and recovery actions. Tested on data collected from Hurricane Sandy. (Yabe, T.; Rao, P.S.C.; Ukkusuri, S.V., 2021)

Social media-aided hyperlocal help network to support resource disbursement to hurricane-affected residents: Rather than a centralized help disbursement model, social media information from Twitter/X identifies users and connects them with local volunteers. This can also be used to support disseminating information on road infrastructure damage to support efforts. (Kumar, D.; Yabe, T.; Ukkusuri Lyles, S.V., 2018)

Citizen responders: Utilizing medically trained volunteers in the community can provide life-saving response actions before the ambulance arrives. This research intended to “investigate the decision problem of dispatching ambulances for priority-differentiated emergencies” and when citizen responder real-time information is utilized. Their results could lead to a more reliable system in incorporating citizen responder support. (Paz, J.C.; Kong, N.; Lee, S., 2022)

Framework for the analysis of social media group behavior during an emergency: Social media analytics to examine group behaviors using tweets during Hurricane Harvey in 2017. The

framework is intended to increase understanding in group interactions to develop operational strategies for communicating with the public. (Kim, J.; Park, H., 2019)

Assessment on Social Media Analytics and Reporting Toolkit (social media visual analytics system on first responder operations): This DHS-funded research interviewed first responders about the barriers to using social media data for situational awareness during disasters. (Snyder, L.S.; Karimzadeh, M.; Stober, C.; Ebert, D.S., 2019)

Interactive learning framework to address challenges in the classification process: Challenges include “high noise in the deluge of data,” “effectively determining semantically relevant information,” “changing definition of relevancy by each end user for different events,” and “classifiers cannot be interactively retrained for specific events or user-dependent needs in real-time.” The authors developed an interactive learning framework to improve the classification process; their results suggest the approach outperforms state-of-the-art ML models. The framework was also integrated with the extended Social Media Analytics and Reporting Toolkit (or SMART) 2.0 system and elicited first responder feedback on the effectiveness. (Snyder, L.S.; Lin, Y.-S.; Karimzadeh, M.; Goldwasser, D.; Ebert, D.S., 2020)

Communication infrastructure: After a disaster damages public infrastructures and telecommunications, network resources are set up to help “bridge the communication gaps.” The authors propose to design, develop, and test a strategy for more efficient temporary communication infrastructure with intelligent deployment. They suggest that the resource deployment problem is an “integer linear programming optimization problem and show [its non-deterministic polynomial-time hardness].” The solution is a “near-optimal polynomial-time heuristic solution.” Their results suggest this strategy “outperforms its variant and baseline approaches when compared in terms of end-to-end network latency and message delivery.” (Hazra, K.; Shah, V.K.; Silvestri, S., et al. 2020)

Evacuation simulator A-RESCUE 2.0: An agent-based regional evacuation simulator coupled with user-enriched behavior to support more effective evacuations with traffic flow pattern considerations. Experimentation on the Miami-Dade County network suggests the parallelization scheme effectively improved computational performance. (Gehlot H.; Zhan X.; Qian X., et al. 2019)

DroneCOCoNet: A framework for drone video analytics that intelligently processes large video datasets using edge computational offloading. (Qu, C.; Calyam, P.; Yu, J., et al., 2021)

Unmanned aerial system (UAS) traffic management: The authors discuss the challenges and potential solutions through collaborative efforts with key stakeholders (e.g., “transportation, aviation, communications, networking, control, information systems, big data, computing, and cyber-physical systems”). (Wan, Y.; Atkins, E.; Sun, D., et al., 2021)

Method for cloud instances selection: Accessing real-time network cameras for public safety actions. Lower-cost alternative to pay-per-use cloud computing. Experiments using Amazon Elastic Compute Cloud-validated the method. (Mohan, A.; Kaseb, A.S.; Lu, Y.-H.; Hacker, T.J. 2021)

Data processing framework using multimodal sources: Evaluated in applied use cases in public safety regarding the effects the framework had on situational awareness. (Nesen, A.; Bhargava, B., 2021)

4.3.6 Texas A&M University

Primary research topic: *Flood impacts assessment during response and recovery efforts.*

Many authors cited the impacts from Hurricane Harvey in 2017 as the catalyst for their research.

Technologies/Research Areas

Deep-learning model: FastGRNN-FCN (or Fast, Accurate, Stable, and Tiny Gated Recurrent Neural Network-Fully Convolutional Network) for urban flood prediction and situational awareness. Harris County, Texas served as the testbed. The model showed accurate prediction for spatial-temporal flood propagation to provide emergency response professionals with warning tools. (Dong, S.; Yu, T.; Farahmand, H.; Mostafavi, A., 2021)

Crowdsourcing for urban flood planning: Utilizing crowdsourcing photos of submerged stop signs and comparing to pre-flood photos, the photos were then analyzed using a deep neural network and image processing for floodwater estimations and provided the most effective and optimal flood-free path for search and rescue or evacuation pathways. (Alizadeh, B.; Li, D.; Zhang, Z.; Behzadan, A.H., 2021)

Hybrid ML pipeline using geotagged social media data to improve situational awareness during disasters. Using a fine-tuned BERT model to classify posts and a graph-based clustering for situational information. Used with the dataset collected during Hurricane Harvey in 2017. (Fan, C.; Wu, F.; Mostafavi, A., 2020)

UAVs in preliminary disaster damage assessments: Using two convolutional neural network (CNN) models (Mask Region-based CNN and Pyramid Scene Parsing Network), UAVs could be trained to detect countable and bulk objects. They could then be used to support disaster damage assessment during response and mitigation actions. (Pi, Y.; Nath, N.D.; Behzadan, A.H., 2020)

AI in building damage classification: More comprehensive visual data than in most current practices in the form of multiple ground and aerial views of the buildings using a multi-view CNN architecture that combines different views of the damaged infrastructure. The developed model demonstrates reasonably good accuracy in predicting the damage levels and can be used to support more informed and reliable AI-assisted disaster management practices. (Khajwal, A.B.; Cheng, C.S.; Noshadravan, A., 2022)

Damage assessment using a hierarchical transformer architecture: A novel deep-learning model to classify building damages based on satellite images post natural disasters. (Kaur, N.; Lee, C.C.; Mostafavi, A.; Mahdavi-Amiri, A., 2023)

Semiautomated social media analytics: Approach for social sensing of Disaster Impacts and Societal Considerations (or SocialDISC). To understand societal impacts caused by community disruptions (e.g., power outages or road closures), SocialDISC labels and clusters posts to be more easily scanned by analyzers. This approach will help analyzers better understand the relationship between disruptions of infrastructures and societal impacts. (Zhang, C.; Yao, W.; Yang, Y.; Huang, R.; Mostafavi, A., 2020)

Disaster City digital twin paradigm: Developed as a unifying paradigm to aid the fragmented research in disaster management, this paradigm includes multi-data sensing for collection, data integration and analytics, multi-actor decision-making, and dynamic network analysis. Integration of AI algorithms to improve situation assessment. (Fan, C.; Zhang, C.; Yahja, A.; Mostafavi, A., 2021)

Human augmentation technologies in the form of use-inspired exoskeletons, a human-centered AI-enabled training framework: Providing learning environments that are adaptive, affordable, accessible, and available. This article provides research considerations into these technologies in context-independent and ER-relevant scenarios. (Mehta, R.K.; Moats, J.; Karthikeyan, R.; et al., 2022)

Digital twin to improve situational awareness: Using Message Queuing Telemetry Transport to handle data transfer and created with Unreal Engine, this form of information would be helpful in both training and real-time assessment situations. (Hatch, N.; Magnussen, W.; Tao, J., 2023)

EdgeKeeper: Cloud-like service coordination to distributed edge computing applications for mobile edge cloud systems. A full-system implementation is available for Android and Linux platforms and is currently available for first responders. Collaboration with NIST. (Bhunia, S.; Stoleru, R.; Haroon, A.; et al. 2022)

4.4 Artificial Intelligence/Machine Learning and Robotics Technologies from 2023

Using the same search results, results were filtered for articles published in 2023 in clusters focusing on ML models and robotics.

4.4.1 George Mason University

Leveraging ML and simulation to advance disaster preparedness assessments through FEMA national household survey data. Public preparedness has traditionally been captured using nationwide surveys, which lack an understanding of attitudes and specific actions toward disaster preparedness. The authors developed a framework to integrate ML and simulation into public preparedness by leveraging a ML algorithm that establishes relationships and demographic characteristics. The approach's effectiveness was demonstrated by applying it to Miami-Dade County. (Jiang, Z.; Chen, Y.; Yang, T.-Y., et al., 2023)

4.4.2 Berkeley AI Research

Incidents1M: A large-scale dataset of images with natural disasters, damage, and incidents. Social media data used as a low-latency data source for real-time updates during disasters. Most methods use text-based filters to mine data and video-based filtering is not as widely explored. Authors present the Incident1M Dataset, "a large-scale multi-label dataset which contains 977,088 images, with 43 incident and 49 place categories." Code, data, and models openly available at http://incidentsdataset.csail.mit.edu. (Weber, et al., 2023)

4.4.3 Rochester Institute of Technology

MEDIC: A multi-task learning dataset for disaster image classification. A "social media image classification dataset for humanitarian response consisting of 71,198 images to address

four different tasks in a multi-task learning setup." AI support in response actions after a natural disaster. Researchers say this is the "first dataset of its kind" to include "social media images, disaster response, and multi-task learning research." (Alam, F., et al., 2023)

4.4.4 University of Texas at Austin

Moving emergency response forward: Leveraging ML classification of disaster-related images posted on social media. The public often believes the posts they publicly share during a disaster will get to first responders. This information can be difficult to find through the non-relevant content. The authors developed a framework for classifying images using "transfer learning and classifies each image using the Visual Geometry Group model 16 CNN and multi-layer perceptron classifiers according to the urgency, relevance, and time period, in addition to the presence of damage and relief motifs." (Johnson, M.; Murthy, D.; Robertson, B.W.; Smith, W.R.; Stephens, K.K., 2023)

4.4.5 University of California, San Diego

Quantifying the risk of wildfire ignition by power lines under extreme weather conditions. Wildfire risk-aware operation planning problem: Pinpoints segments of the public power network to de-energize to reduce the chances of wildfire ignitions in California. ML techniques paired with an extreme weather model. (Bayani, R.; Waseem, M.; Manshadi, S.D.; Davani, H., 2023)

4.4.6 University of Nebraska Omaha

An IoT dashboard monitoring first responders' health and environmental data during HAZMAT emergencies. REaCH project: Real-time interactive dashboard for first responders' health information and exposure information during a HAZMAT incident. This information is relayed to the incident commander for real-time monitoring of exposure levels. The REaCH application accessed the latest IoT technology with multiple IoT sensors for human and environmental information. (Fruhling, A.; Yoder, A.; Jonnalagadda, S., 2023)

4.4.7 University of Notre Dame

Configuring mission-specific behavior in a product line of collaborating small unmanned aerial systems. Drone Response: A software product line to rapidly configure/deploy autonomous small unmanned aerial systems with necessary safety properties. The approach is evaluated with validation tests and fault-based mutation testing. (Islam, M.N.A.; Chowdhury, M.T.; Agrawal, A., et al., 2023)

4.5 National Laboratory Collaboration with Academic Institutions

Using the same search results, analysis was conducted on national laboratories that partnered with academic institutions, federal agencies, and private sector companies in a variety of technologies in EM research. The following publications include collaborations between national laboratories and academic institutions on EM technologies. This resulted in 20 additional publications.

4.5.1 Argonne National Laboratory

ANL did not have a specific cluster topic identified in their published research from the Scopus results ranging from 2018-2023; however, ANL partnered with international academia in three

publications of relevance to EM. One article is not applicable to this study as it is a model for predicting crime rates. The other two articles address the following:

- **Reliable energy alternatives during natural disasters**. (Lei, S., et al., 2018)
- **Cyber-constrained power flow model** for emergency response of smart grids. (Huang, G.; Wang, J.; Chen, C.; Guo, C., 2018)

Both models were published in 2018 and may be more dated than similar models proposed recently.

ANL affiliations include the University of Chicago, Monmouth University, Università della Calabria, The University of Hong Kong, Shenzhen Institute of Research and Innovation, The University of Hong Kong, Zhejiang University, and Southern Methodist University.

4.5.2 Idaho National Laboratory

Idaho National Laboratory (INL) also did not have more than one publication in an identified cluster. Results included:

- Trouble in paradise: **Mutual awareness**, teamwork, and Hawaii false ballistic missile alert: An article in cluster “community resilience.” (Savchenko, K.; Medema, H.; Boring, R., 2018)
- Secure **mmWave cellular network for drone communication**: Employ directional beams required for “millimeter wave (mmWave) transmission in the 5G cellular system [that] can reduce interference among users” and support scalability. (Bhuyan, A.; Güvenç, I.; Dai, H., et al., 2019)
- Assessment of group dynamics during cybercrime through **temporal network topology**: An article in cluster “Robotics, autonomous, radiation.” (Asadi, N.; Rege, A.; Obradovic, Z., 2018)

The research in “community resilience” did not apply to the study and was dissimilar to the other research in the cluster:

- Asadi et al. (2018) share a study completed by Temple University from a Red Team-Blue Team cybersecurity exercise conducted at INL.

4.5.3 Lawrence Berkeley National Laboratory

LBNL partnered with University of Miami and ORNL on cluster “indoor environments,” and with University of California, Berkeley with **3D building reconstruction using drones**. The work in collaboration with ORNL is for a handheld system for chemical, biological, radiological, nuclear, and explosion monitoring and detection. The handheld system is collecting data and post-processing on a different device with a remote analyst with the intention of moving the pipeline directly to the scanner. (Salathe, M.; Quiter, B.J.; Bandstra, M.S., et al., 2022)

One publication was a conglomerate of academia and LBNL as a call to **ML experts for collaboration to address climate change** (Rolnick, D.; Donti, P.L.; Kaack, L.H.; Kochanski, K., et al. 2023). Funding for this includes MIT Media Lab Consortium, National Science Foundation, DOE, Carnegie Mellon University, and Natural Sciences and Engineering Research Council of Canada.

4.5.4 Los Alamos National Laboratory

Los Alamos National Laboratory (LANL) research in Scopus from 2018 to 2023 did not easily fit into one of the identified clusters but demonstrated relevance to EM.

- LANL research analyzed the effectiveness of using **pressure-sensitive adhesive-coated paper and paper spray ionization mass spectrometry** to detect trace amounts of explosives and illegal drugs with the presence of interferents (Carmany, et al. 2022). Affiliations with University of Indiana and U.S. Army Combat Capabilities Development Command. Another research focused on utilizing trained CNN to classify and identify objects with thermal imagery, a partnership with University of New Mexico (Bhattarai & Martinez-Ramon 2020).
- LANL is independently working on **DnMFK**, "a distributed [non-negative matrix factorization] algorithm coupled with distributed custom clustering followed by a stability analysis on dense data to determine the number of latent variables buried in large datasets." (Chennupati, G.; Vangara, R.; Skau, E.; Djidjev, H.; Alexandrov, B., 2020).

LANL partners with private sector entities (https://www.excetinc.com/) and other national laboratories while conducting their research.

4.5.5 Oak Ridge National Laboratory

ORNL published three articles that fit into the cluster "social media data":

- Assessing relevance of tweets for **risk communication**, with University of Southern Mississippi. (Liu, X.; Kar, B.; Zhang, C.; Cochran, D.M., 2019)
- **Mobility pattern analysis** for power restoration activities using geotagged tweets, with University of Tennessee (Kar, B.; Ethridge, J., 2019)
- Using social media to **geo-target EM** efforts, with Texas State University and Dalhousie University. (Kar, B.; Chow, E.; Dede-Namfo, N.; Liu, X., 2019)

Each publication identified research in social media analytics with the intent to improve situational awareness and emergency response actions.

ORNL also had several articles in the cluster "flood risk," partnering with private sector companies and academic institutions in the research from this cluster. Research included two different themes:

- **Model of models to assess and predict infrastructure impacts** (i.e., mitigation) (affiliations with Pacific Disaster Center; Indiana University; University of Missouri; Dartmouth Flood Observatory; University of Colorado; ImageCat Inc, CA (Private); Jet Propulsion Laboratory, California Institute of Technology). (Kar, B.; Bausch, D.; Wang, J., et al., 2020)
- **Impacts on the critical infrastructure systems** involving the electric power grid (affiliations with Brandeis University, Virginia Tech, Pinterest, Georgia Institute of Technology). (Kar, B.; Bobeck, J.; Moss, T.; Hughes, D., 2021; Muralidhar, N.; Tabassum, A.; Chen, L., et al., 2020)

ORNL has independent work in the cluster "Smart City": Graph-based Cascading Impact Estimation for Identifying Crucial Infrastructure Components. The **graph-based analytic system URBAN-NET** estimates cascading impact caused by the disruption of critical

infrastructure components by leveraging the topology of a critical infrastructure network. (Lee, S.; Chintavali, S.; Tennille, et al., 2022)

4.5.6 Pacific Northwest National Laboratory

PNNL published two articles that matched the search terms in Scopus:

- One article, published independently, aimed to improve first responder communication and situational awareness by **eliciting first responder opinions** through a survey. (Schroeder, J.M.; Amaya, J.P.; Bays, R.M.; Manz, D.O.; McMakin, A.H., 2018)
- The second article focused on "a proactive posturing of power system elements and formulate a **security-constrained optimal power flow** informed by cross-domain hurricane modeling as well as its potential impacts on grid elements." PNNL partnered with the University of Texas at Arlington on the proactive posturing work. (Quarm, E.; Fan, X.; Elizondo, M.; Madani, R., 2022)

4.6 Level of Impact Assessment Results

Publications from the literature review were organized based on capability need categories to further distill the information. This allowed for a more manageable approach to review similar technologies for interoperability and impact. This analysis method of consolidating technologies based on the need also provided ideal conditions to determine overlap or highlight potential opportunities for future connections. The final portion of the level of impact assessment combines the capability need categories with a visual side-by-side representation of the different research topics.

The following analysis was completed on research identified between September and December 2023.

4.6.1 3D Geolocation

Geotagging social media information research is being conducted in national laboratories, research centers, and academic institutions. The literature review produced publications from ORNL, TAMU, and GA Tech. These institutions may experience the same implementation challenges (policy, lack of trust in AI algorithms) and may be developing models similar in nature. It may be of interest to determine if different research projects focusing on geotagging social media information complement or supplement each other. Further examination could also explore whether the unrelated research attempts to address the same standardization and AI policy limitations in using social media information in emergency response efforts. The Office of Management and Budget issued a policy for AI use by U.S. federal agencies (2023). Those researchers using AI/ML may experience similar policy and governance challenges.

Sample Research

Geolocation research explored several different angles:

- Georeferencing tweets to track mobility patterns during disasters (ORNL: Kar & Ethridge, 2019).
- Geotagging tweets to identify and rank emergencies based on geographic and semantic dimensions (GA Tech: Wang & Taylor, 2019).

- Geotagging tweets to develop a framework for situational awareness information during disasters (ORNL: Kar et al., 2019; GA Tech: Suprem & Pu, 2019; GA Tech: Salley et al., 2021; TAMU: Fan, Wu & Mostafavi, 2020).
- Using robotics to scan infrastructure during disasters and construct 3D images for identification and classification. The LBNL pipeline uses a commercially available software (Pix4D) in combination with image processing methods, suggesting a potential high level of interoperability. (LBNL: Wudunn et al., 2020; GA Tech: Yajima et al., 2021).

4.6.2 Communication

This capability need may look different, depending on which EM mission area the research is concentrated. The literature review results produced examples for preparedness, response, and recovery efforts. The research results have distinct differences in the data streams and overall necessity for data integration.

Sample Research

Preparedness

- ANL and George Mason University are both researching community preparedness and utilizing ML techniques to improve data collection and analysis (George Mason University: Jiang et al., 2023; ANL: Choi et al., 2020).
- Community resiliency repository framework (George Mason University: Nguyen, et al., 2021).

Response

- Temporary communication network infrastructure when communication resources are limited or impacted (Purdue University: Hazra et al., 2020).
- Image classification framework using social media information and reduce non-relevant posts (University of Texas at Austin: Johnson et al., 2023).
- Technologies that utilize 5G cellular networks while integrating data between devices (NIST: Liu et al., 2023).
- Integrating satellite technology into wireless communication systems to support a common operating picture (Georgetown University: Wood & Frazier, 2022).

Recovery

- Scalable, efficient framework for harmonizing crowdsourced geographic multimodal data to improve recovery actions (ORNL: Thakur et al., 2021).

NIST Evaluations

NIST supports the first responder community in several ways, including by conducting evaluations on publicly available and emerging technologies in communication. The findings in NIST evaluations can be significant to the general body of knowledge in EM research.

Examples of NIST evaluations in emergency communication devices and systems include the following:

- NIST evaluated a communication device that integrated data between devices (Liu, et al., 2023). This assumes a high level of interoperability and may support communication solutions for first responders and emergency managers in the EOC.
- NIST primarily completes evaluations on technology or landscape assessments on the current research rather than independent R&D (Garey et al., 2021; Dawkins et al., 2021; Buchanan et al., 2023; Morrison et al., 2021; Ramakrishnan et al., 2021; Garey et al., 2020; Wang, Rouil & Cintron, 2019). The results of their evaluations could be beneficial to the body of knowledge in EM and could have a profound impact on future investments.

4.6.3 Data Integration

Social media analytics and social media data in general was the primary research topic, as shown in Figure 3. Therefore, research in data integration was categorized as either social media focused or non-social media focused. As a result, similar, complementary, or supplemental research was combined.

Sample Research

Data integration with a focus on social media analytics

- Identification, classification, and categorization of social media information:
  - Understanding and categorizing infrastructure restoration efforts following disasters (George Mason University: Chen et al., 2021; TAMU: Zhang et al., 2020).
  - Determining severity in social media posts using a BERT model (George Mason University: Chen et al., 2021; George Mason University: Hembree et al., 2021; University of Texas at Austin: Powers et al., 2023).
  - Trainable classification model to improve reliability of real-time information (Snyder et al., 2020). This is a current S&T-funded project with collaboration between Purdue and University of Colorado at Boulder.
  - NIST-led efforts in a sponsored four-year Text REtrieval Conference Incident Streams track to categorize social media information that can potentially inform other institutions focusing on social media mining. Integrating results and findings may impact research agendas in social media analytics.
- Multi-formalism modeling platform used to improve situational awareness (PNNL: Coleman et al., 2019).

Data Integration outside of social media analytics:

- Cloud-like service using mobile edge computing for search and rescue operations (Bhunia, et al., 2022). Collaboration between TAMU and NIST.
- Using digital twins to improve situational awareness (TAMU: Hatch et al., 2023; Fan et al., 2021).
- Using distributed non-negative matrix factorization method to integrate large datasets (LANL: Chennupati et al., 2020).
- Crisis mapping using an informatics ecosystem by integrating IoT data, social media, and smartphone messages (PNNL: Walker et al., 2018).

- At Purdue University they developed a model in cloud computing selection for cost-effective visual analytics (Mohan et al., 2021).

Dual Capability Need Research

Some publications are categorized as threat and hazard detection/analysis but are inherently also a solution that can be categorized as potential data integration solutions. Some examples include:

- ORNL's handheld systems for chemical, biological, radiological, nuclear, explosion monitoring and detection with the intent to integrate the information directly into the scanner (Salathe et al., 2022).

- Berkley AI Research's Incidents1M; large-scale, openly available dataset of images (Weber, E.; Papadopoulos, D.P.; Lapedriza, A., et al., 2023).

- University of Nebraska at Omaha's REaCH; an interactive dashboard to monitor responder health and exposure data (University of Nebraska Omaha: Fruhling, Yoder & Jonnalagadda, 2023).

- University of California, San Diego's research in quantifying risk of wildfire ignitions by integrating ML techniques paired with an extreme weather model (Bayani, R.; Waseem, M.; Manshadi, S.D.; Davani, H., 2023).

- University of Notre Dame's "Drone Response," a software product line for small UAS, or sUAS, deployment in response efforts (Islam et al., 2023).

4.6.4 IT Protection and Cybersecurity

The original search terms identified very few publications focusing on IT protection and cybersecurity in EM. Search terms were expanded to develop the dataset to include publications on cybersecurity, cyber threat or malware, or cyber resilience in EM-focused topics. This produced 12 publications from U.S. institutions, which can be interpreted in several ways. During cybersecurity incidents, emergency managers are responding to the symptoms of the cyberattack. Based on the severity of the event, emergency managers may be actively involved. As operations transition to more digital assets, this may also increase emergency manager participation in cyberattacks as well. Additional efforts focused on this capability need provided minimal supplemental findings.

Research examples identified include the following:

- A prototype tool from MITRE that is described as providing a "common operating picture of cyberspace" to support network security and maintain situational understanding during cyberattacks (MITRE, 2015). However, this technology is dated, originating in 2015.

- Research conducted by George Mason University's Fotouhi Tehraniin et al. (2021) ties in security issues identified with online services during disasters.

4.6.5 Pandemic Response

Following the COVID-19 pandemic, emergency managers have a stronger understanding of the cascading impacts a contagion has on the world. Expected impacts were compounded by the

unexpected, including human behavior changes and economic strain (Lesperance & Tietje, 2020). Although the breadth of the research identified in the literature review spans beyond the EOC or an emergency manager's responsibilities, the impact on emergency managers is and would be immense:

Sample Research

- Portland State University's research in human-agent teaming to model both virus and human behavior changes (Shmerko at al., 2023). The authors propose their protocol approach can help model how a contagion would behave, but also recommend the application be used in modeling human behavior patterns such as the spread of panic, fear, or rumors. It may warrant further investigation into whether a beneficial collaboration with research in geotagging social media data and Portland State University's work exists. Using geotagging social media information, researchers at Purdue University examine how fear or misinformation spreads and creates noisy environments that hinder data collection (Kim & Park, 2020).
- Rapid retooling: Forward-looking approach to a hybrid manufacturing process and emerging hybrid technologies to support the U.S. tool and die industry (ORNL: Saleeby et al., 2020). Research in strengthening U.S. manufacturers will strengthen the national response to future pandemics. Including emergency managers in these conversations can bring clarity to the issues and support strong solutions.
- IoT systems to track and communicate the spread of an infection (PNNL: Yang et al., 2020). IoT systems and human-agent teaming are not the same, but are researchers identifying ways to improve interoperability between data streams and with different systems?

4.6.6 Resource Management/Jurisdiction Coordination

Similar or complementary resource management research was identified at George Mason University and Purdue University. Both researched how to utilize social media information to support humanitarian efforts (George Mason University: Purohit et al., 2018; Purdue University: Kumar et al., 2018). Both universities' research includes classifying and categorizing social media information to promote effective responses on help requests during a disaster.

The literature review produces limited tangible solutions to gaps in jurisdictional coordination. UW conducted a survey-informed study on commercial off-the-shelf CIMS, such as WebEOC, and the experiences of applicable stakeholders (Scholl & Holdeman, 2013). Results indicate the systems lack necessary elements including interoperability and scalability, particularly during multi-jurisdictional responses for large-scale emergencies. The limited number of publications from the literature review addressing this gap with tangible solutions does not support the operational prioritization voiced from EM stakeholders.

Sample Research

- Data-driven predictive framework using ML approaches and spatiotemporal data sources for evacuation traffic management (North Dakota State University: Afrin et al., 2023).
- Strategy for emergency power supply locations during disasters (NREL: Satkauskas et al., 2023; ANL: Lei et al., 2018).

4.6.7 Threat and Hazard Detection/Analysis

Due to the intentionally broad scope of this capability need category, different capability needs are addressed. To compare similar research agendas, this capability need category was organized based on the type of hazard being analyzed.

Examples of overlapping or similar research and current collaborations and topics for potential future investigation include the following:

- TAMU research in flood prediction and modeling is being paired with damage assessment concepts and crowdsourcing data (Kaur et al., 2023; Dong et al., 2021; Pi et al., 2021; Khajwal et al., 2022; Alizadeh et al., 2021). It would be beneficial to determine the level of interoperability of the models to current systems and whether research in AI supports in flood prediction and damage assessment models adhere to policy and guidance (Dong et al., 2021; Khajwal et al., 2022).

- Berkley AI Research and Rochester Institute of Technology are both researching the effectiveness of social media information paired with image databases to support disaster relief efforts (Berkley AI Research: Weber et al., 2023; Rochester Institute of Technology: Alam et al., 2023). Their information is publicly available.

Multiple concurring research agendas offer differing perspectives regarding concerns of power outages and restoration efforts during power outages. Further examination could evaluate potential relevancy and connections to improve grid resiliency during man-made threats.

Other Sample Research Based on Hazard Type

Natural Hazard Phenomena

- Flood level forecasting and prediction (George Mason University: Khalid & Ferreira, 2020; Rahman et al., 2023).

- Sensor networks paired with data analytics to improve current flood forecasting models. Partnerships with academia, industry, and local authorities at GA Tech (Clark, 2019).

- Using AI/ML for tracking and predicting severe storms (GA Tech: Toon, 2023).

- ORNL proposes a model-of-models approach for data integration (Kar et al., 2020).

- Crowdsourced images to determine flood depth and structure damage (TAMU: Alizadeh, 2021).

- Facilitate operators in pinpointing segments of the public utilities network to shut off and mitigate wildfire ignitions (University of California, San Diego: Bayani et al., 2023).

Damage to Critical Infrastructure

- Current collaboration with ORNL and GA Tech researching temporal segmentation framework to capture major pattern changes during power outages (Muralidhar et al., 2020).

- Solutions for maintaining power to critical infrastructures during disruptions (NREL & PNNL: Khatana et al., 2022).

- Estimating critical infrastructure impacts using a national laboratory-developed analytic system (ORNL: Lee et al., 2022).

First Responder Exposure to HAZMAT incidents

- REaCH is an IoT real-time interactive dashboard to monitor responder health and exposure data (University of Nebraska Omaha: Fruhling, Yoder & Jonnalagadda, 2023).

4.6.8 Unmanned Aerial Vehicles/Unmanned Aerial Systems

Use of UAV/UASs is of interest to federal, state, and local emergency managers and private citizens. Much of the discussion focuses on the policies and governance around their use. However, specific techniques exist to improve UAV/UAS use in emergency response, including integrating or improving drone communications. Researchers are exploring ways to utilize UAV/UASs to improve situational awareness.

Sample Research

- Purdue University is developing techniques to advance and improve the use of UAS in emergency response (Weldon & Hupy, 2020; Qu et al., 2021; Wan et al., 2021).
- INL, MIT Lincoln Laboratory, and NASA Ames Research Center are all working on concepts for including UAS in emergency communication networks (Bhuyan et al., 2019; Allen & Mazumder, 2020; Andrade & Hulse, 2023).
- Purdue University video analytics framework named “DroneCOCoNet” that utilizes edge computation (Qu et al., 2021).
- INL research into a separate millimeter wave (mmWave) cellular network for drone communication, creating a “drone corridor” in the sky to support the growing number of drones utilized in emergency response efforts (Bhuyan, A.; Güvenç, I.; Dai, H., et al., 2019).
- Small UAS, or sUAS, are used in emergency response actions for mission-specific tasks. University of Notre Dame has developed “Drone Response,” a software product line for sUAS deployment (University of Notre Dame: Islam et al., 2023).

4.6.9 Workforce Training/Staffing

Researchers are exploring how to integrate extended, augmented, and virtual reality experiences into first responder training. Technologies and frameworks for virtual reality training environments may present challenges in funding and budget restrictions. If the training environments can be scaled to fit jurisdictional size and available resources, these implementation barriers could be significantly reduced.

Sample Research

Workforce training and staffing is described in several different ways and example research includes:

- Virtual reality training environments hosted by privately owned company V-Armed (https://www.v-armed.com/about) in collaboration with national laboratories and academic institutions (Louisiana State University).

- Video analytics framework to improve training evaluations (George Mason University: Li et al., 2023).
- AI-infused system for multimodal stream analytics to focus on mitigation and preparedness efforts. This framework is intended to reduce cognitive overload from the multiple data streams used in training exercises (George Mason University: Pandey et al., 2020).
- Human-centered AI-enabled training framework that integrates physical and augmented reality (TAMU: Mehta et al., 2022).
- Development model for integrating extended reality environments into first responder training (NIST: Ledgerwood et al., 2023).
- Evacuation simulators to support real-work networks (Purdue University: Gehlot et al., 2019).

4.6.10 Other

This capability need was included to capture research that may not fit into the previous categories. These research topics and concepts added value to the overall research efforts and provided a more comprehensive view of EM research.

Sample Research

- George Mason University has been conducting research and publishing findings on community resilience from 2018 and 2021 (Purohit & Moore, 2018; Nguyen et al., 2021).
- INL is researching personal resiliency in natural and man-made disasters, also highlighting preparedness (Sabharwall et al., 2021). Similarities, such as overlaps and complementary components, may exist in the work being completed at George Mason University and INL.
- Stanford Urban Resilience Initiative and Stanford Future Bay Initiative both seek to “quantify resilience, engineering analysis for decision support, harnessing non-traditional data and resources” (https://urbanresilience.stanford.edu/).
- Duke University developed the “Resilience Roadmap” where tracking and reporting progress on resilience primarily focuses on climate resiliency to climate-induced incidents.
- Community and personal resilience to better understand behavioral patterns and better prepare communities for disasters (George Mason University: Purohit & Moore, 2018; Nguyen et al., 2021; INL: Sabharwall et al., 2021).

5.0 Analysis

Using the interoperability and implementation ratings, the publications that described a platform, system, framework, or model (PSFM) were plotted in the appropriate quadrant. Research containing PSFM was more predominately identified in the literature review as proposing a new or advancement in current technology and therefore most applicable.

5.1 Level of Impact Assessment Results

In Figure 6, identified research with an associated proposed technology was plotted in its respective quadrant to visually compare between and within capability need categories.

Capability need icons can be found in the key for Figure 6. This visual representation of the landscape assessment provides several benefits:

- Method to view potentially overlapping or complementary research within a single capability need.
- View research efforts that may potentially have less restrictive barriers in both interoperability and implementation barriers.
- View research assessed to have potentially a high impact from implementation barriers. Research in these quadrants (Low Implementation/Low Interoperability; Low Implementation/High Interoperability) are not considered to be assessed as less valuable. These research projects should be viewed as potential opportunities where collaboration or augmented efforts could lead to productive resolutions to barriers.
- View research assessed to have potentially a low rating in interoperability. Research in these quadrants (High Implementation/Low Interoperability; Low Implementation/High Interoperability) is research that either did not clearly specify their research could be integrated into a current system, or explicitly stated there would be interoperability challenges. It would be most appropriate to consider research in these quadrants as potential opportunities. These research efforts might be opportunities for collaboration in ways that would improve interoperability.

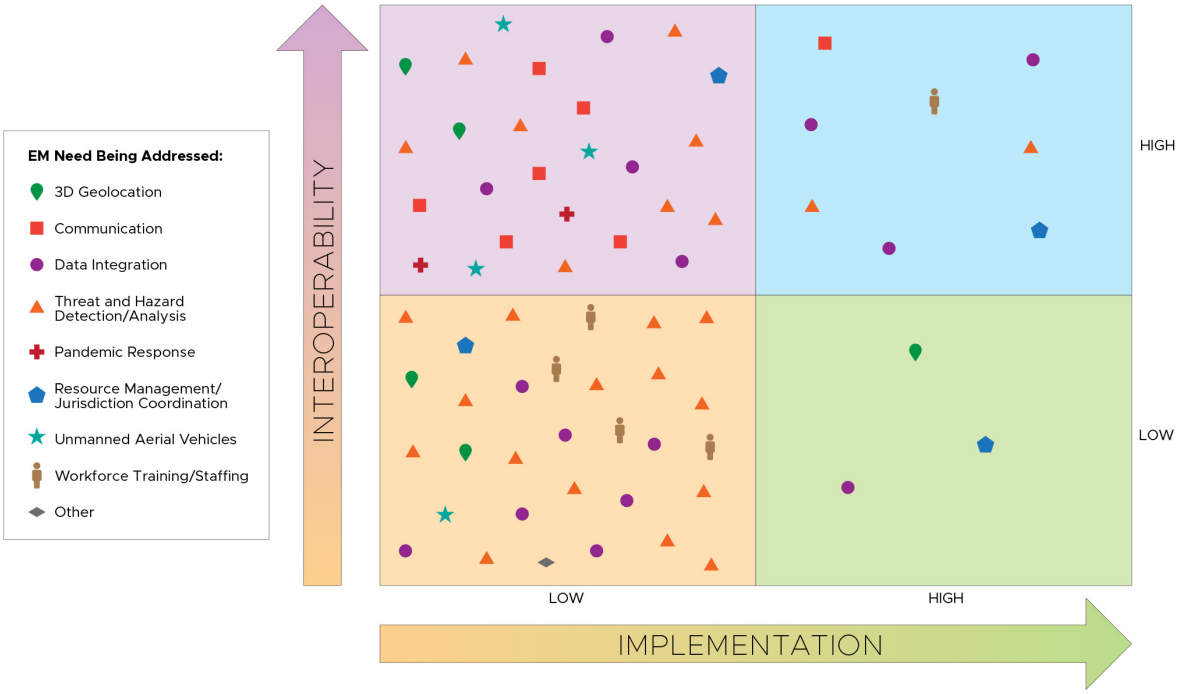

Figure 6. Implementation and Interoperability Graph

5.1.1 Influence of Implementation Barriers

Implementation barriers are influenced by many factors, including policy, standardization, emerging technologies, and the current state of practice. Implementation barriers should be

considered on a spectrum of perceived impact. Research in each quadrant may be minimally impacted by but not limited to:

- Regionally specific content. Impediments may lessen if the research can be applied at a national level.
- Current policy. As this changes, so may the implementation rating.
- Training resources. User-friendly technology is inherently easier to implement.
- Initial cost and potential maintenance costs.

5.2 Low Implementation / High Interoperability

The research identified to have a high rating of interoperability with potentially significant impact from implementation barriers is plotted in this quadrant and shown in Figure 7.

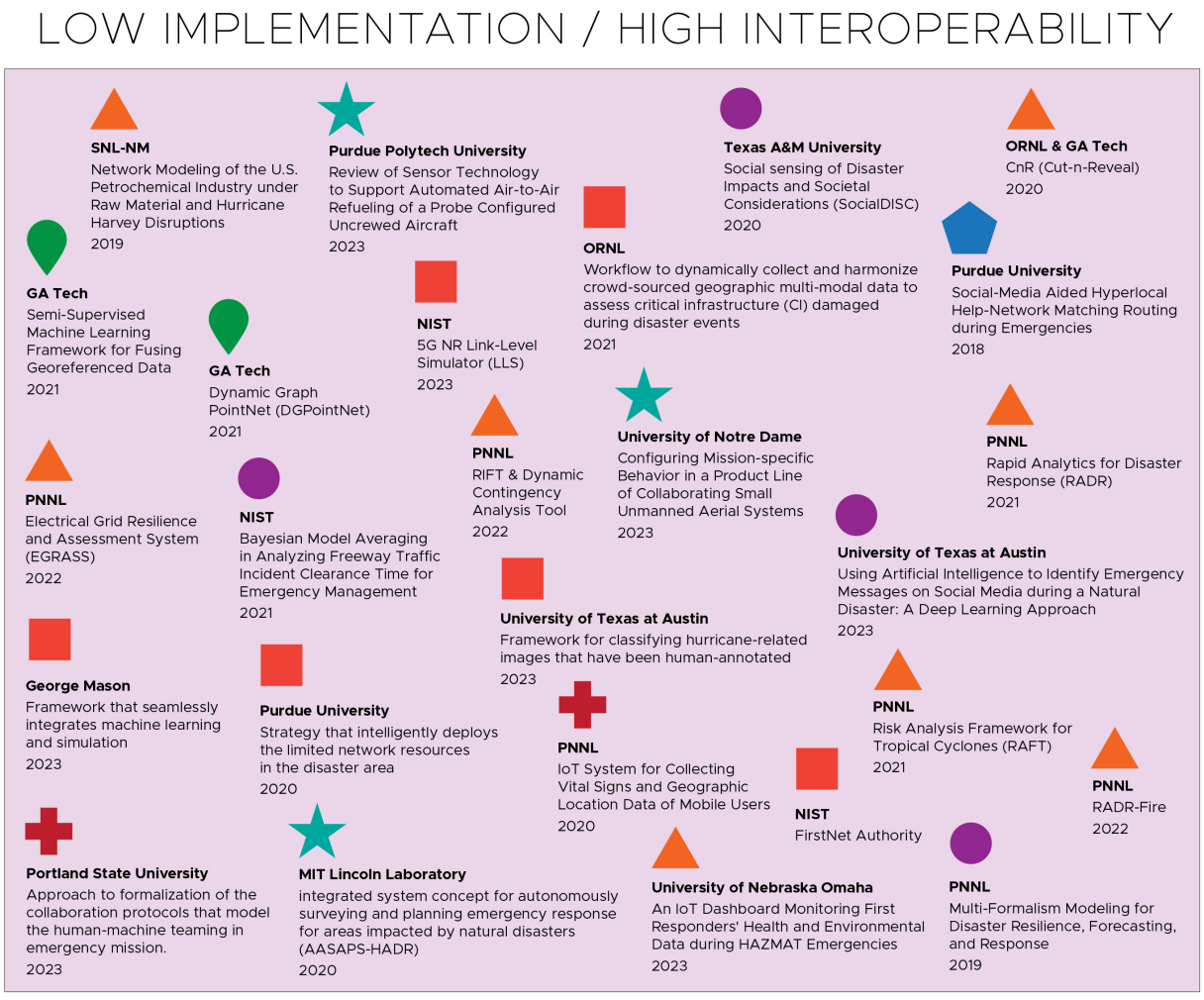

Figure 7. Low Implementation and High Interoperability Quadrant

5.3 High Interoperability / High Implementation

Research plotted in this quadrant, Figure 8, has a high interoperability rating with potentially minimal impacts from implementation barriers. It may be worth further investigation into these research topics to determine if they would provide a solution on a national level.

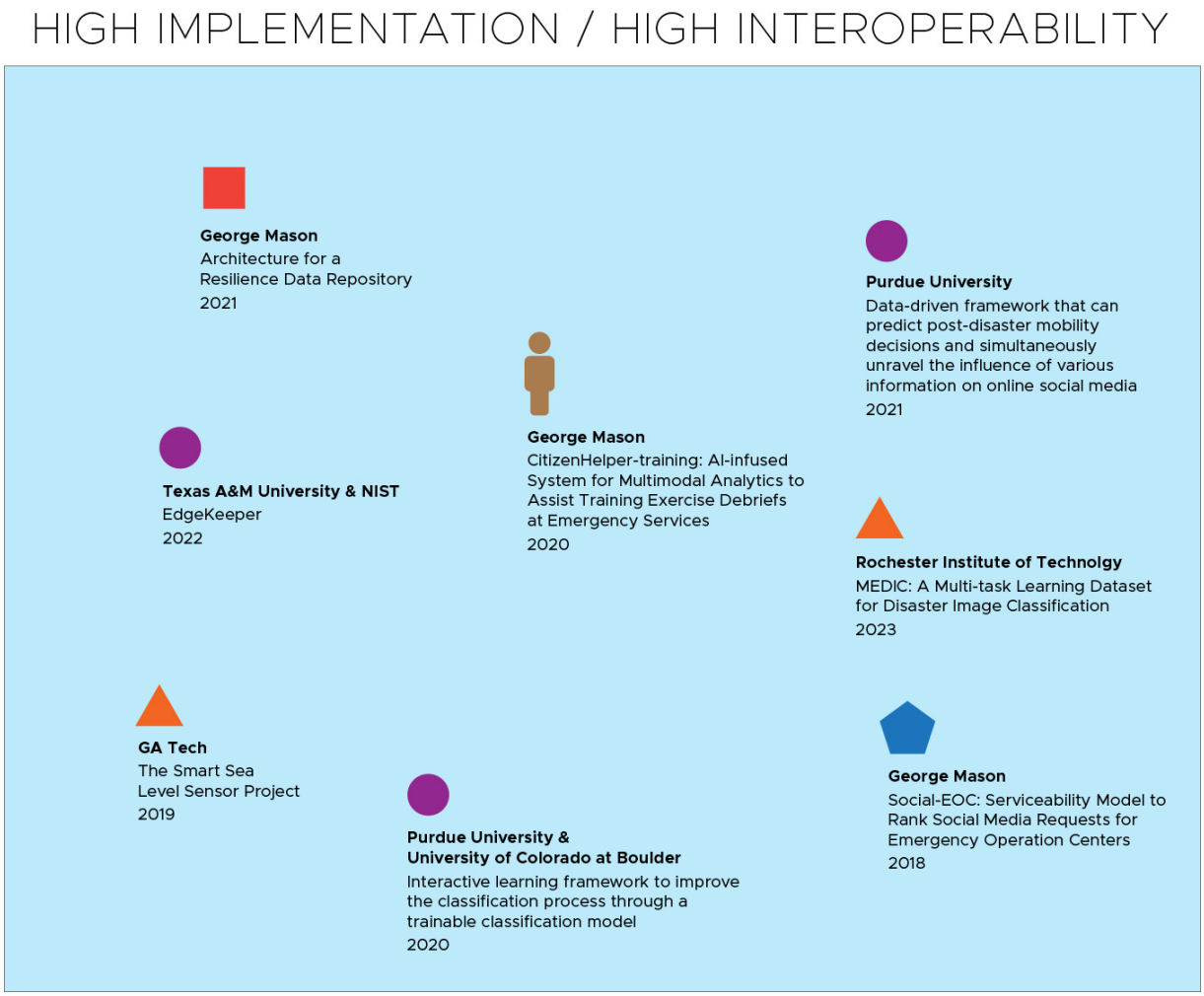

Figure 8. High Implementation and High Interoperability Quadrant

5.4 Low Interoperability / Low Implementation

Research that rated low interoperability and had potentially a significant impact from implementation barriers were plotted in this quadrant as shown in Figure 9.

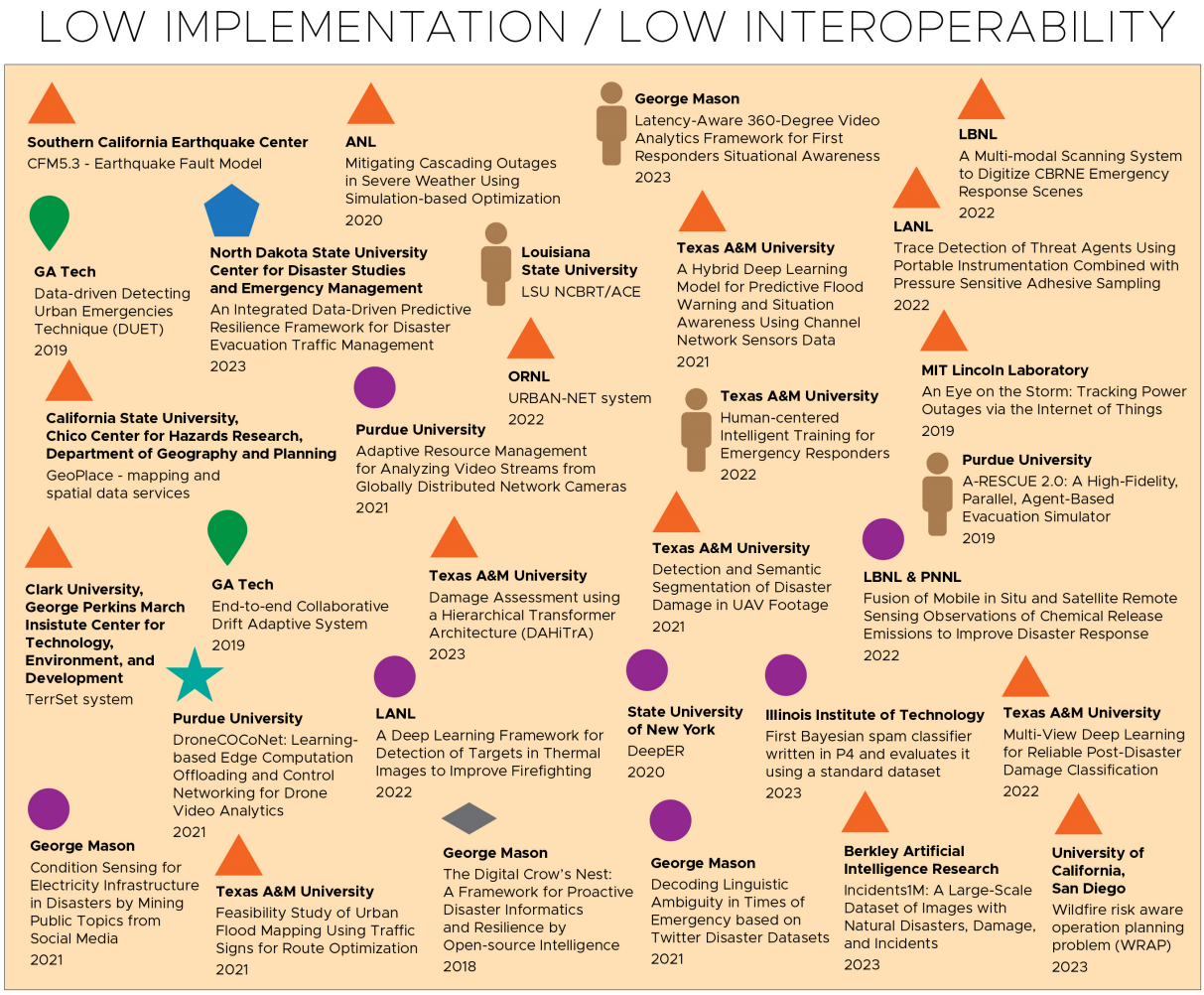

Figure 9. Low Implementation and Low Interoperability Quadrant

5.5 High Implementation / Low Interoperability

Research with the potential for minimal impacts from implementation barriers but perceived low interoperability ratings were organized in this quadrant, as shown in in Figure 10. As with the implementation barriers, interoperability ratings can change with the progression of the research. Proposed technologies that are potentially limited in their ability to scale and adapt to a national level can be altered by the developers.

Figure 10. High Implementation and Low Interoperability Quadrant

6.0 Patents

A search conducted in PATSNAP identified applicable patent applications related to EOCs and similar EM focus areas. The following search terms were used:

- Emergency operations centers
- Emergency call center
- Emergency preparedness
- 9-1-1 call center
- Firefighter
- First responder
- Emergency response
- Emergency management
- Disaster management
- Public safety

The results included over 1,600 records from 2018 to the present. The records were put into Quid for further analysis.

The network view shown in Figure 11 showcases the breadth of patents filed in the EM field. The colors associated with research clusters in the Figure 11 match those shown in Figures 12 and 13.

Figure 12 summarizes patents filed by cluster. The greatest number of patent applications filed were on emergency response systems, priority access, and radiofrequency signals.

Figure 13 summarizes the results by manufacturer. Motorola, LG, and RapidSOS filed the most patent applications in the last five years. The majority of the patents are from large corporations, but a few smaller companies are active, such as RapidSOS, RapidDeploy, and NextNav.

Appendix C highlights select patent applications between 2020-2023 and provides a snapshot of activity related to public safety answering points

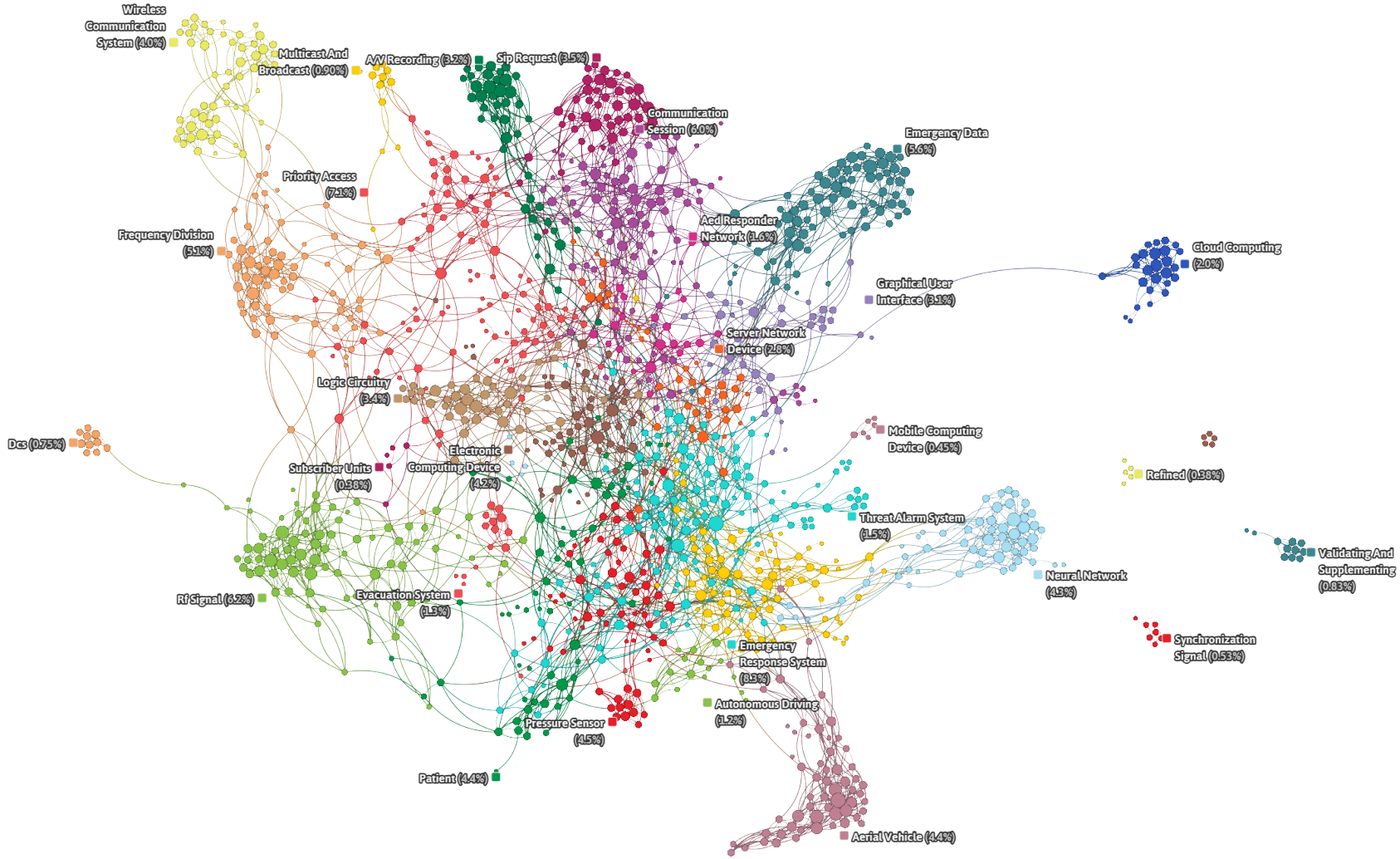

Figure 11. Patent Network View

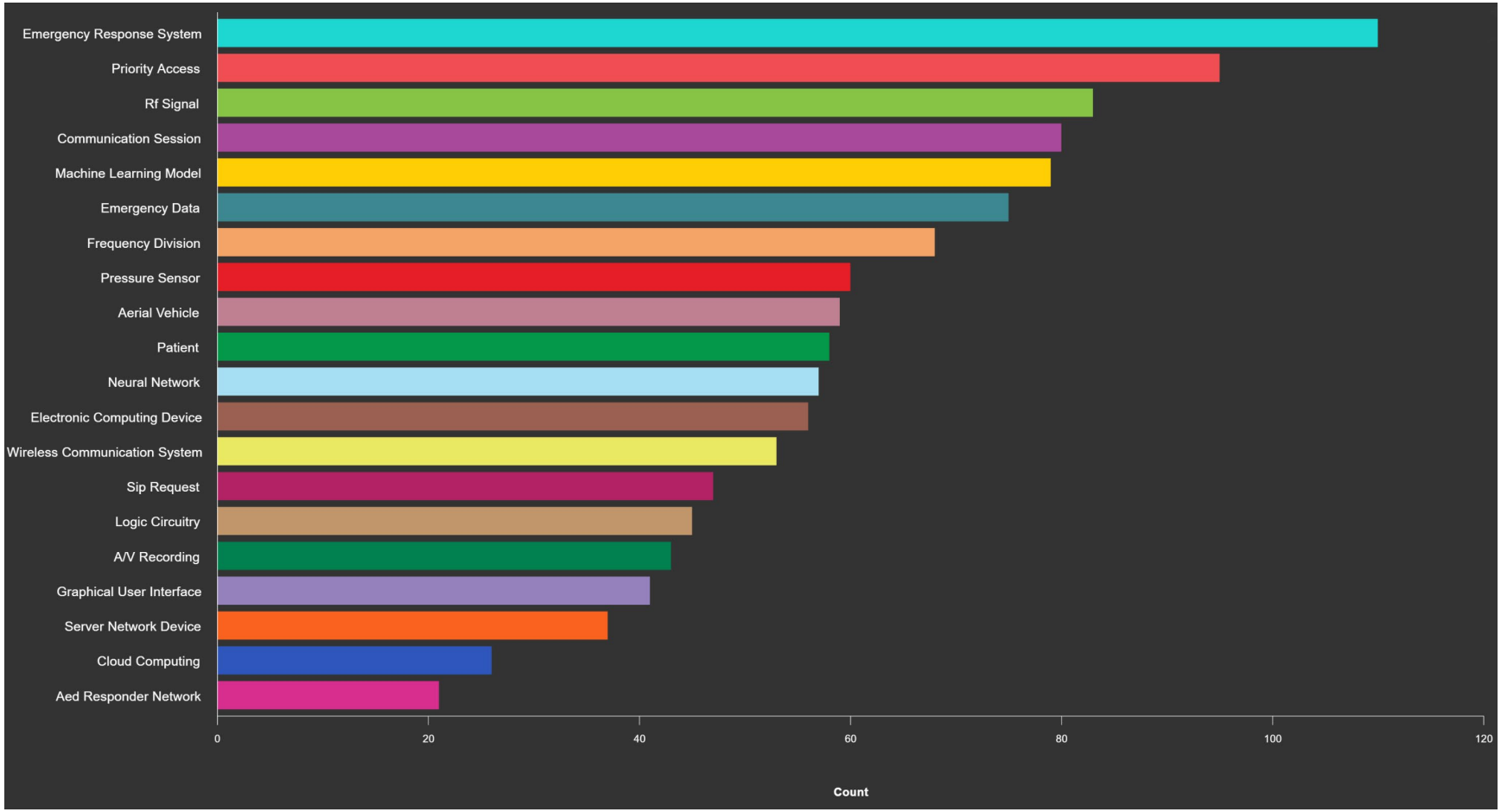

Figure 12. Bar Chart by Cluster

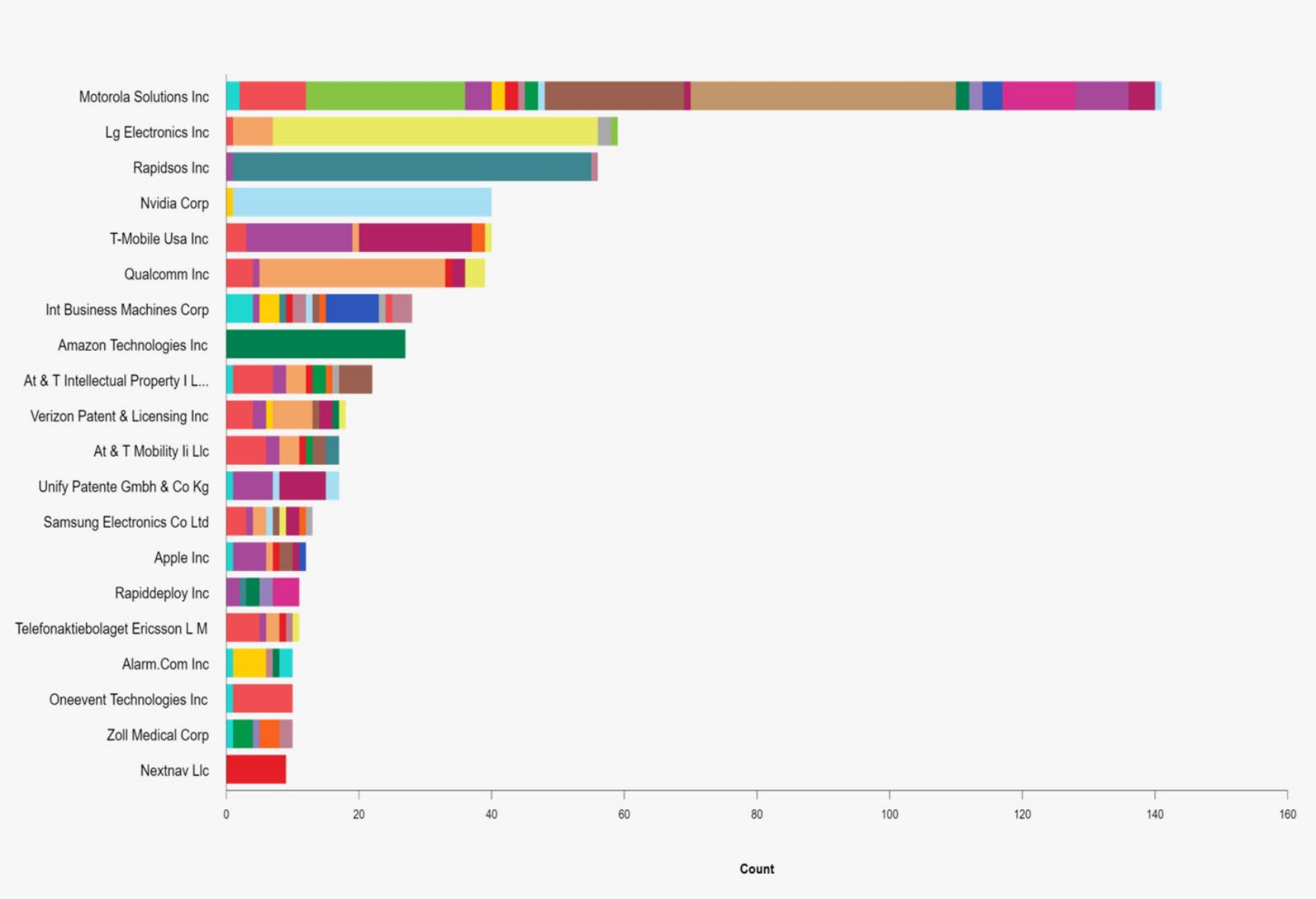

Figure 13. Original Assignee by Cluster (Top 20)

7.0 Conclusions

Using a suite of tools to search for publications and analyze research trends, PNNL identified research areas of high interest among academic institutions, national laboratories, and research centers. Cluster labels in Quid that contributed to a signification portion of the publication records were reviewed for overlapping, complementary, or supplemental research agendas.

Top institutions based on publication volume included George Mason University, GA Tech, NIST, Purdue University, and TAMU. However, other institutions identified in the literature review within overlapping research topics were included in the analysis.

Research topics of interest have 1) identified a capability gap within EM and 2) provided an associated solution. PNNL identified two capability gaps that did not reach this level and may warrant further investigation:

- The lack of scalability and interoperability of current information management systems: Is there a single solution or will there be a suite of tools to integrate the necessary information?
- Technical and operator computer issues in the EOC: When incorporating emerging technology into an emergency manager's space, are they equipped with sufficient resources?

PNNL also identified overlap or opportunities for collaboration in research topics within social media analytics, AI/ML, community resilience, satellite technology, emergency response solutions to power grid issues, evacuation response, Smart City applications and informatics ecosystems, and critical infrastructure damage assessments. Identifying similar research agendas can support investment strategies by showing what people are researching and where they are not. Both perspectives increase the knowledge base of EM-specific research that will ultimately improve the tools available to EM practitioners.

For additional information on the project, or to submit an inquiry, please contact PNNL at emotr@pnnl.gov.

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Appendix A – Methodology

This section provides additional detail on PNNL's structured approach to review existing EM R&D, identify and verify capability gaps and needs, and assess results for interoperability and impact. See section 2.0 for more information.

A.1 Defining and Refining the Dataset

Sources used to collect data include databases to search publications (Scopus), patents (PATSNAP), and open sources (OSTI, Laboratory-Directed R&D project lists, Google Scholar) for EM research. Articles were selected based on applicability to specific key search terms that address capability gaps and needs in the EM mission areas (preparedness, mitigation, response, recovery). The scope was limited to 2018-2023 and U.S. institutions as primary contributors, with the possibility to expand to incorporate new research and international with future funding.

The search terms selected were informed by PNNL's review of existing resources, such as the PR reports, and previous work within the first responder and public safety communities and projects at PNNL, such as the First Responder Roadmap (Lesperance, A., et al., 2023). Key search terms were further down-selected to elicit technology-focused publications in EM, disaster management, and crisis management, and are outlined in Table A.1. The number of key search terms was limited to what could be reasonably covered within the timeframe of the assessment.

Table A.1. Key Search Terms

Key Search Terms		
Climate change and extreme weather	Data sharing/data integration	Infrastructure vulnerability
Community resilience and equality	Disaster science	Resource management
Crisis information management system	Emergency management	Situational awareness
Crisis management	Emergency operations center	Supply chain management
Cybersecurity/cyber resilience	Incident command systems	Threat categories
	Information sharing	Workforce training

In addition to research identified via PNNL's search tools, a data call was sent to DOE national laboratories to include R&D projects that may not have open-source publications.

Next, the key terms were used in Scopus[1] searches for peer-reviewed publications, PATSNAP[2] for patents, and other open sources (i.e., OSTI, Google Scholar) to identify applicable R&D

[1] Scopus is a scientific database with abstracts and references from thousands of publishers, including scientific journals, books, and conference proceedings, covering research topics across scientific and technical disciplines.
[2] PATSNAP is an AI-powered patent analytics tool that uses ML to analyze patent data.

efforts. The initial searches yielded approximately 36,000 journal articles and 1,600 patent publications. The publication data was further refined by limiting publications to the primary author being a U.S. institution and topics with a technological focus to better target emerging technologies. Additional sub-searches using Quid[1] further down-selected to the most relevant documents and records focused on key topic areas and associated concepts. PNNL analysts also removed duplicative entries (such as repetition of technical papers and conference presentations) or entries where the term “emergency management” was not relevant or consistent to this project.

Findings were combined into an annotated bibliography in the form of a spreadsheet available separate from this report. The spreadsheet includes a separate README tab with user-friendly instructions for how to sort, filter, and search over 300 publications. The spreadsheet was organized per the following outline:

- Summary of the research or abstract
- EM capability gap addressed
- Source of funding
- Emerging technology associated with research
- Interoperability or multipurpose use assessment
- Impediments or barriers to implementation

The following sections provide additional detail on PNNL’s approach to refine, analyze, and capture the results in an accessible way to easily inform future research and DHS S&T investments.

A.2 Identifying and Verifying Capability Gaps and Needs

The EM capability gaps and needs were identified through previous work within the first responder and public safety communities and projects at PNNL. From these efforts the literature review validated or provided additional insight on capability needs identified in the EM research.

In the context of this research, a defined distinction exists between “gap” and “need.” A capability gap is a limitation in a specific context (e.g., lack of or too much real-time information on situational awareness without a way to synthesize and act). Gaps indicate uncertainty in accomplishing tasks or objectives. Capability needs connect gaps with the proposed solution (e.g., ability to integrate real-time incident data) (Project Responder 6, 2020). The identified capability gaps from the literature review can then be connected to associated capability needs.

A.2.1 Project Responder 5 and 6 Reports

The DHS S&T PR efforts document capability gaps for response agencies with the goal of identifying and prioritizing the needs across disciplines. The number of capability gaps specifically directed toward EM in the PR5 and PR6 final reports are limited and the representation of EM managers in the overall study was only 10 percent (compared with fire, law enforcement, emergency medical services, and public safety communications). However,

[1] Quid is an AI-powered commercial software tool for data analysis and visualization of indexed resources, consumer data, and market intelligence.

EM managers' participation and their connectivity with other first responder disciplines can validate the findings in this study.

The literature review further validated the following EM capability gaps identified in PR5 Final Report (published in August 2017) and PR6 Final Report (published in December 2020):

- The PR5 Final Report identified the ability to receive and integrate video feeds from a variety of sources to augment EM.
- The PR6 Final Report identified the ability to coordinate spontaneous unaffiliated volunteers with EM organizations.

A.2.2 First Responder Roadmap

The First Responder Capability Roadmap Project, led by PNNL on behalf of DHS S&T, analyzed the PR reports to identify persistent capability needs identified throughout the years (Lesperance et al., 2023). Persistent capability needs identified in PR reports and applicable to EM include:

- 3D geolocation
- Data integration
- Virtual reality training
- Communications
- Threat and hazard detection
- Coordination across jurisdictions
- UAVs or UAS
- Cybersecurity

Given recent events, a pandemic response capability need was added to the list. The need for virtual EOCs became apparent during the COVID-19 pandemic (Delisle et al., 2021). Impacts from the pandemic may have developed technologies and solutions with specific motivating factors and should be assessed as its own capability need. Additionally, an "other" category was added to include capability needs that fit into the established needs.

A.2.3 Assessing Interoperability

Emerging technologies can often pose integration challenges to transitioning from research to operational use with both state-of-the-art and legacy systems. The assessment sought to answer the question: **Does the technology integrate into current operating systems, or does it need a new standard developed?**

Interoperability was evaluated based on conformance to enterprise architecture and standards and given a rating of "high interoperability" or "low interoperability."

A.2.4 Conformance to Enterprise Architecture and Standards

The interoperability assessment followed the Federal Enterprise Architecture Infrastructure Reference Model (Figure A.1). Using this reference model, the multiple facets of compatibility and integration could be measured using three domains: platform, network, and facility interoperability.

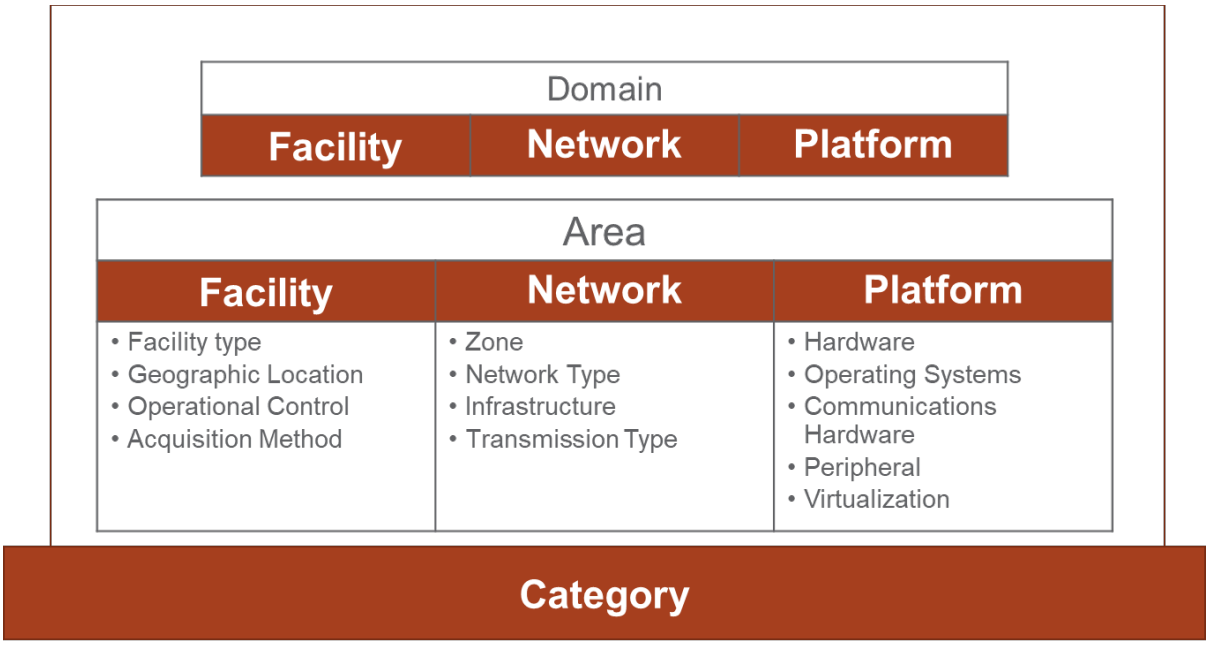

Figure A.1. Federal Enterprise Architecture High-Level Infrastructure Reference Model

Many technologies identified in this landscape assessment are at a level of development that makes determining interoperability challenging. If it is not overtly stated to integrate into existing systems, further investigation is required to determine interoperability. To address this, the interoperability assessment focused on technologies' compliance with open standards in information sharing and exchange, voice and data communications, internet protocols, network architectures, cybersecurity, and trust (in data, systems, and devices). See Appendix B for additional information on industry-specific standards.

The level of interoperability was determined based on the self-disclosure of conformance to open standards in the publication or document. Compliance with open standards in information sharing and exchange, voice and data communications, internet protocols, network architectures, cybersecurity, and trust (in data, systems, and devices) were prioritized. However, few studies explicitly identified interoperability as a goal or purpose, and few stated the applicable standards to which the technology would be governed.

A.2.5 Literature Review for Capability Needs

Of the 227 peer-reviewed publications that were part of the initial literature review in 2023, PNNL categorized the publications by which capability need they addressed. Table A.2 summarizes the categorization of the publications by relative frequency.

As PNNL reviews and updates more research referenced within the annotated bibliography, the distribution of research of capability needs may fluctuate.

Table A.2. Research Topics Distribution by Category

Category	Percent of Publications (%)
Threat and Hazard Detection/Analysis	32%
Data Integration	24%
Communications	11%
Resource Management/Jurisdictional Coordination	11%
3D Geolocation	5%
Workforce Training	4%
UAVs	3%
IT Protection/Cybersecurity	2%
Pandemic Response	2%
Other	6%

A.3 Implementation Assessment

In addition to an interoperability assessment, publications with identified technology were evaluated for potential implementation barriers. A PSFM was more predominately identified in the literature review as a technology. Through this evaluation process, comparisons between similar or complementary research could be made to identify overlaps among institutions in specific research topics. Inferences about the potential multipurpose uses can also be drawn from comparing similar research projects.

Two definitions are necessary for this assessment: implementation barriers and multipurpose use cases.

A.3.1 Implementation Barriers

Implementation barriers were identified based on evaluation of open-source information. Implementation barriers were also identified in previous PNNL research. PNNL researchers Schroeder et al. conducted an online survey requesting the opinion of 250 U.S. first responders about the “effectiveness, security, and reliability of past, current, and future [IoT] technology” (Schroeder et al. 2018). Through this study, the top barriers identified to adopting a new technology included budget restrictions or costs, insufficient training resources, insufficient interagency collaboration, device and platform interoperability, and inefficient communication network reliability. These top barriers were used to develop the foundation for this portion of the impact assessment and to categorize implementation barriers. However, the literature review results produced no technologies or research in the “inefficient communication network reliability” category. This may be due to the type of respondent in the 2018 PNNL study. This category was excluded from the list, and the barrier category “policy” was added.

Based on the potential barriers, each evaluated entry was given an implementation rating of “high implementation” or “low implementation.” High implementation indicated a perceived minimal impact from the implementation barriers. Low implementation indicated a perceived significant impact on implementation.

A.3.1.1 Implementation Barriers Definition

Each barrier category is subjective and based on open-source information, which can often be limited. Parameters used to categorize each implementation barrier were used to establish and maintain conformity. Parameters are as follows:

- **Budget restrictions or cost**
  - Could it be expensive equipment?
  - Is it a single-purpose or single-use piece of equipment?
  - Does it potentially require a subscription purchase or have an element or continual updating (potential for obsolescence)?
- **Insufficient training resources**
  - Is it a system that might require an IT professional to install and use?
  - Would it be something that needed a significant amount of training to use?
- **Insufficient interagency collaboration**
  - Would the PSFM have to be installed in multiple different locations for data integration?
  - Does it require multiple different jurisdictions to use the same PSFM?
- **Device and platform interoperability**
  - Does the research indicate potential issues with scalability or flexibility for different locations and different size municipalities?
  - Are there potential challenges with scaling from a local level to state and national levels?
- **Policy**
  - Does the PSFM include integrating AI/ML?
  - Are there other governance issues identified in the research?

A.3.2 Multipurpose Use Cases

The phrase “multipurpose use cases” indicates research that:

- Applies a standard technology in a different setting.
- Uses state-of-the-art technology to develop an innovative solution to a persistent problem.
- Connects similar capability needs to one solution.

Assessment of multipurpose use cases was completed in two ways: 1) with overt opportunities presented by the authors or 2) with PNNL suggestions. Using the technologies identified in the literature review, those identified by the authors as having an innovative approach, connecting different capability needs, or applying a technology in a different setting are noted as potential multipurpose uses. If no obvious connection leading to a potential multipurpose use was inferred, but the technology appears to have applicability in another mission area of EM, this was noted as a suggested follow-up action.

A.4 Level of Impact Assessment – Evaluating Interoperability and Implementation

Publications with a PSFM that had sufficient open-source information to categorize both an interoperability and implementation rating were plotted on a 4-box decision quadrant graph to indicate potential level of impact on EM research (see Figure A.2). Issues with either interoperability or implementation barriers do not preclude a technology from further investigation or suggest that one quadrant is more valuable. It provides identifying information that supported the results and conclusions in the following sections.

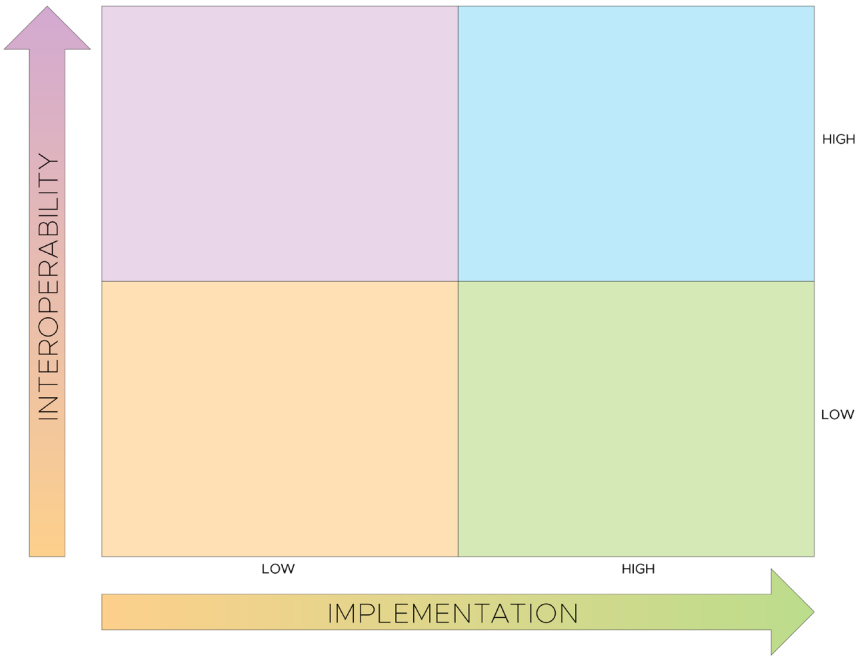

Figure A.2. Assessment-based Strategic Planning and Decision-Making

A.5 Limitations and Challenges

The findings herein are primarily based on a high-level review of technical literature. Technology and patent literature featured in the literature review should be complemented with a variety of additional information sources.

The literature review focused on published peer-reviewed articles, which reflects only a small portion of research, and the results can be skewed or lagging indicators due to the age of the publication, public and policy interests, political climate and urgency, or funding trends. Therefore, this study sought to guide decision-making for further analyses and assessments and cannot be comprehensive. Additionally, given the significant overlap with terms and mission areas of emergency preparedness, disaster management, crisis management, and so on, no firm demarcations exist between them. Furthermore, the Scopus results are limited to peer-reviewed publications and information available on open-source databases and publicly available websites.

Appendix B – Targeted Standards

The literature review identified the following non-exhaustive list of standards referenced within the research publications:

Information Sharing/Exchange

- National Information Exchange Model (NIEM) 5.2 Release (Current) – https://niem.github.io/niem-releases/5.2/
- National Institute of Standards and Technology (NIST) IR 7497 Security Architecture Design Process for Health Information (HIEs) – https://csrc.nist.gov/pubs/ir/7497/final
- International Organization of Standardization (ISO) 35.030 IT Security Including Encryption – https://www.iso.org/ics/35.030/x/
- International Organization of Standardization (ISO) Information Security Management Systems – https://www.iso.org/standard/27001
- American National Standards Institute (ANSI) INCITS 398-2008 Information Technology – Common Biometric Exchange Formats Framework (CBEFF) – https://webstore.ansi.org/standards/incits/ansiincits3982008
- EDXL-DE-V2.0: Emergency Data Exchange Language (EDXL) Distribution Element, v 2.0
- International Electrical and Electronics Engineers (IEEE), 1512-2006 – IEEE Standard for Common Incident Management Message Sets for Use by Emergency Management Centers – https://ieeexplore.ieee.org/document/1673309?arnumber=1673309
- OASIS Open Applicable Standards – https://www.oasis-open.org/standards/

Voice and Data Communications

- European Telecommunications Standards Institute (ETSI) Public Safety and Emergency Communications – https://bit.ly/3ZKIG6P
- International Electrical and Electronics Engineers (IEEE), Applicable Standards – https://standards.ieee.org/standard/

Internet Protocol

- National Institute of Standards and Technology (NIST) Special Publication 1800-16 Securing Web Transactions TLS Server Certificate Management – *https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1800-16.pdf*
- National Institute of Standards and Technology (NIST) Interagency Report 7316 Assessment of Access Control Systems - https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nistir7316.pdf
- Association of Public Safety Communications Officials (APCO) ANS 1.112.1-2014: Best Practices for the Use of Social Media in Public Safety Communications

Network Architecture

- International Organization of Standardization (ISO) 03.100.70 Management Systems Including environmental management systems (EMS), road traffic management systems,

energy management systems, health care management systems, etc. – https://www.iso.org/ics/03.100.70/x/

Cybersecurity

- National Information Exchange Model (NIEM) 5.2 Release (Current) – https://niem.github.io/niem-releases/5.2/
- National Institute of Standards and Technology (NIST) Framework for Improving Critical Infrastructure Cybersecurity Version 1.1 – https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.04162018.pdf
- National Institute of Standards and Technology (NIST) Computer Security Resource Center – https://csrc.nist.gov/publications/sp

Other

- Emergency Management Standards and Schools, National Clearinghouse for Educational Facilities (2009) – https://files.eric.ed.gov/fulltext/ED507902.pdf
- Federal Aviation Administration (FAA) – https://www.faa.gov/aircraft/draft_docs/mmel

Appendix C – Select Patent Examples

Table C.1 highlights select patent applications between 2020-2023 and provides a snapshot of activity related to public safety answering points (PSAPs).

Table C.1. Select Patent Examples

Original Company Assignee	Clusters	Invention Title	Application Date	Grant Date
Apple	Session Initiation	Method for establishing emergency communication, involves communicating with PSAP, where communications are relayed between user equipment (UE) and PSAP by cooperating UE through function of core network	2021	
Apple	Session Initiation	Method for establishing emergency communication for host UE device, involves routing traffic to PSAP through SOS Access Point Names based on approximate location of host UE	2021	
Bandwidth	Session Initiation	Method for emergency response location correction, involves routing voice over internet protocol emergency call to PSAP with corrected emergency response location	2021	2021
Banjo	Validating And Supplementing	Method for validating and supplementing emergency call information removing private information, involves associating validated location with obtained event truthfulness probability, and sending event to PSAP	2020	2020
Banjo	Validating And Supplementing	Method for validating and supplementing emergency call information, involves sending event to PSAP and notifying PSAP of additional data related to original emergency call	2019	2019
Intrado Corp	Electronic Computing Device	Apparatus for performing insight determination from audio file from PSAP in telephone communication network, has processor that stores descriptive identifier of reoccurring topic in text files, and outputs descriptive identifier and number of occurrences to user interface	2020	2023
Intrado Corp	Session Initiation	Apparatus for providing emergency alerts in real-time to PSAP, has processor generating voice call to telephone number of call station, and transmitting voice call and attached tag to call station	2020	2022
Motorola Solutions	Public Safety Incident	Method for selecting PSAP on call, involves communicating on call with second communication device and PSAP as selected by network server at first communication device	2021	2022
Motorola Solutions	Session Initiation	Method for routing emergency call between PSAP and in-field first responders, involves comparing identity and location of emergency caller to identities and locations of first responders associated with incidents	2021	2022
Motorola Solutions	Patient, Emergency Response System	Method for assigning role to PSAP user, involves serving corresponding interface to call-taking application, first-responder-dispatching application that combines the call-taking and dispatching application	2020	2021
Motorola Solutions	Public Safety Incident	Duplicate call-handling method for PSAP device, involves determining, by PSAP device, remaining information to be collected based on duplicate call policies and received information	2019	2020
Motorola Solutions	Session Initiation	System for transferring computer-aided dispatch incident data between PSAP station computing devices, sends request including identifier identifying PSAP position of second PSAP station, to emergency call-handling server	2019	2020

Original Company Assignee	Clusters	Invention Title	Application Date	Grant Date
Motorola Solutions	Public Safety Incident	Method for PSAP to EOC communication, involves altering PSAP operations based on EOC initiating the response and updating PSAP scripts	2019	2021
Qualcomm	Frequency Division	Method for supporting location services for UE, involves sending location information including civic location to be sent to PSAP for emergency call to location server	2021	
Qualcomm	Session Initiation	Method for supporting location-based routing of emergency call for UE to PSAP for providing communication services, such as packet data, involves obtaining location estimate within a first response time	2020	
Rapid Deploy	Public Safety Incident	Method for handling and displaying data associated with, for example, fire in PSAP of telecommunicator, involves identifying incident for response coordination by user of emergency response system	2022	
Rapid Deploy	Public Safety Incident	System for providing locations of emergency callers, has supplemental signal indicator including visual characteristic indicating that supplemental data signal corresponds to emergency call received at first PSAP	2020	2021
RapidSOS	Emergency Data	Method for providing responder forecast for emergency situation to display on computing device at emergency dispatch center (i.e., PSAP) by using EM system, involves providing responder forecast for display on computing device at dispatch center	2022	
RapidSOS	Emergency Data	Computer-based method for improving location accuracy associated with reported location by emergency location analysis system, involves providing improved location to multiple recipients comprising PSAP	2020	
RapidSOS	Emergency Data	System for delivering emergency data to an emergency service provider, comprises an EM system that delivers an emergency data to a PSAP with a processor, a memory, and instructions	2020	2022
Ericsson	Session Initiation	Core network node for providing a message service center address in communication network, provides message service center address to PSAP of local serving network for advanced mobile location service	2019	
T-Mobile Innovations LLC	Session Initiation	Device-based hybrid horizontal uncertainty enhanced 911 method, involves sending location report to PSAP by using cell ID or enhanced cell ID if horizontal uncertainty for device-based hybrid location reaches threshold value	2021	2023
T-Mobile	Session Initiation	Computer-readable storage medium for providing timely location estimates to PSAP by network when UE initiates call to emergency number, has set of instructions for forwarding call to PSAP	2021	2023
T-Mobile	Session Initiation	Method for providing UE location information during enhanced 911 call to PSAP or gateway mobile location center for determining location of person by emergency responders, involves transmitting determined location of UE to emergency monitoring node	2021	2023
T-Mobile	Session Initiation	Computer-implemented method for improving emergency message reliability, involves maintaining emergency text message session with PSAP until extended message session relay protocol inactivity timer expires	2020	2022
T-Mobile	Session Initiation	Method for testing a PSAP, involves receiving from a device a text-to-911 message directed to a test number of an emergency call center at a network that is directing to the test number of the PSAP and routing the text-to-911 message to an administrative line	2020	2021

Original Company Assignee	Clusters	Invention Title	Application Date	Grant Date
Unify Patente	Evacuation System	Method for performing blockchain-driven inter-PSAP communication using encapsulated virtual chains, involves analyzing retrieved transactions to identify possible capacity needs for future tasks related to distribution among neighbor nodes	2022	
Unify Patente	Session Initiation	Emergency call continuation method for PSAP failures in emergency network, involves matching calls that are active on failed PSAP with end devices assigned to calls	2021	
Unify Patente	Session Initiation	Method for establishing optimized data streams in network, involves instructing PSAP elements to exchange session description protocol-codecs of calls in queues	2021	2023
Unify Patente	Session Initiation	Method for improving emergency response time for mobile callers, involves queuing emergency call by PSAP element and sending rebid request to location information server to get information about current geolocation	2021	
Unify Patente	Session Initiation	Method for dynamic short dial allocation in e.g., emergency systems to support primarily call taker, involves displaying appropriate short dials for emergency services or departments which must be notified to graphic user interface of PSAP device	2021	
Unify Patente	Session Initiation	Method for defeating media-coordinated attacks on emergency call networks, involves downgrading call to audio only and routing call to PSAP element without transcoding	2021	
Unify Patente	Session Initiation	Method for processing emergency incident in emergency communication system, involves sending message to secondary PSAP for handling emergency incident by emergency services routing proxy	2021	2023
Unify Patente	Session Initiation	Computer-implemented method for optimizing bandwidth in PSAP environment, involves providing option for downgrading emergency call to call, and downgrading real-time processing stream to audio call	2020	
Unify Patente	Session Initiation	Computer-implemented method for processing emergency incident reported to PSAP by user of mobile communication device, involves verifying if similar objects are received from co-located mobile communication devices	2020	
Unify Patente	Session Initiation	Computer-implemented method of processing emergency call in emergency communication network, involves transmitting list to PSAP to be displayed at display device of call taker at PSAP handling emergency call	2020	
Unify Patente	Session Initiation	Computer-implemented method for processing emergency call reported to PSAP, involves initiating SIP INVITE request to carrier upon detecting that user of communication device does not respond to callback request	2020	
Verizon Patent and Licensing	Session Initiation	Method for authenticating subscriber identity, involves transmitting subscriber identity to PSAP through secure telephone identity authentication framework that uses subscriber identity	2020	
Zoom	Session Initiation	Method for location determination and telephone number distribution for emergency calls, involves facilitating emergency call between calling device and PSAP based on telephone number from pool of telephone numbers	2023	
Zoom	Cloud Computing	Method for integrated emergency event detection and mapping, involves concurrently routing emergency call to PSAP and to monitoring device registered with software platform to enable operator of monitoring device	2022	

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