Community-led low-cost micro-seismic (MS) sensor network applications for Earthquake Early Warning (EEW)

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Executive summary

This research has investigated the feasibility of a decentralised network of low-cost Microelectromechanical Systems (MEMS) based ground motion detection sensors hosted by the general public to generate EEW applications for Aotearoa New Zealand. The research has taken the design science approach supported by the active participation of members of the general public and a number of relevant stakeholders including researchers, practitioners and members from the civil defence and emergency management community. As the first step, potential user needs, views and concerns with regard to implementing EEW systems and receiving EEW in NZ were identified by engaging with the communities and stakeholder groups. Subsequently, a Community of Practice (CoP) for EEW was formed as a knowledge-sharing platform. In parallel, this research has investigated the strengths and weaknesses of existing low-cost sensors and sensor networks to issue EEW. As the final step, on an experimental basis, a self-configurable EEW sensor network architecture consisting of low-cost MEMS devices hosted by the members of the general public was deployed in the Wellington Region and its performance was evaluated. The research findings highlighted the essential need for close and continuous engagement with various potential end-user groups throughout the design, development and implementation of any EEW system. Further, the findings of this research provided clear evidence to confirm that the proposed type of low-cost EEW sensor network can successfully be implemented by choosing the appropriate sensors and algorithms. The outcomes of the research provide a comprehensive guide to constructing an EEW sensor network with decentralised processing and can be used as a benchmark, which is beneficial in building similar networks in the future. Furthermore, the proposed concept of a decentralised, low-cost sensor network architecture can be applied to implement community-engaged warning applications in other disaster domains, such as developing low-cost warning systems for bushfires.

Keywords

Earthquakes, earthquake early warning, microelectromechanical systems, low-cost, design science, the community of practice, sensor network, public engagement

Contents

Introduction

Interest in issuing EEW around the world is increasing and research has found significant benefits of having such EEW systems to warn the public [1]. In recent times, large Earthquakes (EQs) have caused significant destruction and loss to both humans and infrastructure [2]. Unfortunately, compared to most other natural disasters, advanced detection of imminent EQs is still in its infancy [1]. As a form of a precautionary risk mitigation measure, some countries have better building codes and built infrastructure to withstand EQs. However, most earthquake-prone developing countries find this economically challenging [3]. As an alternative solution, interest in issuing EEWs is increasing across the world [4]. Recent work carried out by A.Prof. Julia Becker, one of the investigators of this research project has found significant benefits of having such EEW systems to warn the public [5]. Even providing a 20-30 second longer warning window was found to be beneficial, as it allows people to take protective actions and to mentally prepare themselves for impending earthquake shaking [5]. However, the costs involved in deploying a densely populated network of expensive seismographs in a vast geographic area limits the realization of such systems not only for developing countries but even for developed countries.

The above-described gaps in research have led us to explore state-of-the-art research on “citizen-led self-aligning and self-healing IoT (internet of things) embedded systems” to foster low-cost EEW applications. In the process, we have developed a CoP as a means of knowledge sharing and closely engaged with several community groups across Aotearoa New Zealand to understand their specific needs, concerns and perceptions of community-led low-cost EEW solutions, in parallel we investigated the current state of the art of low-cost EEW systems implemented, including strengths and weaknesses of various low-cost sensor solutions and networking solutions. Finally, findings from these research activities have guided us to develop a MEMS-based experimental EEW sensor network where the sensors are hosted by the members of the public in the Wellington Region of Aotearoa New Zealand.

The above core activities of the research were conducted by taking an overarching research approach called design science. Design science is an iterative approach that helps put a people-first lens on a public EEW system. It recognizes that a warning system is as much about people and their behaviours as the technical infrastructure. The approach of design science supports designing an artefact (e.g. system, product, or process) with people who want to address a real-world problem and contribute to finding solutions [6][7]. Figure 1 illustrates the cyclical processes to be involved in developing an EEW with the approach of design science.

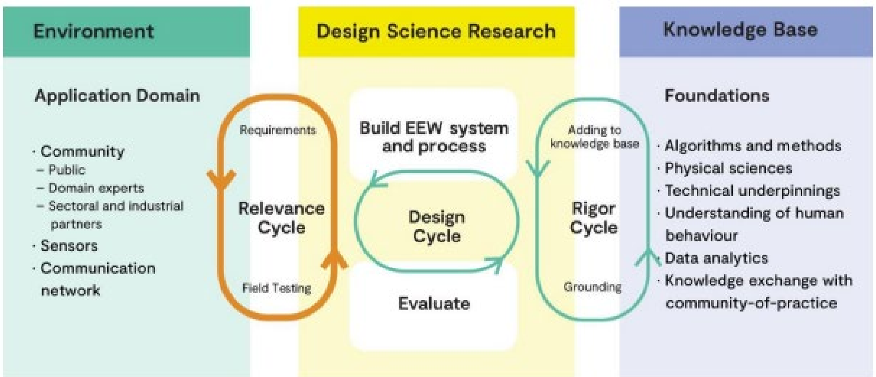

Figure 1: Design Science approach for EEW System design and development

The three cycles of design science ensure that the research project is relevant to its environment (relevance cycle), that it is rigorously grounded on scientific knowledge (rigour cycle), and that the design is iteratively re-evaluated and refined on both environmental context and knowledge (design cycle) [6].

This report discusses the process and activities conducted towards achieving the aims and objectives of the research. Further, in relation to each objective, the report elaborates on findings and outcomes at the end of achieving the anticipated objectives.

Discussion

Stakeholder Engagement

Understanding end-user needs and concerns particularly focus on the relevance cycle, highlighting participatory engagement as a part of the design science approach that elevates a people-centred methodology. As the relevance cycle related activity, the research team engaged with stakeholders using various approaches, including initiating a CoP [8] and facilitating community engagements with the public.

Community of Practice (CoP)

Understanding the viability of EEW for New Zealand requires a multi-faceted transdisciplinary approach that engages with various stakeholders to address complex technical and social issues. Establishing a CoP can support the needed conversations with various stakeholders from research and industry on EEW for New Zealand. A CoP comprises members who share a common concern or passion, and they regularly interact to learn how to do things better. The CoP build relationships to create technical advancements motivated by shared goals [9]. In the disaster resilience space, establishing CoP can enhance a community's resilience as CoP promotes exchange among stakeholders, improves knowledge mobilisation, and facilitates the adoption and use of technological systems [10].

This research project has used a social engagement approach by starting a CoP to support and strengthen the core technological research and development activities of the project. The project started to facilitate conversations with the broader community of researchers and practitioners engaging in EEW. From January to March 2020, the project team identified and corresponded with different stakeholders from universities, research institutions, sensor manufacturers, emergency management authorities, and other interest groups to be part of the CoP. The CoP's philosophy is to maintain engagement with various parties with different project objectives but collectively want to advance EEW for New Zealand. The project had planned for three main activity types for the first year: (1) meet and greet events, (2) information sharing seminars with experts locally and internationally, and (3) requirements gathering activities for EEW systems.

The established CoP was launched with the first online workshop with 29 attendees. The launch workshop aimed to discuss previous EEW research and initiate a collaborative discussion on advancing EEW. It included short presentations from different stakeholders (sectors from academia, business, emergency management, etc.) discussing current research and experiences on EEW. The workshop gave the members of the CoP to meet each other and share their knowledge about the current projects and opportunities for EEW in Aotearoa New Zealand.

Shared Value Workshop

From the initial activities, it became evident that the members of the CoP come from different backgrounds but have a shared interest in advancing EEW for Aotearoa New Zealand. The project team realised that it is important to understand the shared values and the different perspectives of the CoP members. A community with shared values and common interests opens an environment for its members to share knowledge and information [11]. A shared values workshop was designed and conducted in July 2020 to scope the perceptions of EEW and share values among researchers and practitioners.

The 22 workshop participants came from different sectors, including universities, crown research institutes, emergency management authorities, private companies, and outreach programmes. The participants had a diversity of expertise on different topics including structural engineering, information systems, seismology, computer science, warning systems and public alerting structures, risk assessment and management, emergency management, science communication, social sciences, and community engagement,

The online workshop involved semi-structured discussions with the attendees. The project team presented three guide questions for the workshop that helped prompt discussions. The questions were piloted and refined before its use in the workshop. (1) What are your aspirations for EEW in New Zealand? (2) What strengths do you wish to share with the CoP? (3) Where do you think is a good place to start EEW research with communities?

The analysis of the transcriptions indicated that the topics discussed by the participants fall into four broad themes: (1) technology, (2) people, (3) knowledge, and (4) broader perspectives (i.e. broader framework of the early warning system and hazard risk management). The workshop brought about the participants' thoughts on technological considerations, challenges, and benefits of an EEW. The workshop also emphasised that an EEW system also involves the people; the public must understand, trust, and use the system. Furthermore, the effectiveness of an EEW system requires knowledge exchange between the technological and social sides. Finally, the CoP also needs to have an overarching outlook to consider the risks, benefits, and broader considerations of an EEW system.

The participants' general expectations for an EEW system identified from the workshop findings can be summarised in four categories:

- a system that generates useful information that can be used for decision making by end users,
- an EEW system that prioritises people-centred technology solutions,
- a nationally implemented system that uses affordable technology, and
- an integrated design that uses current and new technologies, can incorporate different data sources and be utilised for other purposes.

Webinars Series and CoP Knowledge Sharing

Since the initial launch workshop project team arranged succeeding webinars and workshops to ensure continued conversations on the various topics involving EEW. For the webinars, international subject matter experts shared their knowledge with the CoP. Workshops were also held with the participation of CoP members to have an in-depth discussion on the issues, concerns and expectations of EEW in Aotearoa New Zealand. Please refer to the outputs and dissemination section for the complete list of Webinars and access links to their recordings.

Public Engagement for Community Perspectives on EEW

In parallel to the CoP activities, to study the community perspectives relevant to this project, eight workshops were conducted in four distinct environments across New Zealand, including a major city, four coastal towns, two urban in-land cities, and a small in-land rural community recently affected by a magnitude 7.8 earthquake. Conducting these workshops provided a platform for a collective process of reflection-inaction where the project team and the communities articulate mutual aims and define appropriate methods to attain them. The workshops are considered an essential part of the relevance cycle; they ensure that the process of designing an EEW system is contextualized appropriately in its environment and connected to community needs.

The recruitment approach was through making connections and introductions — for four workshops, the first contact came through arrangements with local Civil Defence groups, and for the rest of the workshops, the research team contacted and initiated meetings with various community leaders. The participants were from various affinity groups and community providers, including indigenous affiliations, migrant communities, surf clubs, retired individuals, urban residents, rural communities, and subject matter experts on earthquake engineering. The community engagements consisted of eight in-person workshops and 140 participants. Conducting research in Aotearoa New Zealand also involves recognizing and supporting indigenous Māori knowledge and designing a clear engagement pathway with Māori [12]. Cultural inclusion means increasing recognition of indigenous viewpoints and bodies of knowledge to foster changes and policies that are genuinely effective, such as seen in the culture-based approaches in the climate change adaptation space [13]. The engagement included a workshop held at a marae with the kaumātua of a Māori community.

Driven by the design science research approach, the team has chosen to use their own proven participatory method — The Comfort Board — to plan, deliver and engage with community groups. The Comfort Board is an approach that enables meaningful conversations with communities on a specific topic [14]. It is especially useful when exploring projects that are not fully realized or implemented, as it uses narrativized scenarios that model future situations (such as an earthquake). The method provides a platform for the participants to deliberate, find common ground consensus, and design potential solutions or recommendations to the issues described. Most importantly, participants narrate the key themes in their own words, within their world views and according to their community's needs and aspirations. The Comfort Board method was delivered via a two-hour workshop encouraging discussion among the participants. The deliberative process has provided an avenue for participants to receive and exchange information, examine an issue critically, and agree on points that will inform decision-making [15]. The Comfort Board uses scenarios that model real-life situations to gather from participants a range of attitudes and experiences to a particular issue or problem based on their own life experiences or life views. To investigate people's thoughts on EEW, five hypothetical scenarios were used, each scenario building on the next, spanning a time frame of 10 years. The five scenarios tackle distinct topics relating to EEW implementation through to use long-term use. Central to the scenario progression is the introduction of prompts to explore different conditions for an EEW system across three stages: before, during, and after an earthquake. Each scenario explored different social and technical variables contributing to the implementation of an EEW in New Zealand. On completing all five scenarios, the final workshop task asked participants to collectively identify and prioritize the common ground themes and concerns voiced across the workshop conversations that they consider most important to increasing comfort.

The community workshops revealed a central principle of 'People, Place, and Protection' — that a New Zealand-based EEW system should protect people in the context of where they live. The participants emphasized the need for a holistic approach considering the intersections between (1) services and technology, (2) communication, and (3) human behaviour.

Analysis of the data from all the workshops found a clear consistent requirement voiced by the public on the need for a holistic system prioritising human needs over technical requirements or feasibility. The central principle underpinning participants' responses was to protect people in the place they live. People's worldviews and lived experience informed their levels of trust and perceived benefit in each of the scenarios. Participants frequently made reference to their geographical locality and the specific impact of earthquakes and associated disasters (e.g. coastal environments with high tsunami risk).

Beyond this overarching theme, people's responses emphasized the need for a holistic approach considering the intersections between three main thematic areas or 'lenses' — (1) human behaviour, (2) services and technology, and (3) communication related to an EEW system. Each of these lenses can be understood as interconnected, informing and responding to each other.

The areas of intersection between the lenses and the overarching theme of people, place and protection suggest the need for an inclusive and evidence-based approach to all components of an EEW system and an education programme for the public that is informative and ensures communities can normalise EEW into their established ways of preparing for disasters. As shown in Figure 2 these can be summarised into a conceptual framework for an inclusive, evidence-based, informative approach to a people-centred EEW system.

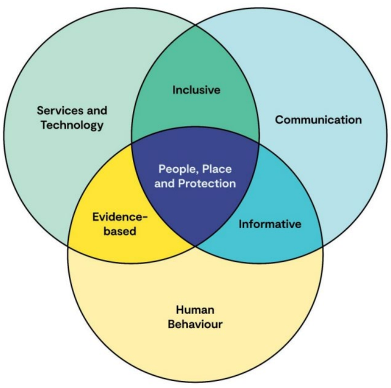

Figure 2: Conceptual Framework for people-centred EEW System

Further, the following synthesis of qualitative data collected from workshop participants is grouped around 14 topic areas:

- In Partnership with Māori
- A Positive Response
- A Holistic Approach
- Inclusiveness
- Accessibility
- Multiple Warnings Modes
- Public Engagement and Communication
- Education and Training
- Fatigue and Anxiety
- False Alarms
- Accuracy and Reliability
- Data and privacy
- Customisation and Settings
- Location Tracking

Review of the state of the art of low-cost EEW systems

An EEW sensor network involves complex earthquake-related processing, which makes generating reliable alerts challenging [16]. Technological advances in seismic instrumentation, digital communication, algorithms, and processing permit the implementation of a robust EEW system [16]. Moreover, to identify earthquakes and send alerts in real time, EEW systems require a network of geographically dispersed ground motion sensors to create alerts. As such, an EEW system can be expensive to implement and maintain. In recent years multiple innovations, supported by low-cost sensors [17] have made it possible to have more affordable systems. Therefore, as an initial step of the research project and prior to proposing a solution, the research team has explored the state of art of low-cost EEW systems. As a result, a comprehensive literature review was conducted. This literature review was driven by an evidence-based EEW classification developed by this project. Having taken the design science approach and positioned it as an activity within its rigour cycle this classification was introduced after investigating the characteristics of almost all the types of EEW systems. In the process of developing the classification, our team has found that there are different approaches to implementing EEW systems. However, to our understanding, no existing framework classifies such approaches to implementing an EEW system according to its characteristics. EEW systems are complex systems, and comprehensive classification of such systems can help better organise the study of an EEW system. This will particularly be helpful for those researching, designing, or implementing EEW systems.

Our investigations have led to findings showing that EEW systems can be classified into two main categories, based on the number of sensors used to detect an earthquake (i.e. on-site networks use a single sensor and regional-based networks use an array of sensors) [18,19,20]. Regional EEW systems can be further classified according to the type of algorithm used. Regional EEW systems are primarily implemented using two different kinds of EEW algorithms, namely: source-based and ground motion-based algorithms [21]. Figure 3 illustrates the classification based on EEW algorithms.

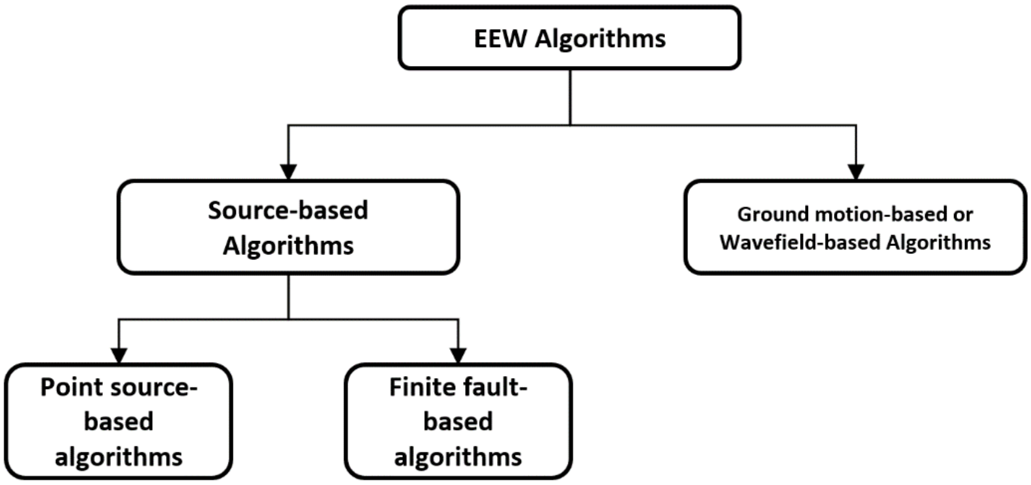

Figure 3: Algorithm-Based EEW Classification

The subsequent explorations of the research were based on the above classification. According to their strong-motion data acquisition system (DAS) class, the four types of ground motion sensors employed in EEWSs are A, B, C, and D [22]. Class A type sensors are high-performance near state-of-the-art sensors that can record ground motion in a high DAS resolution and DAS dynamic range. In contrast, for classes B, C and D, the DAS resolution and DAS dynamic range tend to decrease accordingly, and the cost related to each type of sensor will increase with the performance (with class A being the most expensive) [22]. For example, implementing an EEW system with class A sensors will cost millions, while the EEW system with class C and D sensors needs thousands of dollars for implementation [23]. Therefore, EEWSs can be classified into two groups according to their implementation cost: conventional high-end EEW systems and low-cost EEW systems [22]. The conventional high-end EEW systems are high-cost networks constructed using high-performing class A seismic sensors. The low-cost EEWSs are constructed using lower-classed sensors, mainly class C MEMS-based seismic sensors.

Low-cost alternative technology solutions are emerging to create cost-effective EEWSs instead of expensive high-end EEWSs. Internet of Things (IoT) technologies powered by microelectromechanical systems (MEMS)-based sensors are a part of low-cost solutions [21]. Past research has been conducted on developing EEW systems using low-cost MEMS-based sensors. Examples of systems that use low-cost MEMS sensors include those in Taiwan [24], California [25], Iceland [26], and China [27]. These affordable EEW system deployments have shown the practicality and capacity of MEMS-based sensor networks to deliver EEW. They could become a solution for earthquake-prone countries that may not have sufficient economic capability to afford high-end EEW systems. In addition, low-cost MEMS-based networks can be helpful, as complementary systems, for territories that have already implemented conventional EEW systems.

Exploration made on the low-cost EEW systems can be summarised as below:

	Regional EEWSs		On-site EEWSs
	Source-based Methods	Ground-motion based Methods	
Experimental / Initial stage	Istanbul Japan USA Costa-Rica Canada China	New Zealand	Kyrgyzstan BLESeis Taiwan China Italy Northern India
Public alert generation	Taiwan, China, Quake Catcher Network, MyShake, Community Seismic Network, Earthquake Network, Google, South Korea		Taiwan China

Design and Development of the Community-Engaged Low-Cost Experimental EEW Sensor Network

Having explored the public and stakeholder needs and concerns followed by identifying the strengths, weaknesses and opportunities with the current state-of-the-art of EEW supported by low-cost sensors, this research project has designed and developed an experimental EEW system consisting of MEMS-based low-cost sensors hosted by the general public. Unique to any of the previously conducted EEW research across the globe, we introduced a comprehensive sensor network architecture from scratch, with the specifications of the essential components needed to construct a low-cost, MEMS-based EEW system. Mostly, the previously published literature on EEW systems primarily focused only on discussions of system latency and the accuracy of the network architecture [28,21,23]. In contrast, this research has investigated all the components and steps required to implement an EEW system and compared them with the existing approaches. In addition, the decentralised EEW sensor network architecture proposed in this project demonstrated that the detection of earthquakes and processing of ground-motion data can successfully be implemented at the sensor node. This research explored and implemented an experimental EEW system by employing 100% decentralised processing compared to the currently available EEW approaches based on centralised processing [28,21,23,29]. Even though, previously Fischer and colleagues proposed a decentralised EEW approach, there are no clear findings on the robustness of their system [30]. Further, the system proposed in this project also demonstrated that using a lightweight and easy-to-implement algorithm such as PLUM (Propagation of Local Undamped Motion) can be considered an ideal EEW approach, that is suitable for implementation in resource-constrained environments such as low-cost MEMS-based sensors.

Our work demonstrates that a low-cost MEMS-based sensor network with decentralised processing can be used to produce EEW alerts to the public at a minimal cost compared to both high-end EEW systems such as California's ShakeAlert and low-cost systems such as Costa-Rica's ASTUTI [23]. Further, it should be noted that, with the decentralised processing, the proposed EEW architecture outperforms a system with centralised processing; therefore, there will be no additional costs in implementing a centralised middleware server. The major proportion of the cost of our proposed EEW solution is allocated for purchasing the MEMS-based Raspberry Shake ground motion detection sensors. Furthermore, the annual running cost of the proposed network primarily consisted of the internet usage of the sensors. Implemented as a community-engaged EEW solution, the public is usually happy to absorb the internet charges.

Most of the network architectures constructed for EEW systems in the past were mainly focused on centralised processing rather than node-level processing. From the results of our proposed decentralised processing approach, it is clear that it outperforms the other proposed approaches worldwide [21]. The data transmission delay between the sensors plays a significant role in the system latency of the EEW system. Our results have shown that the standard data communication protocols UDP (User Datagram Protocol) and TCP (Transmission Control Protocol) outperform the commonly used communication protocol MQTT (MQ Telemetry Transport). Even though the UDP outperforms TCP by a minimum value of approximately 35ms, it is always advisable to use TCP as the communication protocol for time-critical applications due to its higher reliability compared to UDP. To compare and evaluate the performance of the communication protocols, along with the proposed SD-WAN (software-defined wide area network) architecture, we implemented a centralised processing architecture by adding an AWS (Amazon Web Services) virtual machine to the network. From the results obtained from the latency calculations, we observed that the system latency of our proposed decentralised processing outperforms the MQTT-based centralised processing approach by a considerable value of approximately 2s. It is also evident that packet loss when using MQTT is a significant drawback for a time-critical application, where packet losses cannot be accepted.

The results have further shown that the system latency of the centralised processing increases with the number of sensors in the network since there is only one processing unit for the complete network, compared to decentralised processing, where each sensor processes the algorithm for the sensors within the 30km radius. Furthermore, the additional processing blocks for the centralised server, such as identifying the area of the particular sensor and the neighbouring sensors in an earthquake event, will also add to the delay. In comparison, our approach will not have such a delay as the sensors only directly communicate with other sensors in the 30km radius area. Our results also have shown that the decentralised processing approach significantly reduces latency by deploying more sensors in the network, which will shrink the travel time of the S-wave between the two neighbouring sensors [31]. Furthermore, for a larger network with a considerable number of sensors, it should be noted that the processing time of the algorithm with the centralised processing approach can only be reduced by improving the processing power of the centralised server, which will eventually raise the cost of the centralised architecture. On the other hand, the cost of the decentralised EEW architectures is becoming more affordable because MEMS-based sensors are getting cheaper, while their processing power is increasing rapidly.

Regarding system latencies, the findings of this research project have clearly shown that the implementation of the TCP-based decentralised processing architecture outperforms other centralised processing architectures implemented around the world.

In addition, redundancy should be considered in case of a failure in the EEW network architecture. In our approach, the redundancy is mainly dependent on the density of the sensors in a 30km radius area since we are processing the algorithm at the sensor node. Therefore, failure of a single or multiple sensors may not cause any major network failure since the remaining sensors in a particular area will continue to process the data and detect earthquakes. On the contrary, in the centralised processing approach, failure to connect to the centralised server or failure of the centralised server itself will collapse the functionality of the entire network, and lead to failure to detect an earthquake. The EEW sensor network architecture proposed in this research is less prone to failures compared to an architecture driven by centralised processing.

In addition to that, most of the EEW approaches found in the previous literature were implemented using MQTT-based centralised processing. However, our findings proved that the TCP-based centralised processing outperforms the MQTT-based centralised processing approach. Even though implementing a TCP-based centralised processing architecture requires the inclusion of a software-defined network at the node level to identify the sensors uniquely, we have identified TCP as a better choice when reducing the system latency of the network, compared to MQTT, for a centralised EEW network.

Furthermore, in this research, we investigated the potential security-related risks and identified security breaches that can be anticipated in the proposed type of community-engaged EEW sensor network environment. To mitigate the identified vulnerabilities, we implemented appropriate measures to secure the proposed EEW sensor network that runs on the ZeroTier: a highly flexible and secure SD-WAN platform. At present, there is hardly any EEW systems-related literature that addresses potential security risks or provides solutions to mitigate such risks.

In addition to the above, the proposed architecture can be easily scaled, implemented, and exported to develop a sensor network by simply provisioning low-cost sensors, installing them in people's homes, and implementing decentralised processing at the node level. Six of the selected hypothetical earthquake scenarios used to evaluate the performance of the proposed architecture were triggered by S-waves. The outcomes after running the scenarios suggest that a low-cost, MEMS-based, decentralised processing network could achieve the fastest theoretical EEW performance compared with the other centralised EEW networks, especially with the anticipated futuristic improvements in low-cost sensors and processing algorithms. These types of low-cost sensors could also support the implementation of hybrid networks with the aim of enhancing and complementing existing EEW networks consisting of expensive Class A type seismographs. Our approach to ground-motion detection with an appropriate alerting mechanism has demonstrated an effective EEW solution, where alerts may arrive early, allowing the system end-users to carry out simple protective actions, such as drop-cover and hold.

Conclusions and key findings

Community of Practice (CoP)

It must also be recognised that Aotearoa New Zealand has a complex and diverse tectonic setting, as such there will be challenges in implementing EEW in the local and national context. EEW is a worthwhile endeavour that has potential benefits, but there are technical and social hurdles to overcome to ensure an effective and trusted system. The CoP workshop findings have shown that, although the CoP members are diverse, there are common aspirations for establishing EEW in New Zealand. The priorities of the participants to EEW differed depending on their various backgrounds. However, the participants generally agreed that a holistic approach supporting constant knowledge exchange is desirable. Neither technology requirements nor the people's needs can be addressed in isolation. Findings from the workshop also substantiated the need to start engaging in EEW conversations with the public. Suggestions on partner programmes and communities from the participants of this workshop will be useful as the project develops approaches to community engagement. Initiating this CoP is considered a crucial first step towards a people-centred approach to addressing the challenges of a viable warning system for New Zealand. The workshop highlighted the importance of having a collaborative framework for EEW research and practice. The productive discussion stemming from the workshop demonstrated that engaging with the CoP enhances the exchange and mobilisation of knowledge. The valuable insights and diversity of perspectives that stemmed from the workshop provided support to continue engaging with the CoP through different activities. These conversations must continue to happen as research in EEW progresses. More focussed discussion can be held with the CoP as different projects address the socio-technical concerns of EEW systems. The EEW CoP, as an ongoing initiative, will be responsive to the various socio-technical issues of conceptualising an EEW system

Public Engagement

The workshops with the different segments of the public set out to explore the views of people regarding implementing an EEW system and to better understand the needs, opportunities and challenges of establishing such a system. Overall, the participants who engaged in the workshop were supportive of an EEW system. Although there were caveats for how EEW would respond to community needs, participants still felt that the potential for any form of prior warning for an imminent earthquake would be better than no warning. They also understood that the development of warning systems would be iterative over time. Further, workshops confirmed the sentiments from past research that the New Zealand public has a positive outlook towards EEW [32][33].

However, despite the positive views, the findings from the workshops have shown that there are challenges to overcome to ensure that a public EEW system will achieve its intended benefits. The participants envisaged a holistic EEW system for New Zealand that considers the intersections between services and technology, communication, and human behaviour. They expected that this holistic system would have a suitable level of public engagement, transparency, and inclusion to ensure that it would benefit the population – balancing human needs with technology.

The community workshops have highlighted three design considerations for developing a public-facing EEW in Aotearoa New Zealand. First, a public engagement strategy should be designed as part of the EEW system. Public education should be prioritized in communicating the system, the appropriate responses, and its role in overall earthquake preparedness for the country. Second, the system should be designed for transparency when dealing with alerting errors. The community workshops have shown that the public generally accepts missed and false alerts, but the designers and custodians of the EEW system must be transparent about its limitations. Third, design considerations should be made for special interests – for instance, integrating tsunami warnings and actions is seen as critical for New Zealand coastal communities. Designing an EEW system is complex and multi-faceted. It may not be possible to address all the needs. Still, these conversations are essential to help prioritize which challenges must be overcome to help deliver an EEW that will ultimately benefit the public.

Current state of the art of technology

The findings from the review of the current state-of-the-art of low-cost EEW solutions clearly suggest that low-cost EEWSs have become a solution for earthquake-prone countries which are not economically able to afford high-end EEW systems. Also, it is evident that the low-cost EEW systems serve as a support system for countries with high-end conventional EEW systems. However, it was identified that 1) most of the low-cost EEW systems were centralised, 2) EEW systems support only a single type of low-cost ground motion detection sensor, and 3) most of the regional EEW systems adopted the source-based algorithms which consume a significant amount of time in detecting and estimating earthquake parameters. Also, the main challenges in implementing a low-cost EEW system were identified as: 1) security measure which needs to be analysed further in terms of constructing a community-engaged EEW system, and 2) detecting human activities related motions from the earthquake's ground motion in smartphone-based EEW systems. Exploring the feasibility of node-level processing, introducing multi-sensor support capability, and adopting ground motion-based EEW algorithms for regional EEW systems are areas for future research. Investigation into these identified research areas and opportunities for low-cost EEW systems is identified as beneficial for building robust, low-cost MEMS-based EEW sensor networks, significantly benefiting regions of high seismicity.

Experimental low-cost EEW network

Guided by knowledge sharing from CoP, findings from the community engagement and the explorations of capability and limitations of the current state-of-the-art of low-cost sensors, in the final phase of the research, we have investigated the feasibility of implementing an EEW sensor network that processes the detection algorithm at node-level rather than at a centralised processor. We also presented a step-by-step guide to building an EEW sensor network with low-cost, MEMS-based sensors. This research provides clear evidence to confirm that the proposed type of EEW system can successfully be implemented by choosing the appropriate detection sensors and algorithms. Therefore, the outcomes of our low-cost EEW experimental sensor network can be considered as providing a comprehensive guide to constructing an EEW sensor network with decentralised processing and can be used as a benchmark, which is beneficial in building similar networks in the future. Furthermore, the proposed concept of a decentralised, low-cost EEW sensor network architecture can be used to implement community-engaged warning applications in other disaster domains, such as developing low-cost warnings for bushfires.

We have demonstrated that the PLUM-based ground motion-based EEW algorithm can be implemented using a network of low-cost, MEMS-based sensors, providing accurate operational EEW at a lower cost compared with scientific-grade seismographs. Furthermore, we investigated the overall system latency of the proposed EEW system and its components in the proposed network. From the outcomes of the transmission delay, along with different standard communication protocols, we can confirm that the use of TCP as a communication protocol running on an appropriate SD-WAN solution can reduce the transmission delay, regardless of the type of processing architecture (centralised or decentralised). In terms of the detection time, by introducing the decentralised processing architecture, we showed that our results outperform the commonly implemented centralised processing EEW sensor network architectures. It should be noted that the detection time of our proposed decentralised processing network does not vary with the number of sensors in the network. Thus, it should show approximately the same results as the nationwide EEW system; however, when it comes to centralised processing, the algorithm's detection time tends to increase with the number of sensors. Furthermore, the packet loss in the decentralised processing architecture is negligible compared to a centralised architecture.

The knowledge gained from the findings of this research should have made a positive contribution towards making changes to the future strategic directions proposed towards earthquake detection and monitoring in Aotearoa New Zealand. This can be justified as the recently published GeoNet Strategic Review 2022 has identified the potential of utilising low-cost sensors on parts of the future GeoNet network [34]. In conclusion, it is clearly evident that the body of work conducted in this research project and various outputs of the research project has generated a significant amount of knowledge and awareness, among various stakeholder groups, including civil defence and emergency management, not only related to low-cost EEW solutions but developing EEW solutions appropriate for Aotearoa New Zealand in general.

Peripheral contributions

In addition to the above-described outcomes directly obtained from the research activities conducted, this research project has further led to initiating activities with schools and school children to generate awareness and education supported by Raspberry Shake ground motion sensors. Further, led by Dr. Marion Tan, the research team has successfully launched the *CRISiSLab Challenge*, a technology competition for schools. This competition has created opportunities for school children to gain hands-on use of technology, computer science, geology, earthquake engineering and other related sciences by working with low-cost ground motion detection sensors.

Future work

While this project provided evidence that an EEW system can be implemented using MEMS-based, low-cost sensors without any centralised processing, we identified several areas that need further investigation and improvement.

The inherent limitations of the PLUM approach have introduced some constraints to our proposed EEW system. While the PLUM algorithm is considered a more robust approach to detecting seismic intensity, it limits the warning time to a maximum of ~10 s. Regarding the further use of S-waves to detect the intensity of shaking, the PLUM approach makes it unsuitable for providing a meaningful warning to the areas near the epicentre. To minimise the inherent limitations of the PLUM algorithm, we intend to investigate the feasibility of predicting the S-wave shaking intensities using the P-waves, which can eventually considerably increase the warning time. Additionally, we will look into different algorithms, which could predict the shaking intensity beyond the 30-km radius defined by the PLUM algorithm.

Further, we intend to implement a community-engaged sensor network comprising different types of low-cost sensors, rather than using a single type of sensor. The successful implementation of an EEW network with multiple sensor types will result in an ecosystem of community-engaged, MEMS-based, EEW sensor networks.

Although we have tested the performance of the implemented measures to enhance the security of the proposed MEMS-based decentralised sensor network, to provide a more accurate judgment, we consider it crucial to test the implemented security enhancements when exposed to real-world threats while operating under real-world scenarios. We intend to carry out in-depth testing of the implemented security enhancements as one of the future activities of our ongoing EEW research. Furthermore, we intend to develop a centralised alert service that could detect and notify users of security breaches in the sensor network and is capable of automating actions upon a suspicious activity (e.g., automatically disconnecting the breached and vulnerable sensors from the network). This feature expects to automatically remove the vulnerable sensor nodes from the network, which will eventually increase the security of the network.

The findings of the project have made a significant novel contribution towards minimising single point of failure of EEW networks in addition there has a been number of advancements when it comes to earthquake and accurate measure of ground shaking with the advances in seismic instrumentation, digital communication, algorithms and processing [35]. Despite minimising single point-of-failure events supported by decentralised data processing with a highly distributed sensor network, the proposed network architecture is still considered vulnerable in terms of providing a reliable service more sustainably with the challenges of not having reliable connectivity to the Internet in a significantly larger number of pockets in the country as well as the bigger challenge of potentially losing internet due to failures of the telecommunication networks after a large earthquake. This problem has aggravated significantly as most of the technological solutions available for EEW and post-earthquake information on building and infrastructure relied on transferring sensed data to a cloud server and hence dependent on the internet to the fullest [35]. There has been a considerable number of research conducted in the last decade exploring the option of maintaining reliable and sustainable sensor networks when there is limited access or no access to the internet. Among such alternative communication solutions, LoRa (Long Range) is identified as one of the best solutions to be considered in future research for developing more robust EEW networks [36]. We have recognised that changes to conventional early warning systems can be completely or partly satisfied by adopting LoRa embedded edge computing solutions, possibly alongside a cloud-based solution. This would bring the system resources closer to the end devices of the network with the aim of reducing latency, sustainable communications, and uninterrupted service levels.

We have already started investigating some of the above-identified areas of further research through RNC (Resilience to Nature's Challenges) funded PhD project and planning to expand investigations further with a new PhD project in 2023 funded by the recent Massey doctoral scholarship round and the funding received from the recent QuakeCoRE RfP funding round.

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Outputs and dissemination

Journal Papers

Chandrakumar, C., Prasanna, R., Stephens, M., Tan, M.L., (2022). Earthquake early warning systems based on low-cost ground motion sensors: A systematic literature review. *Frontiers in Sensors.* https://doi.org/10.3389/fsens.2022.1020202

Prasanna, R., Chandrakumar, C., Nandana, R., Holden, C., Punchihewa, A., Becker, J.S., Jeong, S., Liyanage, N., Ravishan, D., Sampath, R., Tan, M.L. (2022). "Saving precious seconds"—A novel approach to implementing a low-cost earthquake early warning system with node-level detection and alert generation. *Informatics.* https://doi.org/10.3390/informatics9010025

Tan, M.L., Becker, J.S., Stock, K., Prasanna, R., Brown. A., Kenney, C., Cui, A., Lambie, E. (2022). Understanding the social aspects of earthquake early warning: A literature review. *Frontiers in Communication.* https://doi.org/10.3389/fcomm.2022.939242

Book Chapters

Tan et al. (in review). 'Balancing human needs with technology' A design-led approach for exploring an earthquake early warning system in Aotearoa New Zealand.

Peer-Reviewed Conference Proceedings

Chandrakumar, C., Prasanna, R., Stephens, M., Tan, M.L., Holden, C., Punchihewa, A., Becker, J.S., Jeong, S., Ravishan, D. (2022). Algorithms for detecting P-waves and earthquake magnitude estimation: Initial literature review findings. In T. Huggins & V. Lemaile (Eds.) *Proceedings of ISCRAM Asia Pacific Conference 2022.*

Hong, B., Chandrakumar, C., Ravishan, D., Prasanna, R. (2022). A Peer-to-Peer Communication Method for Distributed Earthquake Early Warning Networks: Preliminary Findings. In T. Huggins & V. Lemaile (Eds.) *Proceedings of ISCRAM Asia Pacific Conference 2022.*

Tan, M. L., Prasanna, R., Becker, J. S., Brown, A., Kenney, C., Lambie, E., Johnston, D. M., Stock, K., & Alwis, D. De. (2021). Outlook for earthquake early warning for Aotearoa New Zealand: Insights from initiating a community-of-practice. *2021 Annual Technical Conference for the New Zealand Society for Earthquake Engineering*, 55–63. https://repo.nzsee.org.nz/xmlui/handle/nzsee/2350

Reports

Brown, A., Parkin, T., Tan, M. L., Prasanna, R., Becker, J., Stock, K., Kenney, C., & Lambie, E. (2021). A*n earthquake early warning system for Aotearoa New Zealand? Community engagement findings 2020–2021.* http://hdl.handle.net/10179/16735

Poster Presentations

Chandrakumar, C., Prasanna, R., Stephens, M. (2022, August 29 - September 1). *An ecosystem of low-cost sensors toward earthquake early Warning: An earthquake early warning system with multi-sensor capability* [Poster presentation]. QuakeCoRE Annual Meeting, Napier, New Zealand.

Holden, C. (2022, August 29 - September 1). *Engaging with end-users towards an earthquake early warning system for New Zealand* [Poster presentation]. QuakeCoRE Annual Meeting, Napier, New Zealand.

Prasanna, R., Chandrakumar, C., Nandana, R., Holden, C., Punchihewa, A., Becker, J.S., Jeong, S., Liyanage, N., Ravishan, D., Sampath, R., Tan, M.L. (2022, August 29 - September 1). *Saving precious seconds: A low-cost earthquake early warning system for Aotearoa, New Zealand* [Poster presentation]. QuakeCoRE Annual Meeting, Napier, New Zealand.

Tan M.L., Brown, A., Prasanna, R., Becker, J., Stock, K., Kenney, C., Cui, A., Lambie, E., Parkin, T., Reade, A., Tobin, A., Law, M. (2021, December 6 - 9). An earthquake early warning system for Aotearoa New Zealand? [Poster presentation]. QuakeCoRE Annual Meeting, Online, New Zealand

Tan M.L., Prasanna, R., Cui, A., Chandrakumar, C., Imtiaz, S.Y., Hong, B., Viggers, Z. (2022, August 29 - September 1). *CRISiSLab Challenge: Hands-on learning with Raspberry Shake seismometers* [Poster presentation]. QuakeCoRE Annual Meeting, Napier, New Zealand.

Tan M.L., Prasanna, R., Becker, J., Holden, C., Waidyanatha, N., Punchihewa, A., Jeong, S., Stock, S., Brown, A., Kenney, C., Lambie, E., Nandana, R. (2020, December 7 - 10). *An ongoing project for conceptualising a community-engaged network of low-cost sensors for earthquake early warning in Aotearoa New Zealand* [Poster presentation] QuakeCoRE Annual Meeting, Nelson, New Zealand.

Tan M.L., Vinnell, L., Prasanna, R., Becker, J.S. (2022, August 29 - September 1). *The public's initial insights on the Android Earthquake Alerts in Aotearoa New Zealand* [Poster presentation]. QuakeCoRE Annual Meeting, Napier, New Zealand.

Knowledge Sharing Webinars

2022

Becker, J., Vinnell, L. (2022). T*he human side of earthquake early warning: Intentions, perceptions, and reactions to EEW in Aotearoa New Zealand* [Video]. CRISiSLab Webinar. https://youtu.be/pjBJFJCWp7o

Berman, M. (2022). *From seismometer to smartphone: Android Earthquake Early Warning* [Video]. CRISiSLab Webinar. https://youtu.be/cWSjYZpk5Uc

Prasanna, R., Holden, C., Punchihewa, A., Chandrakumar, C. (2022). *Saving precious seconds: A new decentralised architecture for earthquake early warning* [Video]. CRISiSLab Webinar. https://youtu.be/fJQY23vjwSg

Reddy, E. (2022). *The main thing is to keep the main thing the main thing: Earthquake early warning development in a diverse community of practice* [Video]. CRISiSLab Webinar. https://youtu.be/wze1bFI_i9k

2021

CRISiSLab (2021). *Insights from community-based earthquake early warning workshops* [Video]. CRISiSLab Webinar. https://youtu.be/juRPIZJpA-I

Halldorsson, B. (2021) *Thoughts on earthquake early warning and operational earthquake forecasting in Southwest Iceland* [Video]. CRISiSLab Webinar. https://youtu.be/3215avBfpnk

Kohler, M. (2021) *Community Seismic Network and earthquake early warning* [Video]. CRISiSLab Webinar. https://youtu.be/wfH9StrmQMw

Meira, A., Kuna, V., (2021). *Open earthquake early warning: An open-source initiative to share and create a global community to develop better EEW systems* [Video]. https://youtu.be/Cip7KSvbTww

Yamada, M. (2021) *Earthquake early warning in Japan: On Integrated Particle Filter (IPF) and Propagation of Local Undamped Motion (PLUM) methods* [Video]. CRISiSLab Webinar. https://youtu.be/peoPDEG3slk

2020

Haklay, M. (2020) Citizen science and disaster risk reduction. CRISiSLab Webinar. https://crisislab.org.nz/2020/05/citizen-science-webinar-with-prof-muki-haklay-2/

Low, G. (2020) *Sensors in schools - Raspberry Shake seismographs: Engaging with schools and communities* [Video]. CRISiSLab Webinar https://youtu.be/Yoecgr-qybE

McBride, S. (2020). *Social science and shakealert*. CRISiSLab Webinar. https://crisislab.org.nz/2020/09/social-science-and-shakealert/

Wu, Y.M. (2020) *Development of the low cost earthquake early warning and shakemap system in Taiwan* [Video]. https://www.youtube.com/watch?v=1gwswaE6AWM

Invited Talks & Presentations

- Presentation at the GNS Science Friday Geohazard Show and Tell Forum, 5th Nov. 2021 - Exploring the role of MEMs based ground motion detection devices in developing earthquake early warning systems.
- Presentation to the GeoNet Strategic Review Panel, 28th April 2022 - Emerging trends in sensor technology, earthquake early warning developments, and the potential implications for GeoNet's future.
- Presentation to AI Group GNS Science (wider staff including members from Geonet) 21 July 2022 – Design Science Led Socio Technical Research

Media Appearances & Outreach

- RNZ Nine to Noon - Earthquake early warning system - new research – 15th February 2021
- RNZ Nine to Noon – Kiwi Earthquake Tech Goes Global – 19th April 2022
- RNZ Detail Pod Cast - The warning you might get before the next big quake – 20th June 2022
- Our work was showcased on 16th October 2021 Saturday evening One News
    1. https://www.1news.co.nz/2021/10/16/googles-earthquake-early-warning-system-proves-worth-in-nz/?fbclid=IwAR2Dh6YLUIDqYHGLs7GhShR0B_hOtGTo5mMdK1G9oUEBinUecoY4gKRMs3I
- Toka Tū Ake EQC has released media report share the progress of the project
    i. Researchers mobilise citizen-scientists for insights into community-based Earthquake Early Warning System – 15th February 2021
    ii. Low-cost earthquake warning project gains significant momentum – 10th March 2022
    iii. New Kiwi research uncovers important gap in knowledge about early earthquake warning – 7th September 2022
- Massey University news has published the working progress of the project
    2. https://www.massey.ac.nz/massey/about-massey/news/article.cfm?mnarticle_uuid=8C9315D9-0FC2-4FB0-9BF3-F7882DA02937&fbclid=IwAR1cguCSRaatSPbTFNR9YTsTLAT6QQY8iPW1ubz2tQDWVJlYeR59UT9wTBc
- ANZIIF published an article on their Magazine for member showcasing the progress of the research project - SHAKE, RATTLE AND ROLL by Dr Shauna Sherker – 8th April 2021
- Appeared on Temblor reviewing a similar project in Costa Rica
    3. https://temblor.net/earthquake-insights/can-smartphones-affixed-to-buildings-detect-earthquakes-13269/
- Appeared on Spinoff – Your mobile phone could soon warn you of earthquakes how does it-work , - 05th May 2021 - https://thespinoff.co.nz/science/05-05-2021/your-mobile-phone-could-soon-warn-you-of-earthquakes-how-does-it-work
- Appeared on Stuff - Citizen scientists could be the key to early earthquake warning system- 15th Feb 2021 - https://www.stuff.co.nz/dominion-

post/news/wellington/124244520/citizen-scientists-could-be-the-key-to-early-earthquake-warning-system

- Appeared on Insurancenews.co.au - Seismometers to be installed in New Zealand's North Island- 14th March 2022- https://www.insurancenews.com.au/local/seismometers-to-be-installed-in-new-zealands-north-island
- Appeared on Insurance Business NZ - EQC trials low-cost earthquake warning system – 16th Feb. 2021 - https://www.insurancebusinessmag.com/nz/news/breaking-news/eqc-trials-lowcost-earthquake-warning-system-246516.aspx
- Appeared on Rotorua Now - Research for earthquake early warning system- 19th Feb 2021 - https://rotoruanow.co.nz/news/26158-research-earthquake-early-warning-system.html
- Appeared on East Coast Lab News- Researchers mobilise citizen-scientists for insights into community-based Earthquake Early Warning System - 19th Feb 2021 - https://www.eastcoastlab.org.nz/news/article/191/researchers-mobilise-citizen-scientists-for-insights-into-community-based-earthquake-early-warning-system
- Appeared on Structural Engineer – 16th April 2021 - Low-cost community-based earthquake warning system under development in New Zealand - https://www.thestructuralengineer.info/news/low-cost-community-based-earthquake-warning-system-under-development-in-new-zealand