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A Dense Network of Economical Seismic Sensors Over a 5G Telecommunications Network for Post-Earthquake Rapid Damage Assessment and Response

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ABSTRACT

The concept of an Earthquake Early Warning system over 5G (EEW-5G) has been developed in previous work with Rogers Communications. This system is based on deploying thousands of sensors spaced about 100 m apart, connected wirelessly to the 5G network in a city. Due to its density and low latency, this system can accurately predict and measure the waveforms that strike the city assets during an earthquake. This paper extends this system to include an estimate of the damage suffered by buildings and critical infrastructures during an earthquake. By having an increased resolution of the earthquake waves at the asset level, it is possible to make a more accurate assessment of the damage suffered by these structures. With more detailed damage information, structural inspectors can save valuable time in their onsite inspection of the habitability and usability of buildings, bridges, and other assets. This pre-assessment will also help to prioritize and reduce the time for the repair crews to fix the repairable assets to regain their functionality and for the emergency responders and Critical Infrastructure (CI) operators to allocate the lifeline resources (electricity, water, etc.). The software i2SIM is used to run a test case scenario on The University of British Columbia campus, illustrating the expected gains in time to restore system functionality of the habitable or repairable assets when better damage assessment information is available.

Keywords: 5G network of sensors, critical infrastructure interdependencies, earthquake early warning network, high-resolution damage assessment, shortened system recovery time.

INTRODUCTION

We have developed an Internet of Things (IoT) network of sensors for accurately determining the waveforms of seismic waves across a city during an earthquake. Many earthquake-susceptible cities have a variety of soil conditions across the city. In addition, many cities, such as Vancouver, are located in basins with complicated wave reflections. This diversity of propagation conditions and wave reflections makes it challenging to predict the detailed waveforms at any given location and assess the damage to an asset at this location. Accurate assessment of damage is important to speed up the recovery of the city's functionality.

In our work, we have developed the concept of a dense grid of affordable sensor stations (about $100 each) separated about 100 metres from each other. The grid crisscrosses the entire city area and can accurately measure the detailed waveforms (0.2 Hz to 20 Hz) of the arriving seismic waves. These detailed waveforms can be compared with the fragility curves of buildings and infrastructural assets to make a first assessment of the damage across the city and optimize the inspection, recovery and restoration actions.

The timeline of any disaster can be divided into three periods: pre-disaster, during the disaster, and post-disaster. This paper focuses on the post-disaster timeframe. In this timeframe, particularly for earthquakes, there are two main response actions to consider: (1) to rescue as many lives as possible and (2) to restore critical lifeline services (e.g., power, water, gas, and telecommunications), such that the community can start to rebuild itself and reduce the time it is in disaster state. This paper focuses on actions required to restore the infrastructure to an acceptable level of functionality in the hours and days after the disaster. The optimality of the actions taken in this period will strongly influence the total recovery time.

The past two decades have seen wireless communication systems rise in availability and reliability. 5G networks provide communication and Internet access through extensive urban and suburban infrastructure. Applications relying on wireless technologies receive stable service, quality, and security guarantees. The push for increased resiliency of cellular systems has resulted in public safety systems running on 4G and 5G instead of relying on satellites and other less ubiquitous communication systems. Ultra-Reliable Low Latency Communications (URLLC) is available in the 5G network for mission-critical applications, which allows deploying an earthquake-critical application involving an extensive network of sensors.

In previous work [1], we presented the concept of a dense network of sensors for an Earthquake Early Warning System over 5G (EEW-5G) that deploys a grid of seismic sensors at about 100 m apart wirelessly connected to the 5G network at each location. The grid can be denser in some locations than in others, depending on the variations in the soil propagation characteristics, the wave reflections in the area, and the importance of the infrastructure in the area. In large cities, critical infrastructures (CI) are strongly interdependent, resulting in a complex system. However, technologies like the EEW-5G network to locate the damage and the i2SIM simulator to optimize the allocation of the system's resources can significantly reduce the time needed to recover the system after an earthquake.

MEASURING SEISMIC WAVES WITH HIGH RESOLUTION IN TIME AND SPACE

Dense Network of Seismic Sensors

The Earthquake Early Warning over 5G (EEW-5G) for Smart Cities concept for dense urban areas [1] uses modern telecommunications networks' high-speed, wide bandwidth, and distributed computational capabilities to integrate a large array of seismic sensors covering an entire city area. The high density of the population makes the response after a seismic event particularly challenging [2], and having detailed information and strong coordination of the response events becomes critical.

The dense network of sensors resembles a grid covering the city, with each node in the grid represented by a mini-seismic station (MSe). These MSes comprise a MEMS accelerometer, a processing unit, and a cellular communication module. The MSes in this application are not battery-operated but are connected to the power supply in the building. This way, they can be permanently connected, with fewer maintenance problems, and can continuously detect small earthquakes to further train the underlying model.

The ADXL355 accelerometer, validated for the application, is a low-cost, low-power (200 µA in measurement mode, 21 µA in standby mode) MEMS accelerometer [3]. It has an ultra-low noise floor (22.5µg/√Hz all axes), digital output (integrated 20-bit ADC), minimal offset drift over temperature, and long-term stability-enabling precision applications with minimal calibration. In addition, it measures 3-axis ground acceleration where the measurement range can be selected (ranges of ±2 g, ±4 g, and ±8 g), and it captures magnitudes of intensity from 3 to 10+.

Since the MSes detect ground motion, they are firmly mounted to structures and buildings. Each station's data is associated with a specific address on the sensor grid. We consider the optimal placement of MSes to be one city block or 100 meters apart. This space resolution, accompanied by a corresponding time sampling and processing resolution, allows us to capture frequency components of up to 20 Hz of the earthquake waveforms.

For a city area of about 15 km by 15 km, we need about 20,000 MSes. Each MSe has a cost of about $100, which gives us a cost of only $2 million for the hardware part of the grid. Coordinating measurements from 20,000 sensors simultaneously is a challenge that was solved in our work, as described in [1]. To manage this number of sensors with the speed needed for an early warning application (within one or two seconds), sensors are grouped into clusters. Each cluster is assigned for processing to a separate MEC (Multi-access Edge Computer), as shown in Figure 1.

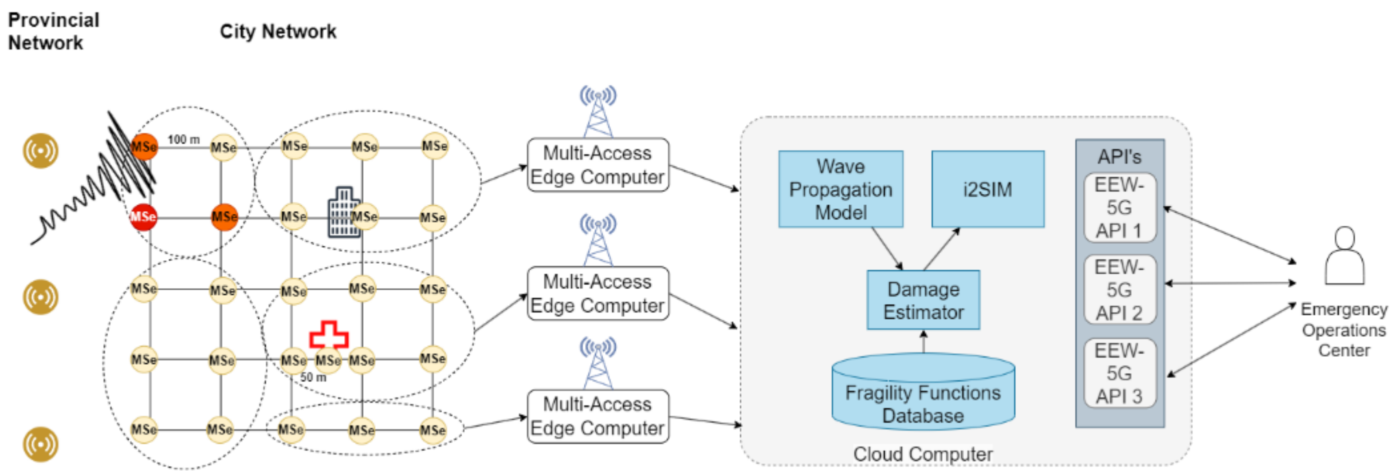

Figure 1. Global view of the 5G network connected to the whole EEW-5G system.

System Workflow

The diagram in Figure 1 illustrates the EEW-5G workflow. The MSes are deployed across the city, separated by about 100 m. They are attached to walls or structures and connected to an electrical supply. The data from the seismic sensors is transmitted wirelessly to a base station in the 5G network and sent to a MEC Computer.

Each MSe has a direct communication link to the sector's MEC and sends data directly to the MEC Agent. After initial processing and synchronization of the data packets, the wave data is sent to the Cloud computer, which hosts the wave modelling server, the damage assessment server, and the i2SIM server for decision optimization.

The MEC Agents also deliver instructions from the Cloud server to execute local actions to controllers connected to the MSes, such as sending local alarms, opening circuit breakers in the power grid, and opening valves in the gas and water networks.

The Cloud hosts the database of fragility curves and the damage assessment server. The Cloud also hosts the i2SIM server to coordinate and optimize the recovery response. i2SIM will communicate with desk computers at the Emergency Operations Centre (EOC), where the emergency response managers will coordinate the response with the first responders.

The i2SIM server is run by the Emergency Operating Centre (EOC), and the results are sent to the EOC, structural inspectors, and disaster responders. However, only the EOC can interoperate with the Cloud software. The other users will access the results through web-app desktops and mobile apps.

Earthquake Wave Propagation Mathematical Model

The physical network of the EEW-5G solution consists of N physical nodes where the MSes are located. Virtually superimposed on these nodes are the solution algorithm mathematical nodes. These solution nodes coincide with the geographical points where the mathematical solution for the wave values is calculated. These points are connected, forming squares, where the sides of the squares are wave propagation links (sides of the squares in Figure 2).

The modelling of the propagation links forming the grid is based on general wave propagation models developed originally in the context of the EMTP (Electro-Magnetic Transients Program), which is extensively used for power system transients [4,5]. The proposed Grid Wave Model (GWM) models the propagation of the waveshapes as they travel in a certain path, including multiple excitation sources and reflections. The parameters of the model depend on the propagation medium (soil). Since the propagation of the earthquake waves occurs across a geographical area, and the waves suffer multiple reflections along this area, the grid arrangement can capture the back-and-forth reflections in its grid of nodes. The grid of nodes can also capture multiple types of earthquakes and simultaneous faults.

The GWM model fundamentally differs from current models for seismic wave propagation, such as predicting the magnitude of the strong S-wave after detecting the P-wave. This is because GWM is based on a space-time discretization that accounts for non-uniform propagation due to changes in the earth's parameters (soil density and compactness) and changes in geological conditions at each location in the city. From a damage assessment point of view, this is very important because the structure's response depends highly on these geological conditions. In addition, this discretization of the modelling components results in a discrete time-domain solution in which the numerical computational errors are fixed at each decoupled node, thus allowing for the next node to be solved without error accumulation.

The numerical solution of this model is very efficient because it takes advantage of the decoupling between nodes provided by the travelling time of the wave between nodes. This decoupling drastically reduces the computer solution time from N^2 to N at each solution time step. For a city area of 15 by 15 km, with a spacing of 100 m among sensors, the number of solution nodes is about N = 20,000. Conventional methods that solve for the full wave, like finite elements, require N^2 = 400 million operations, which is too long for this application using conventional 3 GHz CPUs. With the GWM algorithm, the solution requires only N = 20,000 operations, which will take a few milliseconds in a 3 GHz CPU.

The dense network of sensors and the wave propagation model provide us with a high spatial and high temporal resolution of the incoming seismic wave as it propagates throughout the city. The fine spatial resolution allows us to estimate the damage information at the asset level. The high time resolution allows us to consider up to about 20 Hz of the earthquake frequencies, enabling an accurate damage estimation for a wide variety of structures.

Current seismic hazard risk analysis methods, such as probabilistic seismic hazard analysis (PSHA), contain many pockets of uncertainty. When these models are used to calculate structures' fragility function, uncertainties accumulate in each structure's fragility and consequence functions. Higher-resolution fragility curves are expected to match the availability of higher-resolution seismic waveforms in the future. At this time, with the proposed application in place, the bottleneck would be the uncertainties in developing these fragility curves.

Network resilience

Since the Mini-Seismic Stations are powered by the electrical grid, after an earthquake strikes, some MSes might stop reporting data due to an electrical failure. In addition, the shaking may physically damage some stations, while others may lose wireless connectivity due to collapsed communications towers. This scenario is illustrated in Figure 2(b) for lost individual stations in red and in Figure 2(c) for a group of lost stations. The latter can happen when the ground shaking impacts a Base Station or a MEC's location.

In these situations, creating virtual nodes and extrapolating their data with the solution from the Grid Wave Model (GWM) will compensate for the gaps in direct data recordings. The Damage Estimator performs this reconstruction with the available seismic data retrieved (Figure 1) using the following partial sources of data:

- Interpolated data from the non-impacted stations.
- Partial data collected in the early warning period before the earthquake strikes.
- Data calculated by the grid-propagation model (GWM) that has been updated by the propagation before the earthquake strikes.

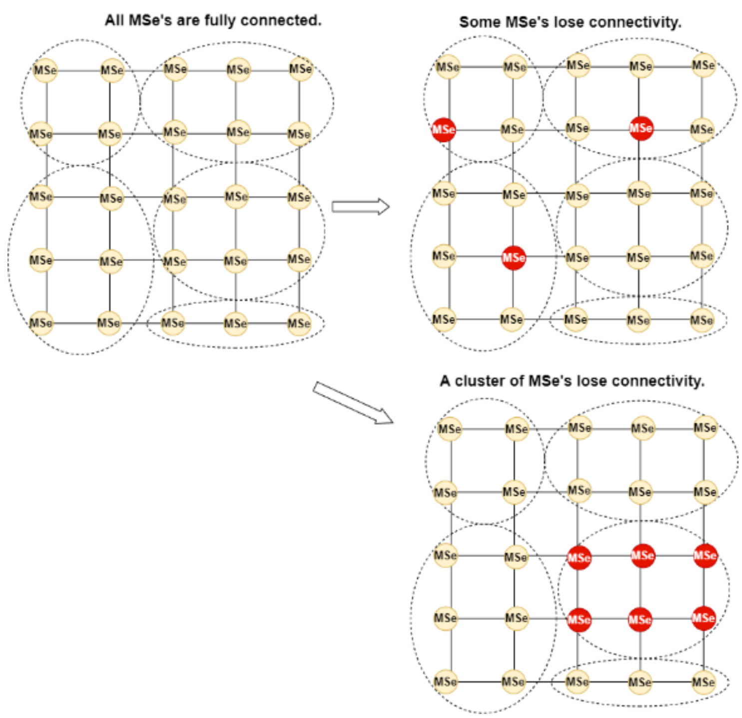

Figure 2. Failure of sensor stations: (a) Left – all sensors are working and capturing the waveform data (b) Top-Right – a few stations have lost connectivity, (c) Bottom-Right – a whole MEC has lost connectivity.

POST-EARTHQUAKE DAMAGE ASSESSMENT

Earthquake Fragility Curves

Fragility curves of structures (buildings, bridges, roads) are developed based on the spectral acceleration of the ground motions at the site where the specific hazard curve is defined [6]. For structures (e.g., a building or bridge), damage state classifications have been defined based on type, age, and construction [7]. The system of sensors proposed in this paper provides the full waveforms measured in all city locations and, therefore, detailed information on how the seismic waves propagate across the city. The availability of this detailed information can encourage the development of more precise criteria to build fragility curves for the city's assets and internal subsystems of these assets (e.g., walls, columns, ducts, and internal lifelines). Furthermore, enhanced detail in the structures' behaviour and more precise knowledge of the excitation functions (seismic waves) will result in a much lower level of statistical uncertainty in the damage assessment. The discussion in this paper is based on the assumption that this higher certainty is available in the damage assessment.

Timeline of the Damage Assessment

Post-earthquake damage assessment is the practice of inspecting structures (buildings, bridges, roads) for structural and non-structural damage immediately after an earthquake to determine the state of re-occupancy. This immediate post-disaster inspection is integral in reducing the number of possible casualties due to secondary effects, such as damaged power lines, gas lines and other life-critical hazards. In addition, safe occupancy and lifelines downtime will also reduce the need for emergency resources, such as temporary shelters, and quickly recover a sense of normality in the community [8].

Post-earthquake damage evaluation follows the ATC-20 and similar guidelines [9, 10]. There are four evaluation stages: (1) an initial windshield area assessment conducted by building officials or emergency response managers (in the order of 10 – 30 seconds per building); (2) a rapid evaluation of the buildings to place green, yellow or red placards on the structures (approximately 30 minutes per building); (3) a detailed specialized evaluation of the buildings (in the order of 1-4 hours per building) for careful visual inspection of the building, and finally (4) a detailed engineering evaluation if needed (longer than four hours per building). Recently, performance measures have shifted from simply building re-occupancy to building usability and serviceability post-earthquake. To measure the usability of a building, the lifelines of the building must be functioning and must be sufficient for that building.

Guidelines

FEMA P-58 is the performance-based seismic design guideline, which uses the probabilistic seismic hazard assessment (PSHA) methodology for performance assessment. The FEMA P-58 framework has been extended in the Resilience-based Earthquake Design Initiative (REDi) methodology and other frameworks to model the system's functional recovery by including the individual component delays in the total delay of the infrastructure [11, 12]. Functional recovery is "*the post-earthquake state in which the capacity is sufficient to maintain pre-earthquake functionality*" [13], and current functional recovery guidelines include both safety and recovery time to define a re-occupancy level. Although including individual component delays helps estimate the individual structure's downtime, the current methods still do not include the interdependencies among the critical infrastructures (energy, water, communication, transportation, and other buildings) to determine the system's total functional recovery level [13].

INFRASTRUCTURE INTERDEPENDENCIES SIMULATOR (I2SIM)

The i2SIM tool used in this paper can model the interdependencies among critical infrastructures as the system is being restored (electricity, water, communication, transportation) and can optimize the deployment of the available human resources (inspectors, first responders, repair crews). Immediately after a disaster, all the resources must be coordinated most efficiently to speed up reaching a certain level of functionality.

In advanced technological societies, essential services are delivered by Critical Infrastructure (CI) systems: electricity, water, transportation, communications, health, etc. These systems are tightly interconnected for efficiency, but failures in one of them may result in others not being available. As a result, recovery after a disaster must be coordinated to restore multiple services simultaneously. For example, if there is damage at the power substation, which feeds both the water station and the hospitals, the water station and the hospital will lack power. If the substation redirects the remaining power to supply the hospital but not the water station, although the hospital may now have sufficient power, it may not be able to operate because it lacks water.

Our research group at the University of British Columbia has developed the Infrastructure Interdependencies Simulator (i2SIM) to model interdependencies among critical systems using a control system model that relates multiple nonlinear inputs and outputs. i2SIM has been under development since 2004 [14]. It has been used in several national and international projects [15, 16, 17], as well as in research specific to modelling the resiliency of large systems [18, 19], the economic well-being of a city [20, 21], and more recently, modelling the trajectory of the COVID19 pandemic [22].

i2SIM relates the inputs of each functional unit (e.g., a hospital) with its output in a relationship table called a Human Readable Table (HRT). Every operational unit in the system is represented by its HRT, encapsulated in an entity called a Cell. This way, the system operator only needs to know the inputs and output of its system and does not need to know the internal workings of the Cell. This encapsulation allows cooperation among large systems without compromising their individual security and privacy and allows each system to communicate with each other in a common language [23].

Figure 3 below illustrates the limiting factor concept in a functional unit (the emergency room unit in a hospital) that requires multiple inputs. In this example, even though the emergency room unit may have enough doctors, electricity and little structural damage post-earthquake, the operability of the emergency room to treat a certain number of patients per hour is limited by the availability of water. If extra water was allocated to another infrastructure limited by a different resource (for example, the school had suffered more structural damage), then the extra water assigned to the school could be redirected to this emergency room, which would increase the number of treated patients per hour (as indicated in the green box) in Figure 3. In i2SIM, the reallocation of resources is done through an entity called the Distributor, which splits the resource produced by a Cell into slices to be delivered to the other Cells. How much of the total is allocated to the other Cells is optimized depending on the system's global objective.

Output	Power	Water	Doctors	Integrity	Injured
treated (People/hour)	electricity (MW)	hp water (KL/hour)	doctors (People)	integrity (%)	injured (People/hour)
20.0	2.5	1.0	4.0	100.0	20.0
15.0	2.0	0.6	3.0	80.0	15.0
10.0	1.5	0.3	2.0	60.0	10.0
7.0	1.0	0.2	2.0	40.0	7.0
5.0	0.5	0.1	1.0	20.0	5.0
0.0	0	0	0	0	0

Figure 3. Example of a Human Readable Table (HRT) for the Emergency Room of a Hospital.

As shown in the above Emergency Room example, the resources can be physical, such as doctors, electricity, and water, or non-physical, such as structural integrity. In addition, the inputs are independent of each other, and the input-output relationship of one input to the output can be nonlinear. The HRT shows which of the resources constrain the infrastructure's operability. i2SIM does not make any assumptions about the infrastructure's behaviour; it only keeps track of the relationships among resources [24].

i2SIM can be used at any stage of the disaster (pre-disaster for planning and post-disaster for response) because the objective function can be chosen according to the particular needs of the situation. For example, in the initial minutes of the post-disaster timeframe, the main objective is to minimize the number of human casualties. First, the emergency responders are sent to the locations where the victims are triaged. Then, the victims are transported by ambulance to the available emergency rooms in hospitals and other medical centers. Knowing which hospitals are available with sufficient resources can save minutes or even hours and be essential for critical patients. This coordination can be achieved by the ambulances communicating with the Emergency Room operators in an organized manner.

After the first minutes to hours, the next stage in the post-disaster recovery timeline is to restore the services to a level of functionality as quickly as possible. In this stage, the main objective is to quickly restore both functionality and serviceability of structures so that the city's well-being is minimally disrupted. After an earthquake, this means first inspecting the structural integrity of the buildings and equipment and ensuring lifelines availability for safe re-occupancy; next, repair crews need to be sent to restore the functionality of certain services in the buildings and infrastructure. Allocating the site inspectors to the structures that are most critical for restoring a certain level of functionality and allocating reduced resources to support this functionality will help to reduce the restoration time. This concept will be demonstrated in the following case study.

CASE STUDY

In this case study, we assume that an M7.0 crustal earthquake occurs 10 km away from the University of British Columbia Vancouver Campus at 8:30 am on March 15, 2023. The date and time are chosen so classes are in session and students live in the campus residences. A crustal earthquake was chosen because its proximity to the city means it will significantly affect the city's infrastructure [25].

The study shows that an improved system recovery can be achieved by reducing the inspection time. As a result, a faster reallocation of the lifeline resources (e.g., electricity, water, gas) to the structures labelled as structurally safe is possible. We assume buildings that suffered more than 60% damage will be unsafe. In this case, the objective is to focus on increasing the functionality of the residences because that is where most people will be displaced and require temporary shelters.

In the scenario, we assume that the earthquake has damaged one of the transformers at the Main Substation at UBC. This is a reasonable assumption, given that these transformers were installed 30-40 years ago and are more vulnerable to damage [11]. The other critical infrastructures (water, gas) have suffered structural damage of 30% and 20%, respectively.

The inputs for each Critical Infrastructure Cell (electricity, water, gas) include the resource amount and the structural integrity. For example, the HRT for the electrical power station is shown in Figure 4. At the assumed operating conditions, the limiting factor is Integrity (as shown by the red circles).

Output	Power Supply (Input)	Elec Integrity (Input)
power (MW)	power (MW)	integrity (%)
55.0	55.0	100.0
41.25	41.25	75
27.5	27.5	50
13.75	13.75	25
0	0	0

Figure 4. HRT for the electrical substation.

Because the electrical distributor feeders run through 10 km of underground duct banks [11], if there is little knowledge of where along the duct bank the failure has occurred (e.g., 20% knowledge), the electrical crew will be required to inspect the entire feeder. For example, if the fault had occurred at the end of the line, it could take 8-10 hours (480 to 600 minutes) to inspect the entire feeder, as shown in the red circle in Figure 5. However, with our dense sensor network providing knowledge at a more granular level (e.g., 75% knowledge), it would be possible to decrease this search time to 250 minutes (4 hours), as shown by the purple circle.

In i2SIM, we model these changes through the time delay parameter in the component called Channel. A Channel takes in a resource and, after a certain time delay, which can be controlled by an HRT, releases that resource. Figure 5 shows the HRT controlling the Channel's time delay for the electrical crew inspection time, which feeds the Channel. Figure 6 shows the complete i2SIM model.

Output	Signal (Input)
crew time (minutes)	information (%)
630.0	0
600.0	5.0
540.0	10.0
480.0	20.0
420.0	30.0
360.0	40.0
300.0	50.0
280.0	60.0
260.0	70.0
250.0	75.0
240.0	80.0
240.0	90.0
0.0	100.0

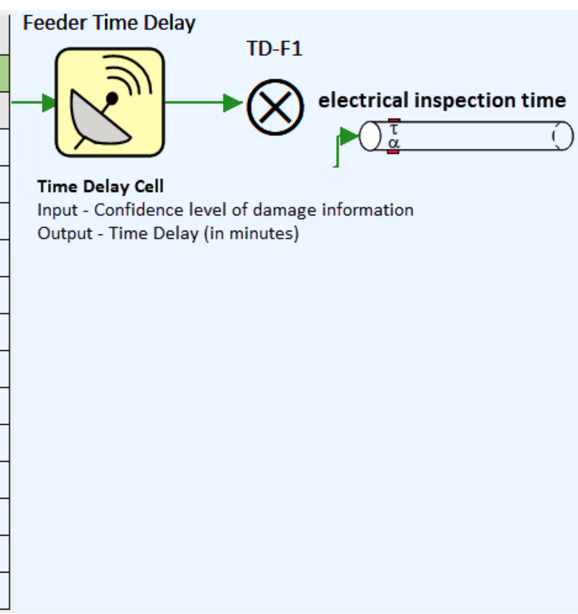

Figure 5. The HRT controlling the Channel's time delay for the electrical crew inspection time; the input is the confidence level of the damage information, and the output is the time delay of the crew (in minutes).

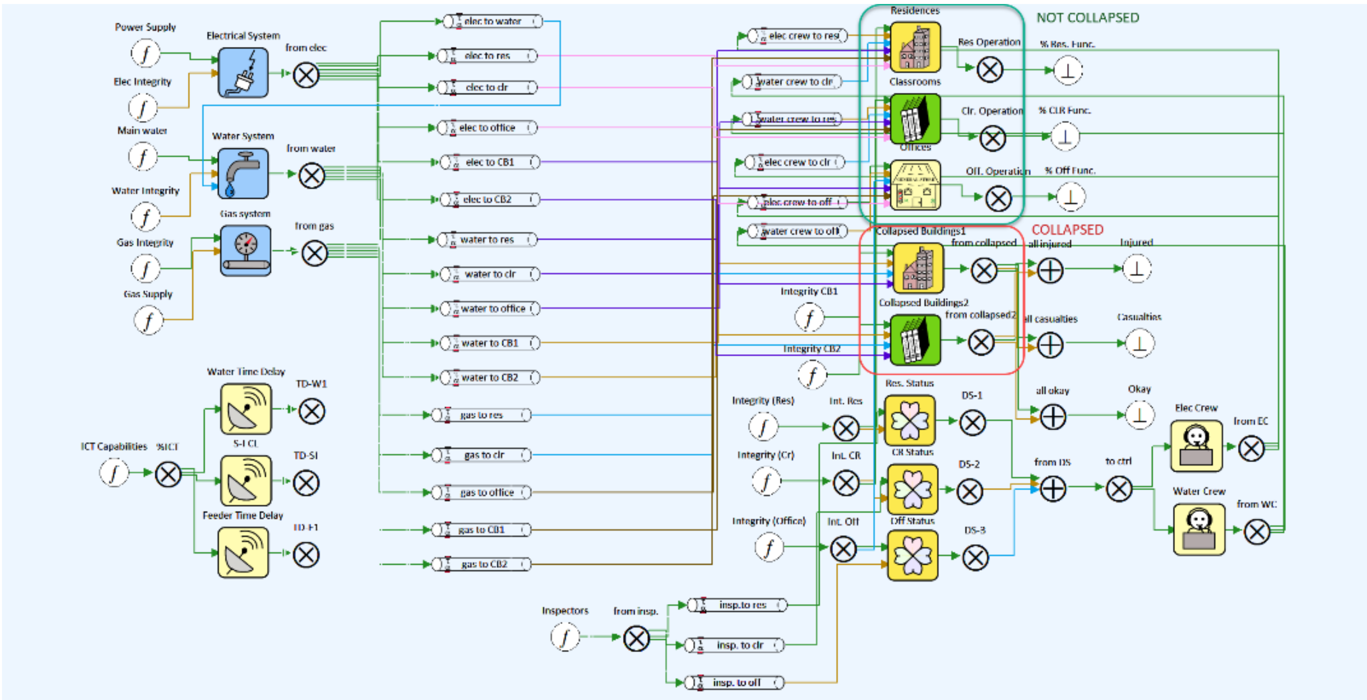

Figure 6. The i2SIM Model.

Prior to the scenario, we assume that an initial windshield area assessment has already been done (taking about 10-30 seconds per building [10]), and the simulation begins with the initial rapid assessment. With this assumption, we can label the collapsed buildings as Collapsed (circled in red in Figure 6) and the non-collapsed buildings as Not Collapsed (circled in green).

We have 36 inspectors onsite, who, in groups of four, are evenly distributed among the remaining three building clusters: Residences, Classrooms, and Offices (indicated in green in Figure 6). If three buildings per building cluster can be inspected simultaneously (and assuming 15 buildings per cluster), without the EEW-5G system, the site inspection time would be (on average) 150 minutes per building cluster (5 groups x 30 minutes per group). However, the EEW-5G system could reduce the inspection time to 60 minutes (5 groups x 12 minutes per group). After the inspectors have finished their initial evaluation, the electrical and water crew can inspect the lifeline integrity at the three building clusters.

We compared two scenarios: the first of not having the EEW-5G system in place; the second of having the system in place. In the first scenario, it is assumed that the knowledge of where the damage is located is only 20%. This limited knowledge corresponds to a time delay of 120 minutes for the site inspectors and 480 minutes for the crew inspection, for a total inspection time of 600 minutes (10 hours). In addition, there is no reallocation of the lifeline resources (electricity, water, and gas), limiting the functionality of the Cells that have suffered the least structural damage (the Not Collapsed buildings). In the second scenario, having more detailed knowledge (75% knowledge) of the damage location reduces the site inspection to 40 minutes and the crew inspection to 250 minutes, for a total of 4.8 hours. In addition, the lifeline resources are reallocated from the Collapsed buildings to the Not Collapsed buildings (particularly the Residences). The results are shown in Figures 7 and 8.

Figures 9 and 10 compare the Residences recovery level with and without the i2SIM resource optimization. Figure 9 shows that although there are enough electrical crew and the structural damage is only 25% (the structural integrity is 75%), the residences are limited by the lifeline resources (power, water, gas). Therefore, the residences are operating at a level on the fourth operating row (around 25%). However, after the optimized reallocation of the resources, the Residences are only limited by the structural integrity, and the overall functionality has increased to the second operating row (between 50 to 75%).

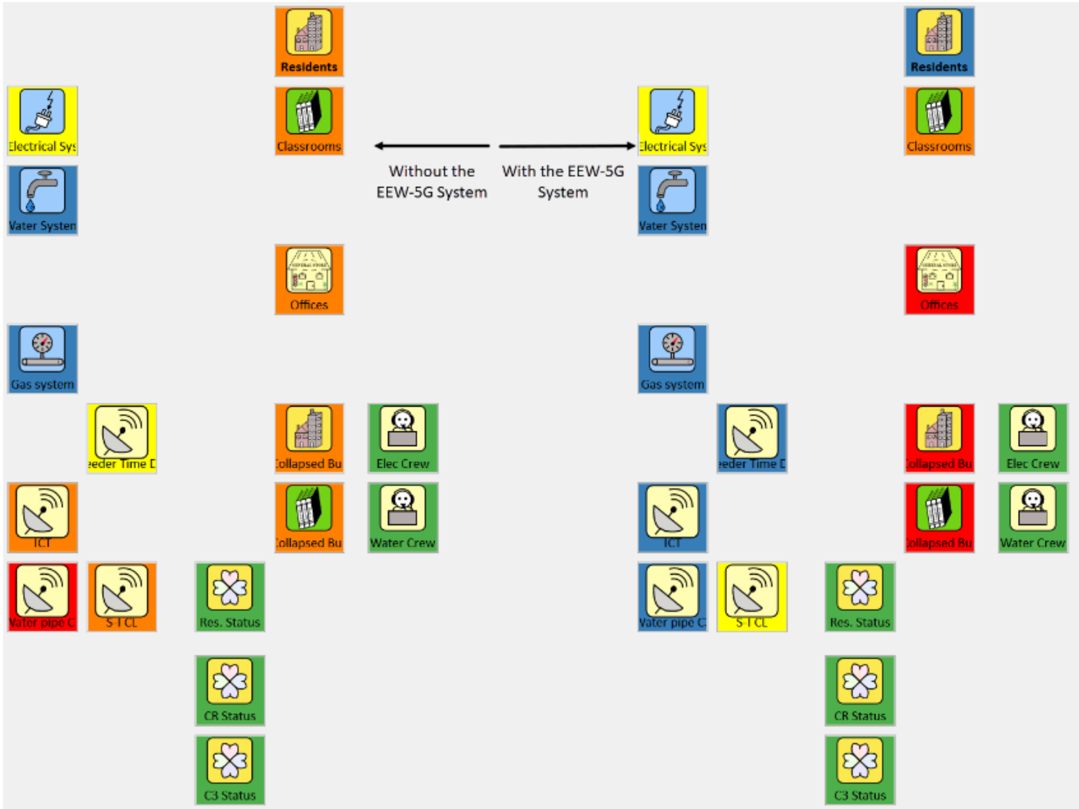

Figure 7. Before and After Using the EEW-5G System.

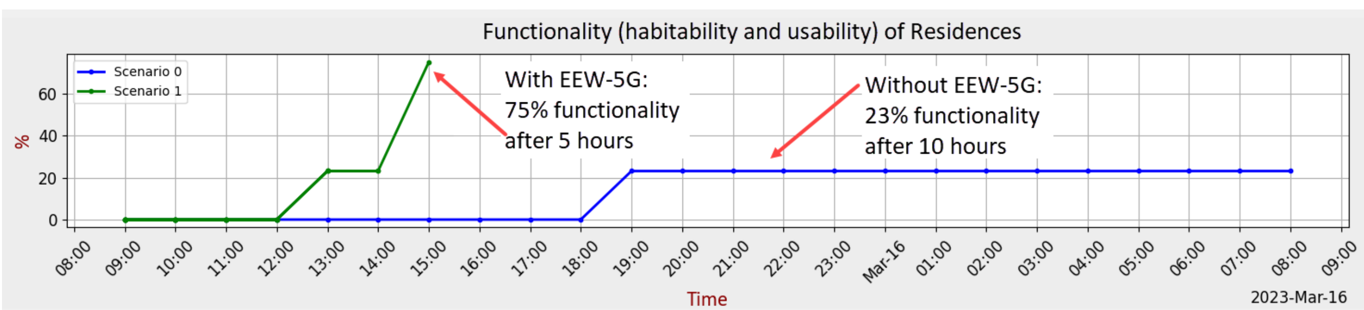

Figure 8. Functionality (habitability and usability of Residences) comparing with and without the EEW-5G System.

Output	Int. Res	elec crew to res	water crew to clr	water to res	gas to CB2	elec to res
functionality (%)	integrity (%)	elec crew (People)	water crew (People)	water (ML/day)	gas (Kbtu)	power (MW)
100.0	100.0	4.0	4.0	10.0	0.5	20.0
75.0	75.0	3.0	3.0	8.0	0.4	15.0
50.0	50.0	2.0	2.0	6.0	0.3	10.0
25.0	25.0	1.0	1.0	4.0	0.2	5.0
0.0	0	0	0	0	0	0

Figure 9. Without i2SIM's resource optimization.

Output	Int. Res	elec crew to res	water crew to clr	water to res	gas to CB2	elec to res
functionality (%)	integrity (%)	elec crew (People)	water crew (People)	water (ML/day)	gas (Kbtu)	power (MW)
100.0	100.0	4.0	4.0	10.0	0.5	20.0
75.0	75.0	3.0	3.0	8.0	0.4	15.0
50.0	50.0	2.0	2.0	6.0	0.3	10.0
25.0	25.0	1.0	1.0	4.0	0.2	5.0
0.0	0	0	0	0	0	0

Figure 10. With i2SIM's resource optimization.

CONCLUSIONS

Restoring the functionality of a large city after an earthquake can be a challenging process. Modern cities have a large population density and a high degree of interdependencies among their critical infrastructures (electricity, water, communications, transportation, health, and other services). At the same time, large modern cities have an extensive network of telecommunication services, including 5G wireless networks. This 5G network provides an opportunity for building an extensive network of sensors that only need to be "plugged-in" to this network. Then, their data can be instantaneously gathered and analyzed at a central computer in the Cloud computer.

In our research at UBC we have developed an asset-level Earthquake Early Warning system wirelessly connected to the 5G network in a city. The capabilities of easy accessibility, low-latency response, wide bandwidth, and the computational power of MEC and Cloud computers have allowed us to extend the state-of-the-art in earthquake early warning and fast coordinated response.

This paper discusses the capability of producing detailed earthquake waveforms to assess the damage produced by an earthquake on all city assets. The proposed solution comes at a very low hardware cost (about $100 per station) for a total cost of $2 million to deploy a network of 20,000 stations separated by 100 metres and cover an area of 15×15 km.

With accurate seismic waveforms for all assets and assuming that high-quality fragility curves for these assets are stored in the Cloud's database will allow us to perform an accurate initial virtual assessment of the damage caused by the earthquake across the city. In turn, knowledge of the damage locations provides site inspectors with an initial estimate of the damage to the building, allowing infrastructure site inspectors to speed up assessing buildings and assets for occupancy.

A case study for the University of British Columbia campus is presented. The i2SIM software used in the scenario coordinates the damage assessment, estimates the output available from the plants (electricity, water, etc.) and human resources (inspectors, repair crews, etc.), and determines the best allocation of these resources to restore functional operability of the system as soon as possible.

The scenario results show the gains in restoration time by having better information about damage assessment and by optimizing the allocation of the lifeline sources so that more resources are allocated to those buildings that can be re-inhabited.

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