EQS^3: Earthquake Sensing and Signaling System Using Retired Mobile Devices

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Abstract - *Since earthquakes often cause serious damage on property, the earthquake early warning system (EEWS) has been recognized as a practical solution to reduce earthquake hazards. The aim of EEWS is to alert people when earthquakes are expected to arrive at their locations. To accomplish it, the EEWS relies on earthquake science and monitoring sensors which are pre-allocated at different areas. Due to the prevalence of smartphones with acceptable gravity-sensor (G-sensor), they are considered as one of the best candidates to be the sensors in EEWS and several open projects have been formed to develop such systems. This paper proposes a quite simple and efficient earthquake sensing and signaling system (EQS^3), which is capable of sensing shaking events by means of pervasive and retired smartphones and determining whether earthquakes happen within one second only.*

Keywords: earthquake sensing and signaling system, G-sensor, smartphone.

1 Introduction

In the past decades, progress has been made to invest the earthquake early warning system (EEWS) in countries neighboring the Ring of Fire. Among these countries, Japan [1], the United States of America [2], and Taiwan [3][4] have made the most significant achievements. The EEWS is not designed for predicting where or when earthquakes arrive, but using the properties of seismic wave to sense potential earthquake events and make decision of issuing alerts to people as soon as possible via different networking technologies such as TV broadcasting, cellular short message service (SMS), internet, and so on. As EEWS may alert people seconds ahead of earthquake arrival, it could be a useful tool for reducing earthquake hazards.

Normally, seismic body waves are classified as the body waves and the surface waves [5]. The primary wave (P-wave) is the fastest (5.5~7km/s) kind of body waves. The other type of body waves is the secondary wave (S-wave), which is slower (3.2~4km/s) than the P-wave. The S-wave is typically more destructive than the P-wave because of the higher amplitude. Owing to the speed of seismic waves are much slower than the speed of network communication, if we are able to detect the P-wave in advance of the coming S-wave, the rapid signaling capability is the chance to reduce the damage caused by earthquakes.

In this paper, we propose an earthquake sensing and signaling system (EQS^3), which consists of three subsystems, the sensor, server and monitor subsystems. Considering the smartphone (SP) fulfills the capability requirements of shake sensing, internet access and application execution, the sensor subsystem intuitively reutilizes the retired SPs as residential sensors as well as locally pre-determines whether the series of sensed events meets the given earthquake patterns or not. More specifically, the installed application on SP is in charge of monitoring and analyzing the data obtained from embedded gravity-sensor (G-sensor) in real-time manner. Once the earthquake event has been detected, the SP sends an earthquake event message to corresponding server in EQS^3 right away. Without loss of generality, the accuracies of G-sensors in SPs may be quite different and may generate unnecessary false-alarms. As a consequence, we also develop embedded device (ED) with sensitive vibration sensor [6] for monitoring the valuables in enterprises, meanwhile improving the overall accuracy of EQS^3. The server subsystem is formed by two kinds of servers, named as earthquake server (ES) and bootstrap server (BS) respectively. The former is used for collecting earthquake events sent from SPs and making the final decision within a given short period, say one second, as well as broadcasting alert to all participated SPs if necessary. The latter is used for SP bootstrapping, which assigns the SP to an ES according to the relationship between IP addresses of SP and active ESs. In other words, the SP is always commanded by the BS to associate with the ES which is the nearest one to the SP. To accomplish such task, every ES periodically sends keep alive messages to the BS and every active sensor also periodically checks with BS whether there is new ES which is closer than the serving ES. The monitor subsystem is used to monitor the health of the system and log all events in EQS^3.

2 Related Works

The main types of EEWS are distinguished as infrastructure-based, sensor-based and community-based EEWS. Infrastructure-based EEWS uses seismometers to detect seismic wave and is usually developed by national organizations. For example, Japan provides Japan Meteorological Agency (JMA) [1], which maintains hundreds of seismometers all around Japan. These seismometers are able to detect seismic wave and then send alert to the public by broadcast media. Another kind of infrastructure-based EEWS is called as California Integrated Seismic Network (CISN) [2]. CISN gathers and calculates waveform parameters from the stations, which are installed at UC Berkeley, USGS and

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Caltech, and then dumped in a statewide waveform parameter pool. Next, CISN's EEW algorithms detect and characterize each event. Finally, the decision module determines the result about whether the earthquake happens or not and delivers an alert message to all subscribed users.

Sensor-based EEWS uses low costs sensors such as accelerometer and speedometer to detect seismic wave. Although sensor-based EEWS can build a large sensor network due to the low cost of sensors, the accuracy is lower than the first type. MyShake [7] is an example of sensor-based EEWS. In order to let mobile devices participate in EEWS, MyShake had been developed to identify the different characteristics of seismic wave and artificial motions. The earthquake detection algorithm was designed using past earthquake data and acceleration data recorded by smartphones to distinguish different situations. According to the research, multiple smartphones are tested and the acceleration data is stimulated by two different tests, which are noise floor test and shake table test. Noise floor test is to stimulate the internal noise of the device itself plus the environmental sources and the shake table test is to imitate true shaking during earthquake. The algorithm assesses a 2s window to determine whether the motion is earthquake or not. Recently, MyShake is freely available on Google Play Store. Taiwan Earthquake Research Center (TEC) [3] is also classified as sensor-based EEWS. It is a platform combined Palert, which is a sensor embedded with Micro Electro Mechanical Systems (MEMS). With the rapid reporting messages of Palert, the system offers early warning to the regions that are located at a distance greater than 50 km from the epicenter.

Community-based EEWS makes the use of the social networking site (e.g. Facebook, Twitter etc.) to gather current information about emerging situations of danger, and to alert interested parties timely. This method also called Social Sensing, which is based on the concept that people provide a series of information similar to those received from sensors.

3 Earthquake Sensing and Signaling System (EQS^3)

3.1 The Architecture of EQS^3

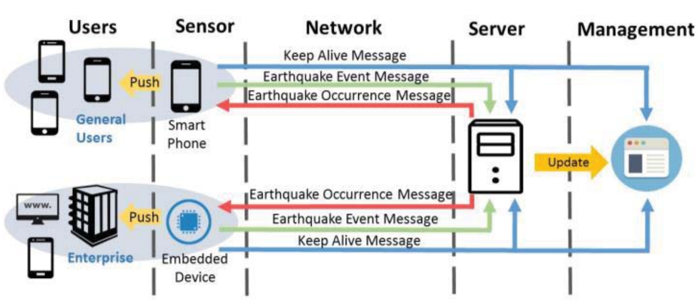
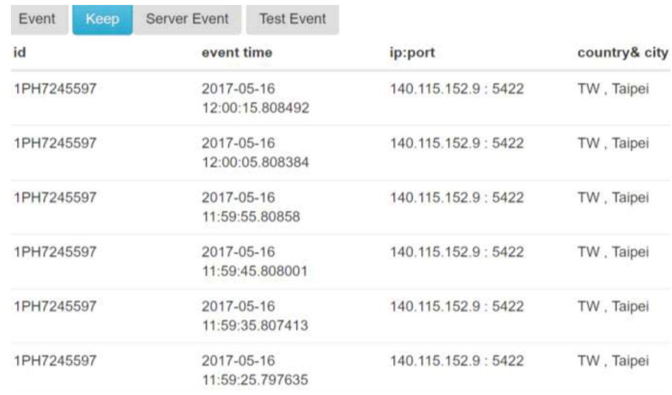


Figure 1. The architecture of EQS^3.

Fig. 1 illustrates the basis architecture of EQS^3. Every sensor, including the SP and ED, periodically sends keep alive (KA) messages to the ES (blue arrows) and the ES uses an in-memory database to store the information of alive sensors, such as coordinate, IP address and port number, etc. The monitor subsystem, as shown in Fig. 2, shows the essential information on the website. As mentioned above, to accomplish its real-time performance, the EQS^3 adopts distributed intelligent computing approach where all SPs participate in earthquake decision. That is, every SP continuously filters the noise from its G-sensor and sends an earthquake event (EE) message to the ES (green arrows) whenever a possible earthquake shaking pattern has been detected. On the contrary, the ED always sends an EE message to ES whenever the vibration sensor (shown in Fig. 3) has any positive output. As soon as the ES receives an EE message, it starts an observing window (OW) for accumulating the number of following EE messages sent from other sensors during OW and then determines whether there is earthquake based on the ratio of the number of events and the number of alive sensors recorded in in-memory database. To avoid repeat counting of events, a sensor will only send one EE message to the ES during OW. Considering the earthquake event often sustains for a certain period of time, the EQS^3 also desires to control the interval between two consecutive OWs, say T, by limiting every SP to send no more than one EE message to ES in window T. As soon as the ES believes the occurrence earthquake event, it starts sending earthquake occurrence (EO) messages back to active sensors (red arrows), one for each. The EQS^3 further supports an important function that the notified SP will send push notification (PN) message to the on-hand smartphone(s) of specific people (yellow arrows), who installed the SP at home.


Event | Keep | Server Event | Test Event

id	event time	ip:port	country& city
1PH7245597	2017-05-16 12:00:15.808492	140.115.152.9 : 5422	TW , Taipei
1PH7245597	2017-05-16 12:00:05.808384	140.115.152.9 : 5422	TW , Taipei
1PH7245597	2017-05-16 11:59:55.80858	140.115.152.9 : 5422	TW , Taipei
1PH7245597	2017-05-16 11:59:45.808001	140.115.152.9 : 5422	TW , Taipei
1PH7245597	2017-05-16 11:59:35.807413	140.115.152.9 : 5422	TW , Taipei
1PH7245597	2017-05-16 11:59:25.797635	140.115.152.9 : 5422	TW , Taipei

Figure 2. The monitoring website.

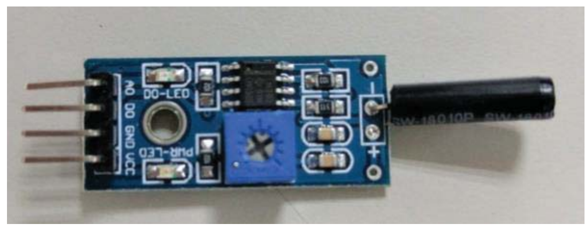


Figure 3. Vibration sensor of the embedded device.

3.2 Software Modules of EQS^3

The entire EQS^3 is established by a set of algorithms and mechanisms, which have been developed and integrated into a library named as LibEQ. The LibEQ contains seven different modules described as follows.

3.2.1 EQ_detection Module

Even an SP has been installed and mounted by wall, the G-sensor of SP may still generate varying acceleration values of z-axis because of different levels of sensitivity, accidentally touching by users or seismic waves. To distinguish these cases, the EQ_detection module adopts a simple and low complexity earthquake detection algorithm of our previous work [8], which transforms the series of data (i.e., acceleration values) into sets of moving average by means of sliding window. As long as the mean variance of the extreme points in these sets exceeds the threshold, it determines this case as an earthquake event. In other words, it applied exponentially weighted moving average (EWMA) algorithm to eliminate the effect of shakings in a short period by setting the weighting coefficient to 1/8. Based on the raw data published from National Central Weather Bureau in Taiwan, [8] have showed that accuracy of earthquake detection can reach as high as 90% and 93.5% when sliding window is set as 1s and 2s respectively.

3.2.2 EQ_credibility Module

Every sensor has a probability of generating false EE message because of the broken device, installed environment or artificial factor. Hence, EQS^3 is required to adjust the credibility of every sensor according to their behaviors. The EQ_credibility module, which is executed on SP dynamically, adjusts the credibility of SP if it ever sent false alarm to ES. There are two situations defined as false alarms. The first situation is that when an SP has sent an EE message to ES but it fails to receive the EO message sent from ES within a specified time window, say 10s. The second situation is that as an SP receives an EO message from ES but it did not send EE message to ES. Whenever false alarm occurs, its credibility is decreased by the following equation:

$$C_{next} = C_{now} - C_{now} \times n_f/3, \qquad (1)$$

where C_{next} and C_{now} are the credibility after and before adjusted respectively, and n_f is the number of generating false alarms within a certain period of time. The credibility is controlled in the range from 0 to 1 and it is carried on the EE message sent from the SP to ES. The incremental method of credibility is the same as slow-start algorithm used in Transmission Control Protocol (TCP) [9]. From our observations, this mechanism significantly avoids rapid changes of credibility at the early stage after generating false alarm.

3.2.3 EQ_interface Module

This module provides the communication interfaces between sensors and servers. It uses the User Datagram Protocol (UDP) and Libev [10] to handle data packets to achieve the goal of fast transmissions.

3.2.4 EQ_GeoIP Module

GeoIP [11] is an auxiliary database which records the geographic location of any IP address. With the provided coordinates sent from sensors and this module, the monitor subsystem in EQS^3 is no longer difficult to figure out the venue of an earthquake as it is aware of locations of SPs which ever send the EE messages to the ES.

3.2.5 EQ_Redis Module

This module is designed for the ES to record information of active SPs and corresponding events. Redis [12] is an in-memory databased created and maintained by an open project. It can not only eliminate the frequency of accessing external storage such as hard disk but also speed up the access latency. In other words, it updates and searches information more rapidly than conventional SQL database, which is an essential requirement of the EEWS. From our testing, the latency of accessing any key from the Redis database with 10,000,000 keys is around 25us on regular personal computer.

3.2.6 EQ_judgement Module

The ES keeps investigating into the received messages from all sensors. Once it receives an EE message from a sensor, it starts an observing window (OW) for accumulating the following events in order to make the final decision. The hypothesis of EQS^3 is that in case of occurrence of earthquake, those sensors installed in nearby area are expected to send EE messages at the same time. As the EQS^3 supports multiple ESs around the world, the distance between a pair of sensor and ES should be controlled within a reasonable range, say 100km, and the period of the OW is set as 1s. Equation (2) is the simple rule of judging whether there is earthquake event :

$$\sum C_i \geq f(A,B)/2, \qquad (2)$$

where C_i is the credibility of the *i*-th sensor which sends an EE message and the function $f(A,B)$ is the number of active sensors located within the overlapping area between two circles, where one is centered at coordinate A of the first reporting sensor with the radius 7km (which is the propagating distance of the P-wave in one second) and the other is centered at coordinate B of the ES with radius of 100km. If the accumulated credibility of receiving EE messages exceeds the threshold within 1s, the ES believes there is earthquake and then sends the EO messages to all the alive sensors, as mentioned before.

3.2.7 EQ_bootstrap Module

The main function of the BS is to manage all the ESs and allocate new sensors (i.e., SP and ED) to associate with the nearest ES. As earthquakes may occur at anywhere, ESs shall be installed at different areas to serve the people who lived there. As long as an ES becomes online, it first registers its information, i.e., IP address and coordinates, into the BS. With the records of all active ESs, sensors are assigned to the nearest ES after inquiring the BS during the bootstrap stage.

(a) (b) (c)

Figure 4. The UI of applications for smartphones.

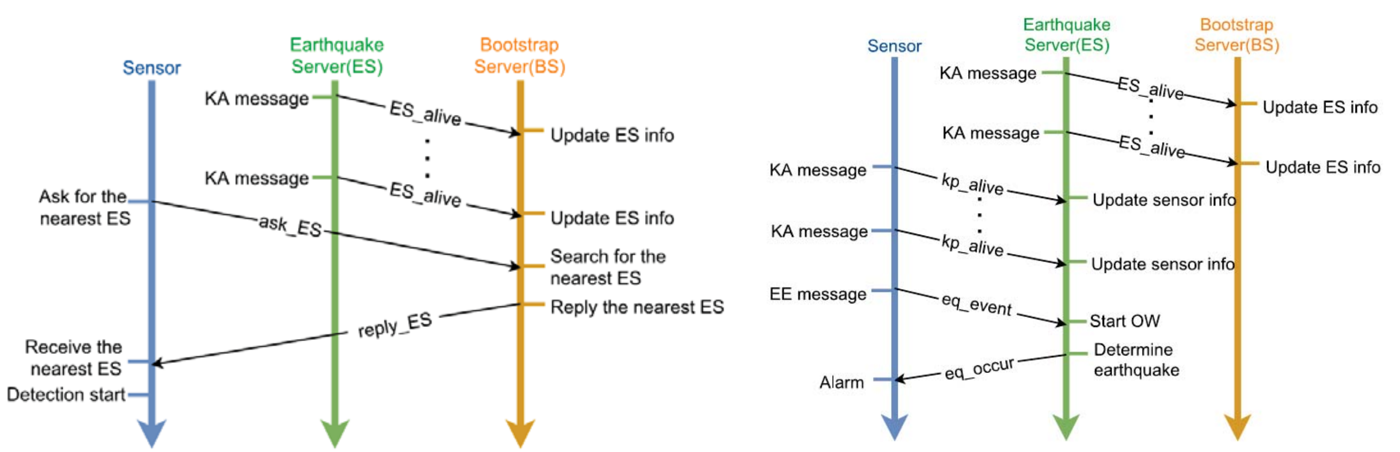
Figure 5. The mounted smartphone on the wall for ES-APP.

3.3 The Applications for Smartphones

People may be happy to receive earthquake notifications from the EQS[3] anytime and anywhere. Therefore, we developed two different applications for smartphones and the UIs, as shown in Fig. 4. One application called as Earthquake Sensor APP (ES-APP) is used for the retired SP (installed at fixed locations such as home or office, as shown in Fig. 5) in order to sample and analyze the sending data. Fig. 4(a) illustrates the UI of ES-APP and Fig. 4(b) shows the case that ES-APP receives an EO message. The QR code shown on ES-APP is used to be scanned by the application named as Earthquake Notice APP (EN-APP). EN-APP is developed for the smartphones carried by users. By pairing the ES-APP and EN-APP, the ES-APP will send PN message to corresponding ES-APP when it either detects the earthquake event or receives the EO event from ES. Fig. 4(c) and 4(d) respectively show the received PN message of EE and EO messages in EN-APP.

3.4 The Interactions Among Sensor, ES and BS

Fig. 6(a) and 6(b) illustrate how the sensor, ES, and BS interact with each other. First, ES periodically sends KA messages to BS. With the information of all the ESs, BS is capable of managing the bootstrapping of all sensors. Second, sensor inquires the BS for the nearest ES. After receiving the IP address and the port of the nearest ES, the sensor starts sending KA messages to corresponding ES and detecting seismic waves. Fig. 6(a) illustrates the bootstrap stage. To ensure that the EQS[3] works well, these processes will be repeated again and again.



(a) bootstrap stage (b) detection stage

Figure 6. The interactions among sensor, ES and BS.

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After the bootstrap stage, the EQS^3 is ready to detect earthquakes and broadcast earthquake alerts. Fig. 6(b) shows the detection stage. Once the acceleration values match the earthquake pattern, the sensor sends an EE message to the ES. Then, the ES starts an observing window and gathers the EE messages from sensors. If an earthquake is determined by the ES, it sends EO message back to all the sensors immediately.

4 Conclusions

This paper has proposed a simple earthquake early warning system (EEWS), named as earthquake sensing and signaling system (EQS^3). The EQS^3 aims at recycling a great quantity of retired smartphones which equips with network transceiver(s) and gravity-sensor (G-sensor) to quickly build a practical solution for alerting people the occurrence of earthquake events.

5 Acknowledgement

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