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Technologies of Internet of Things applied to an Earthquake Early Warning System

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HIGHLIGHTS

- A hierarchical architecture of smartphones in order to obtain real-time seismic information.
- An Earthquake Early Warning System using IoT protocols for communication.
- Advantages of Message Queue Telemetry Transport applied to an efficient notification process.
- Sensor Web Enablement to handle data from heterogeneous sensors.

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ABSTRACT

Internet of Things (IoT), more than smart homes and connected appliances, is to reach physical knowledge in real-time and remotely; and taking advantage of the smartphone's increasing diffusion, it is possible using its embedded sensors to monitor the environment, anytime and anywhere; this could be the solution to many community problems as well as natural hazards. This paper focuses on the solution to one of the most deadly natural hazards, earthquakes; taking seismic data of Ecuador, a country with an average of 6 earthquakes per day in 2013. Technologies of IoT like Sensor Web Enablement Framework (SWE) and Message Queue Telemetry Transport (MQTT) give the benefit of achieving an Early Warning System capable of anticipating up to 12 seconds the maximum seismic peak in the epicentre zone through smartphones. The system is supported by a wireless sensor network and its main components, requirements and design decisions are described. It considers time and spatial analyses, not present in any other work, making it more precise and customizable, and adapting it to the features of the geographical zone and resources. A preliminary evaluation of the solution was conducted to determine its strengths and weaknesses in terms of response time. The obtained results indicate that the energy consumption is as relevant for end-users as their personal security.

1. Introduction

Social networks, distributed networks and real-time systems are becoming the most important components for the new computer age, the Internet of Things (IoT). IoT allows digital interconnection of everyday (smart) objects with the Internet [1] in order to build so called Smart Environments [2]; objects as electronic ones, or home appliances which may be controlled by developed applications over a Smartphone (SP), or any personal device, e.g. [3]. The latest Ericsson Mobility Report (NASDAQ: ERIC) reveals that for next year the total number of mobile subscriptions will exceed the world's population thanks to the growth of 7% annually, with 120 million additions registered just the first quarter of 2014. The mobile broadband subscriptions also continue to grow and will reach 7.6 billion by the end of 2019, representing more than 80% of total mobile subscriptions [4]. So, this multi-sensor electronic device is becoming a fundamental part of the bridge to the knowledge of physical world, reaching information anytime, and anywhere.

The combining of the SP's sensors (accelerometers, gyroscopes, GPS, etc.) and the different connectivity options (WiFi, Cell, NFC, etc.) allows to have well-equipped IoT devices on our hands and, through these, automatically monitor our movements, locations, and workouts throughout the day; and beyond that, it can be the key to the solution of problems in other areas as transportation [5],

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medicine [6], weather [7], social [8], or the seismology, that is the field our research focuses; and involve us in the new topic of smart cities [9].

While it is true that the quality of Micro-Electro-Mechanical Systems (MEMS) sensors, as well as the ones embedded into SPs, is lower than specific seismic devices, it is also important to consider that with the data collection from a large number of SPs, known as mobile crowd-sensing (MCS), it is possible to obtain a huge low-cost network that uses individual sensing SPs capabilities [10].

Although an earthquake is totally unpredictable, this research presents a real-time and economic countermeasure to this natural hazard. Through opportunistic applications [11] and online services into SPs is possible to monitor a whole area, learn their physical characteristics, and most important, detect seismic movements to raise early warnings in order to provide extra time for making better decisions. Just to mention, the seismic activity is increasing, and consequently the risk that it occurs also is of interest; so that in April 2014 there was a world record number of large earthquakes (greater than 6.5) [12]. There are places more exposed to this type of natural disaster such as the countries which make up the "Pacific Ring of Fire", where at least 80% of all earthquakes are produced [13]; taking the case of Ecuador, a country in which the validation of this proposed architecture is based, where only in 2013 it registered 2420 seismic events (6 earthquakes per day) and around 10% exceeded a magnitude of 4.

The SP market is full of highly varied devices with different characteristics Hw and Sw. And if there were not a process of unification, this would lead to restriction of sensors, decreasing the number of devices on the network, and therefore creating less accuracy. The Open Geospatial Consortium (OGC) [14] solves this problem by defining the Sensor Web Enablement (SWE) framework and specifically to its Sensor Observation Service (SOS) component, which defines a unified communication standard for sensors and sensor services achieving a higher level of compatibility. And it means lower costs and better quality sensor communications because we are using a single protocol instead of several proprietary ones, which involve serious problems in interoperability [15]. Most of our research focuses on coupling the type of communication to the system requirements: standardization sensor data, quick access to data, real time communication, and immediate notifications. So we have used the paradigm of distributed systems SWE.

In conclusion, this research uses the SP's sensors as an accelerograph, which detects a seismic-peak through a mathematical procedure; and at the same time, with more users, it achieves a low-cost mobile network that corresponds to the Layer-1 in the proposed architecture. A server, named Intermediate Server (IS) in the Layer-2, and it analyses all the data from SPs in Layer-1 and determines if there is a seismic event or not, and if so, it notifies to users through a light-weight Internet-of-Things connectivity protocol. The system optimizes the distributed calculations in the SPs; communication capabilities and integration in order to provide extra time for early warning in seismic scenarios. Furthermore, this research envisions a post-event management, where each SP helps the CC by sending information such as comments, pictures and videos; helping in the process of achieving a global view of a disaster evolution.

The rest of the paper is organized as follows: The previous and related works in the area with their respective contribution can be found in Section 2. Section 3 contains the proposed architecture structure and its justification. While in Section 4 the evaluation and results are cited, in Section 5, the conclusions of our research are presented. Future work is also referred in this section.

2. Motivation and previous work

The use of SPs in the field of Earthquake Early Warning Systems (EEWS) is booming: The project [16] detects seismic events using MEMS accelerometers where, if the acceleration exceeds a set threshold value, the information is transmitted to a server and calculates the intensity and the hypocentre distance. Both, [17,18] are projects that use static devices composed of a fixed accelerometer and a personal computer providing good accuracy by means of P and S waves [19] as peak detection mechanism. Contrary to [16], our seismic detection uses dynamic thresholds for distinguishing between a repetitive sudden movement by the user and an actual seismic event. Our architecture involves additional challenges as incorporating heterogeneous devices, thus gaining in scalability; new detection algorithms, mobility and suitability to the application environment demands unlike [17,18]. In contrast to our work, [18] performs accurate validations without taking into account either the processing time or the computational cost, something that is implicit in its working process, due to SP usage. Furthermore [17,18] are complemented by our work, covering widely the future work proposed by both. [20] still has great limitations of usage and efficiency because an accurate orientation, due to issues with the compass, cannot be obtained if the device is in constant motion, and consequently forces the system to remain stationary.

The system [20] uses SPs to measure the acceleration and then determines the arrival of an earthquake. Furthermore, in contrast to our proposal, which uses an accelerometer as the principal sensor, [20] includes a compass sensor for peaks validation. The project [21] uses MEMS accelerometers, a seismological processing unit and 3 types of alarms. The effective warning time in average is 8.1 s to be detected and 12.4 s the time from the maximum vibrations. On the other hand, there are different EEWS using other types of communications. In Taiwan, [22] was put into operation an Earthquake Early Warning using Virtual Subnet Network achieving to detect an seismic event in 30 s with an average of 22 s after the origin time to cities at distance were greater than 145 km from the source. Surpassing the results of the projects mentioned above, the proposed architecture achieves to detect the acceleration peak in 12 s, in the epicentre (Results in Section 4); even becoming higher for longer distances. Other project [23] gathers data from SPs and implements a distributed decision-making process using virtual servers provided by the Google App Engine architecture [24]. And likewise, [25,26] detect quake waves and reports the event using Google Cloud to Device Messaging (C2DM). One day a disaster might happen and Google cease service, [23,25,26] would cease to work too. To be more realistic, if Google stops working for an hour, these projects would not work the same amount of time, without idea of what happened. Therefore these projects are and will be depending on Google.

A service oriented approach for sensor access and usage is used by several groups: [27,28] use their proprietary standards and data repositories, each one with different functions, access and use of sensors. SWE and its SOS component have been successfully applied to indoor [29] and outdoor scenarios. An Internet based urban environment observation system [30] is able to monitor several environmental variables (temperature, humidity, seismic activity) in real time. In conclusion the SWE's approach offers a standard method to use sensor data to enable a rapid response to a disaster scenario. And this work takes advantage of this.

Finally, citing the post-event management, a project that is worth emphasizing is [31] which is a European-Union project with 1.2 million euros. It researches current media as Facebook, Twitter or YouTube, and uses them in crisis management to promote collaboration of first-responders and citizens. The limitation such as the marginalization of people who do not use social media is the critical point because not all people use a social network.

All of them have been the motivation to achieve a different and innovative EEWS. We proposed a future perspective to exploit community resources as SPs together with a reliable and robust real time communication infrastructure, especially during the natural disaster.

3. System architecture

The accelerograph network presented in this paper is based on a three layer hierarchical architecture for EEWS as shown in Fig. 1. In the first layer, the Layer-1, the SPs are used as processing units and send samples to the IS, which has enough resources, and corresponds to the Layer-2 as soon as the SP detects a seismic-peak after overcoming a mathematical process which has been specifically designed to fulfil the requirements of a real-time system (early warnings). Each IS decides whether there was a seismic event or not, and immediately notifies their own users and, at the same time, communicates the incident to the CC, the third and last layer. The data gathered from the sensors are inserted in a SOS (SWE) into the IS. The CC aggregates different applications that make decisions based on the information available in each SOS. The three layers and the SOS will be integrated in a scalable manner until completed the system in order to verify how these in interact properly, cover the functionalities and conform the requirements; and furthermore contribute in non-functional requirements as: agile and easy portability, simple maintenance, ensure the integrity, confidentiality and availability of information (security) in the architecture, reduce the cost in locating errors and indispensable, an economic huge sensor network.

3.1. Layer 1: client application and acceleration processing

The SP application must be simple, non-interfering with the user's daily activities and non-battery consuming, as well as a great help during and after a seismic catastrophe in order to assist crisis managers to make better decisions. Fig. 1 shows the designed and implemented algorithm to detect acceleration peaks representing the destructive power of an earthquake.

An accelerogram is defined as the union of seismic signal and noise *vs.* time. The Discrete Fourier Transform (DFT) [32] is used to change the time to frequency domain, which allows applying low-pass filters to remove high frequencies corresponding to the noise which directly affects the signal peaks. DFT is performed by the Fast Fourier Transformation (FFT) for time windows since it is impossible to use it in an infinity sign. Later the Short Term Averaging / Long Term Averaging algorithm (STA/LTA) [33] is used because of its wide capabilities in detecting events in seismology, the low amount of computation, low energy consumption, contributing towards the overall success of the system. While STA allows the calculation of the present value (VA) from the last N samples, LTA allows to approximate the predicted value (VP) from M samples, where $N < M$, and therefore STA samples are contained in the LTA samples. A seismic peak is considered if the ratio VA/VP exceeds a certain threshold. We handle a dynamic threshold in order to distinguish between user's periodical movements (running, jogging, or walking) and a real seismic peak. This threshold increases if the algorithm STA/LTA (VA/VP) increases, and otherwise it decreases. Samples with a lower value than the calculated threshold are discarded and the IS will continue working.

Then, the application accesses the GPS sensor to get the user's current location, which is necessary for a validation on the IS and important to work into the standard SWE, specifically the SOS. In case the application should not be able to manage this sensor, the sample will not be sent to the IS. Finally, in a hard real-time system it is necessary to maintain the same timeline throughout the architecture, for which, the protocol NTP is implemented in order to synchronize the whole architecture.

3.2. Layer 2: intermediate server

The whole process, performed by the IS, is required to ensure the global reliability of the system, with the following assumptions: (1) The samples of the first layer are independent of each other; (2) the higher number of analysed samples is more reliably; (3) the mathematical and statistical process support the data fusion; (4) ability to receive information from heterogeneous devices. Fig. 2 presents an overview of the IS process. The IS performs spatial and temporal analysis: First, the spatial analysis uses Ecuador's attenuation equations and the Haversine formula in order to determinate which samples (sent by closer users) are in or out of the covered range of the IS (see Section 3.2.1). And second, the temporal analysis (Kruskal Wallis and Window algorithm) is fundamental to determine if the samples, sent by all the users, are sufficiently correlated; or in other words, decide if actually the samples show a seismic hazard to notify. In next sections the Fig. 2 will be described in better detail.

3.2.1. Spatial analysis

Each IS works by physical areas and other projects are limited to subdivide the samples in rectangular areas [23] or other ones do not take it into consideration. The attenuation equations show intensity ratio decreases as the distance increases; in a seismic event, "A" would measure a greater acceleration than the SPs in a farther zone "B". A balance is necessary between effectiveness and number of samples. If the distance is too small, maybe the case that the IS may leave without test samples, and if this is too long, the samples will lose correlation. So, in Ecuador's attenuation equations [34]: setting a magnitude of 5 as minimum intensity with the corresponding acceleration for this intensity, the distance calculated was 35 km. Samples whose latitude and longitude do not satisfy the Haversine function [35] with the IS's location are discarded and must be considered by other IS closer, as in Fig. 2.

3.2.2. Sampling test

Minimum Sample test [36] is necessary to determine if the number of SPs which have sent a seismic peak have been enough to deduce that an earthquake has actually happened. It determines how many active SPs of all those registered in ISs are enough to generalize the population with a percentage of reliability of 0.95%, and a margin of error of 0.05%. Both SP and IS do validations to determine which SPs are alive (active) and which are not. First, SPs send beacons and are constantly monitoring the network for reconnections, and second, the IS validates the last connection's time and, after a fixed time period (30 min) changes the SP's state to inactive state. So, active SPs keep a constant communication with the IS and the inactive ones which do not have data location or network connectivity or have a dead battery, etc.

3.2.3. Kruskal Wallis test

Kruskal Wallis [37] is an analysis variance ANOVA test used to compare samples or group of samples that better fits the seismic data. A periodical sliding windows algorithm has been developed in order to couple the Kruskal Wallis to seismic data vs. time. Fig. 2 shows the configuration corresponding to 5 letters (A, B, C, D, E) that will be tested to find the optimal configuration. This optimal configuration to the periodical sliding window algorithm is (0.3, 1, 20, 5, 1) whose results demonstrate the best correlation measured by the Kruskal Wallis Probability (KWP), the higher number of detected peaks and, most important, the time in advance to an earthquake. All this tests and results are detailed and explained in Section 4 where we can verify that this test satisfies the requirement in time and accuracy.

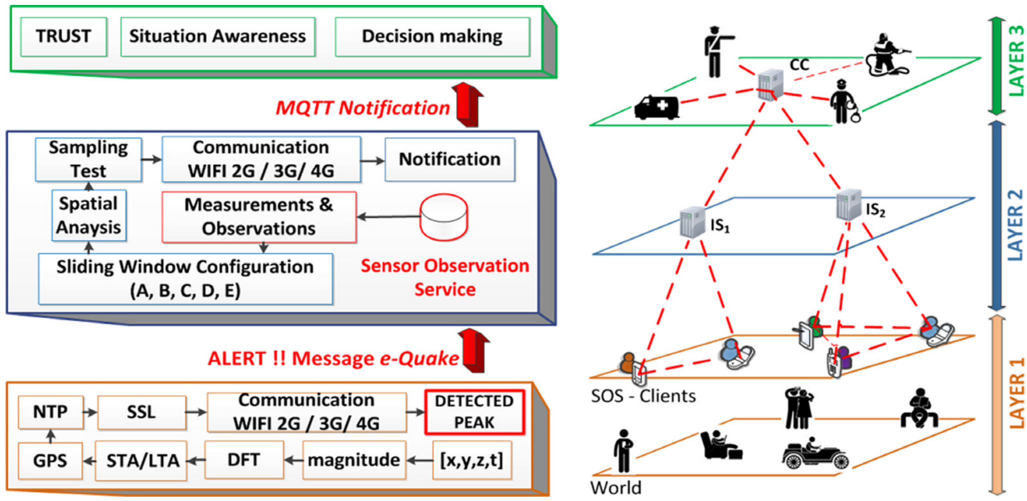

Fig. 1. Hierarchical 3-layered architecture: Layer 1: Sensor network; Layer 2: The intermediate server; Layer 3: The control centre.

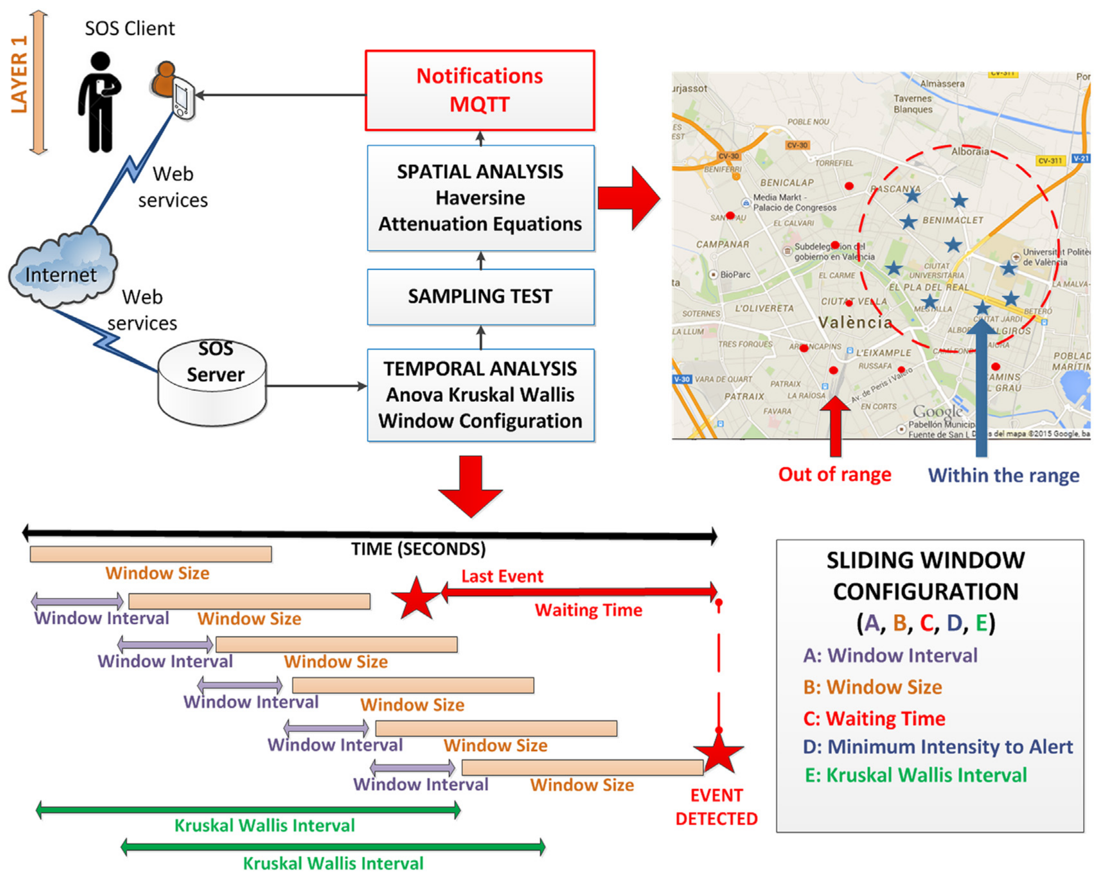

Fig. 2. Intermediate server: Sliding window configuration (A, B, C, D, E) (Kruskal Wallis) and temporal and spatial analysis.

3.2.4. Message queue telemetry transport (MQTT)

If SPs and ISs determine the existence of an earthquake, ISs send an alarm to their users in coverage, and the CC using MQTT [38] as messaging protocol for real time notifications. MQTT is an IoT protocol which provides security with SSL, authentication with prefix and Quality of Service (QoS); and furthermore, it is bandwidth-efficient using little battery power. So, it is just perfect to be used in SPs. This architecture enables a highly scalable solution without dependencies between the data producers (ISs) and the data consumers (SPs) [39]. In case the SP has lower than 10% of energy, the application stops acting as a sensor, but keeps the MQTT protocol for a possible notification. MQTT requires a configuration file where parameters such as security or QoS are modified depending upon the requirements of each system. Even, there are other proposals with the same model of publish/subscribe to improve delivery times, such as [40].

3.2.5. Sensor web enablement—sensor observation service

The term "*sensor web*" was first used in 1997 by a NASA engineer who discovered a novel wireless sensor architecture where each node can act and coordinate as a single group. Another characteristic of these new systems was the asynchronous behaviour, representing a desirable property in most implementations sensors in practice. From a formal point of view, a "*sensor web*" is an autonomous entity capable of perceiving one or more (physical) properties of their environment, so that is able to interpret and react to the measurements obtained on said physical property. It is worth pointing that although a "*sensor web*" does not require the presence of the www to work, employment itself is typical of the www to interconnect various "sensor web". The OGC architecture is different from the above mentioned architecture and requires the use of schemes to integrate very different sets of data, in the same way that TCP/IP can integrate different hardware devices.

This research focuses on the SOS [42] which supports a common data registration model (Fig. 3) from any SP leaving as the only restriction in SOS's capacity; which in our design is distributed (a SOS for each IS) thus achieving gather data flows generated by the sensors without scalability problems. The SOS complies with the Observation and Measurements (O&M) specification for modelling sensor observations, and with the Sensor Model Language (SensorML) specification for modelling sensors and any kind of sensor systems. The O&M, SensorML and SOS, which has been developed in Java, are components of the SWE architecture shown in Fig. 4.

Data quality and QoS interoperability are important issues to address in sensor web standards development activities. A key communication component at application level is the interaction with the SOS. The main advantage is that the interface is provided via web (HTTP) so that each SP, regardless of its characteristics can easily communicate with the SOS. The SOS specification defines different operations on two profiles: (a) The core profile which provides the basic functionality of a SOS: Identification of available sensors (*GetCapabilities*), access to sensor data (*GetObservation*) and Description of a sensor (*DescribeSensor*); and (b) The transactional profile which provides the operations: Register a new sensor (*RegisterSensor*) and insert a new measurement (*InsertObservation*). So, the Fig. 3 presents the flow diagram of the SOS service:

- An interface for sensors or the producer entity (application controlling a sensor or a WSN): it consists in registering each sensor by means of a SensorML in the SOS where the main features are provided (initial position, mobile or not, observed properties or inputs sensed, etc.). The first step is performed by means of a *registerSensor* operation, which allows saving a new sensor. On registration success, the SOS entity replies with a unique ID that identifies the sensor for subsequent operations. Once the sensor has been registered, it can start sending measurements at certain intervals, which depends either on the physical quantity being measured or the need of control required. The operation is called *insertObservation*. The SOS supports both fixed and mobile sensors. In the latter case, mobile sensors must send (besides measurements in the *insertObservation* operation) their current location. The operation is called *updateSensor*
- An interface for external processes (Core Profile), through which any application can access historical data (even real-time data) regarding any registered sensor. The consumer accesses the SOS entity in order to obtain information from the sensors. The *DescribeSensor* operation provides detailed information of a specific sensor and can be used by the producer to obtain all available parameters of an individual sensor. In fact, the description is a *SensorML* message similar to that inserted by the producer in the *RegisterSensor* operation. In order to obtain sensor measurements, the consumer contacts the SOS entity by means of a *GetObservation* operation. The SOS entity replies with an O&M message with the measurements.

Note that, as the SOS service centralizes all sensors, it is possible to search and apply simple spatio-temporal filters, e.g. "get all sensors that monitor temperature" or "get all sensors located in an area".

At the present time, the most important is to achieve extreme information decentralization, and the SWE technology makes it possible to have easy and secure access to the information, enabling a near real time communication that is a very important requirement in this research. The advantage of using this standard, the SWE, is that we are not prescribing any implementation, so each project can build its own services architecture in the preferred language.

It is worth mentioning that has been used the previous version of OGC SWE, the version 1.0. After a preliminary analysis of the requirements, it was verified that the version 1.0 fulfilled everything the server needed to work. The diagram shown in the Fig. 4 refers to the used version. The new version 2.0 presents several enhancements, but the main functionalities remain as in the previous version.

3.3. Layer 3: control centre

The CC must behave as a good command and control post, delivering information about global risks to the emergency management centres (fire fighter, police, ambulance and others), helping them to make proper decisions, as e.g. the Geographic Institute at the National Polytechnic School (IGEPN) [43] in Ecuador. The CC allows a system's extension from a pre-event to a post-event management schema. At a first stage, each SP helps the CC by sending multimedia information such as comments, pictures and video helping in the process of achieving a global view of what is going on in a disaster in real time. And in the second instance, CC helps users make better post-event decisions by providing "tips" about closest aid-centres, safer and faster routes (the user on their own knowledge is totally unaware of the real situation of the disaster). All this through a specific module within the same application developed in the SP, which is activated only when an IS has verified the presence of an earthquake and only for users within this IS. The "post-event module" uses some libraries as the Google Maps Android API Utility one [44], in order to get the user localization in real time and to get appropriate routes to aids centres, which were previously identified and stored in the database CC.

4. Performance evaluation

4.1. Client performance

As the number of SPs increases, the system efficiency improves without scalability issues; that is why the application, named "e-Quake", should have a high customer satisfaction level, which has a direct relationship with the battery consumption that could be the main reason for using or ceasing to use the application. While the developed application is in use the battery of the SPs last for 42 h without charging and that means 68% more than [23] (25 h) that is the result of two points: First, the IoT protocols chosen for communication between layers and early warnings. SWE–SOS and MQTT help to achieve low battery consumption and efficient use of bandwidth; and second, the used sampling frequency that is fourth less than [20] (100 Hz) and [20] (50–100 Hz). And even if this means that the detection process will be decremented because of a low sampling frequency, the choice is justified by (1) user satisfaction achieved through the decrease in battery consumption. (2) Algorithms DFT and STA/LTA will counteract this decline. (3) The crowd-sensing increases the reliability of the overall system.

On the other hand, the application monitors the battery consumption quite often and if it detects a low battery level, it stops working and just keeps running MQTT protocol for alerting the user. So, even if we lose a sensor, we can warn a user just

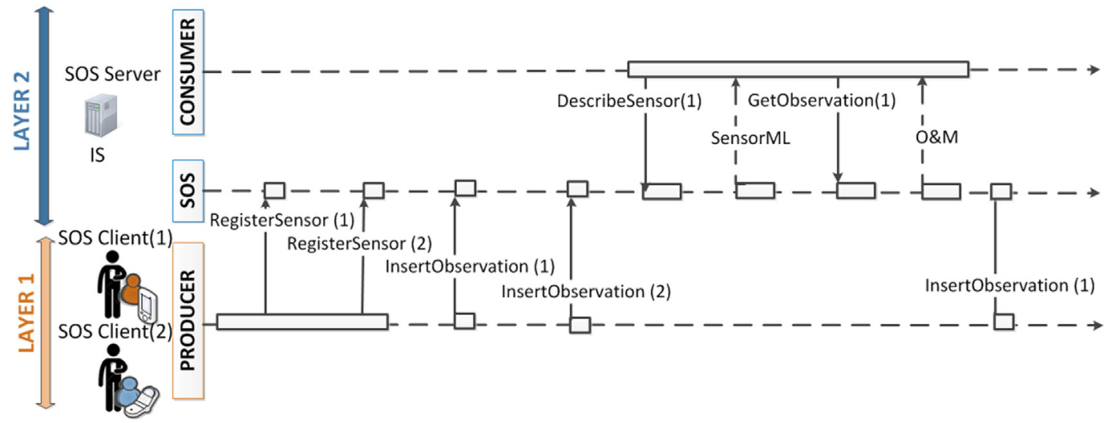

Fig. 3. OGC—SWE Version 1.0. Basic sequence diagram for the SOS service.

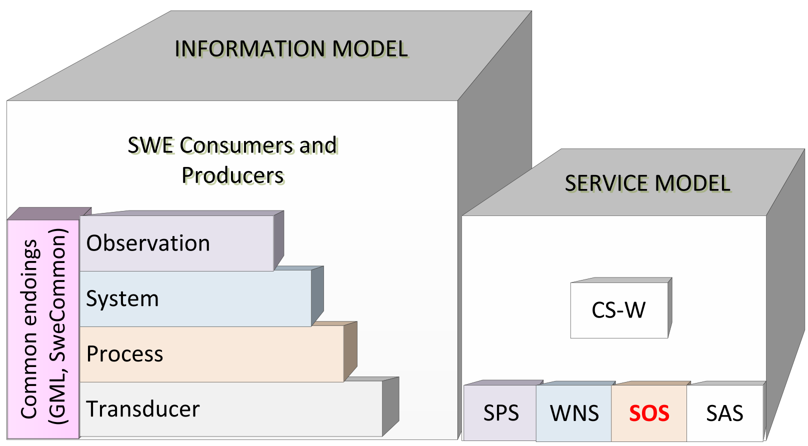

Fig. 4. Main blocks of the SWE architecture [41].

Table 1
Battery consumption of a smartphone using "e-Quake".

# beacons	5 min		15 min	
Communication Battery/Hour (%)	3G 0.1553	WI-FI 0.0245	3G 0.0021	WI-FI 0.00037

by leaving a SP functional. Then, battery consumption is tested by varying the number of beacons sent from the SP in WiFi and 3G ambient as shown in Table 1. The system requires that the SP maintains a constant monitoring. Even if the SP changes its activity state to idle or sleep mode, it does not represent excessive consumption of energy compared to other worldwide used and accepted application which consume only a little less energy than our application "*e-Quake*".

The Figs. 5 and 6 show a comparison in memory storage and battery consumption between different applications measured over a period of 2 months respectively.

(*Tests performed by SPs as Samsung Galaxy III - Galaxy ACE 2; the results may vary slightly with other devices*).

Priority has been given to the battery consumption since it is a critical parameter in disaster scenarios. Neglecting energy resources and using them indiscriminately, could represent that, not only the users would not be alerted or would not know of potential post-event risks that the CC could alert using the information from the SP network, but also, that the users might lose all types of connection (phone and network), leaving them completely cut off.

In working towards a disaster design, it was considered necessary to make the interface screen quite simple, not allowing unusual operations to be easily carried out. The success of a technical product, as "e-Quake" depends on more factors than price, reliability and life cycle; it also depends on factors such as: its handling capacity; ideally, it should be intuitive, easy to use without training; and obviously in this case, real time operations which need careful consideration. This Human–machine operation (HMI) has been developed, taking into account all this points. However, e-Quake has been designed to be flexible in coordinating requests for the HMI, as well as the seismic signal processing.

The SP application has been benchmarked using a calibrated seismograph and a shaking table where SPs rest as in [45]. Although the SPs do not present the same quality of specific accelerometers, these can even perceive the vibration produced by an incoming text message, as we can see the Fig. 7. It is important to mention that the testing procedure validates the efficiency when the mobile is stationary, which usually happens while the SP is in repose, either in sleeping or resting mode (8 h in average), or during office hours or listening to music (8 h more) [46].

In order to validate other possibilities, the application was installed on 40 volunteers' SPs for 2 months liable to daily activities (SP moving: talking, walking or even running, etc.). Fig. 8 shows the SP application when the SP is liable to these activities.

4.2. Intermediate server performance

For a more accurate and real validation, the IGEPN provided seismic-data of recent earthquakes into (or near) Ecuador, from

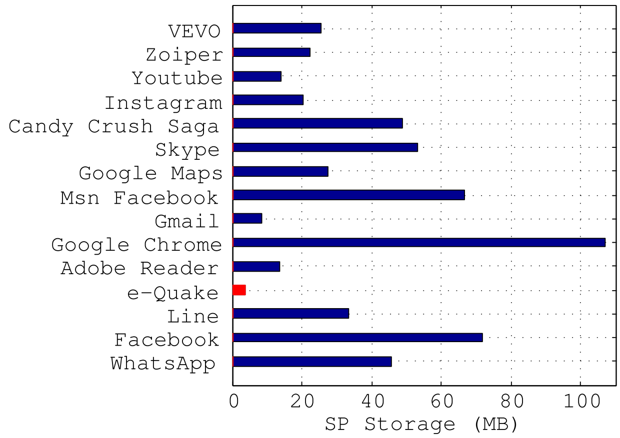

Fig. 5. Memory storage (MB) into a smartphone.

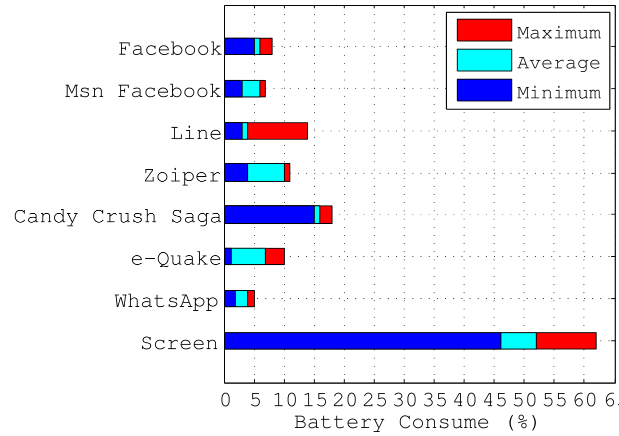

Fig. 6. Battery consume (%) into a smartphone.

2 specific devices (accelerometers) situated in the Quito city and shown in Table 2.

To determine the best configuration-parameters set (A, B, C, D, E) the validation process for each earthquake is accomplished and then comparing them taking account two considerations: First, the parameter C (Waiting Time), which corresponds to the time between two detected seismic-peaks, is set to 1 ($C = 1$), in order to compare which of them (configurations) detects a higher number of seismic peaks (Table 3). If it is too large, a peak (aftershock) cannot be detected, even if it is higher than the last one. Second,

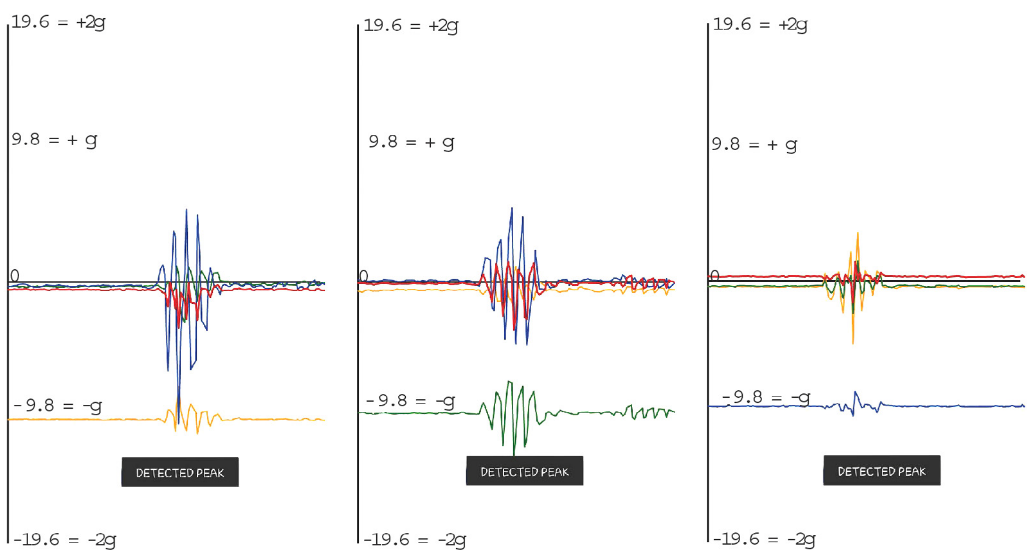

Fig. 7. "e-Quake" screen: Vibration of the arrival of a text message in different positions.

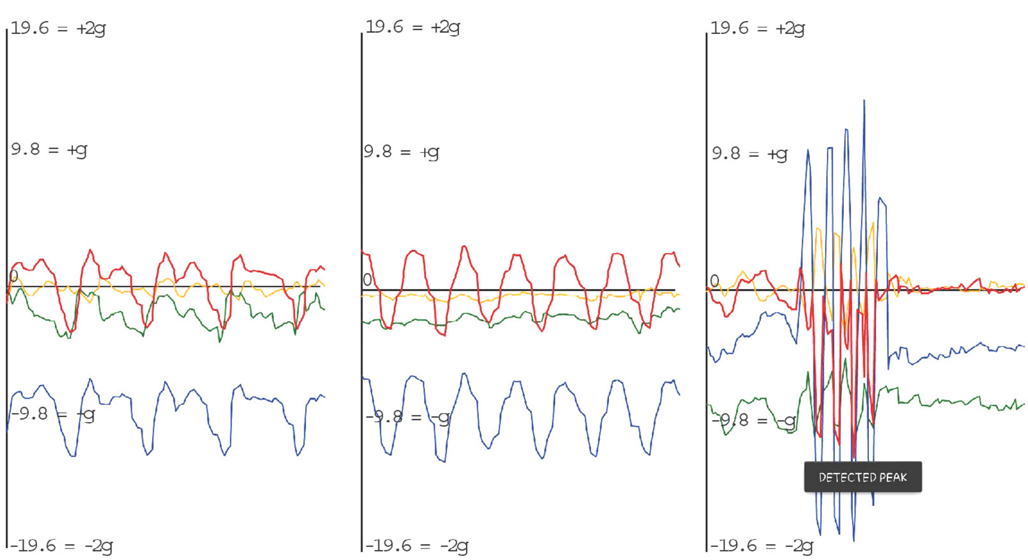

Fig. 8. "e-Quake" screen: User walking. User running. Sudden and abrupt movement by the user.

Table 2
Seismic information from quito accelerographs.

Location	Date	Max. Accel. [gals]	MMI epicentre	MMI quito
Colombia	2013/02/09	12.33	7.4	3.67
Ecuador	2012/02/08	5.48	5.2	2.69
Ecuador	2011/10/29	21.02	4.57	4.57

the parameter D (Minimum Intensity) is set to 2 ($D = 2$) to check that the algorithm is able to sense an earthquake even of very low intensity. However, in the optimal configuration, D is set to 5; according to Modified Mercalli Intensity Scale (MMI) [47], it has a very light potential damage, and is perceived as moderate. So, the analysis in each earthquake signal leads us to choose the best configuration, achieving the balance with the configuration: (0.3, 1, 20, 5, 1):

- This configuration delivers a lower KWP average (0.362) than the other ones; therefore reduce the number of false positives. It also avoids that all data are recognized as a seismic peak, but nevertheless higher than other configurations.
- The Table 3 highlights the good correlation existing between window-samples, and there exists a good data correlation at the just at the instant when the maximum seismic peak occurs.
- This configuration allows arise an early warning 12 s ahead the maximum seismic peak occurs, providing extra time, for even the epicentre zone, which is the best achievement obtained.
- The optimal configuration detects the higher number of seismic peaks into each signal. As e.g. in Pasto-Colombia earthquake reached 11 detected peaks.
- This configuration perceives a lower MMI, implying that would be possible to alert earthquakes whose damage are less, and more, it could become an extra information that IGEPN (or another CC) needs.

As an extra advantage, we have included, as an achievement, area and population unique features in the validation process, obtaining, as a result, an efficient and adaptable to each nation server. Since it is a prevention system (pre-event), it is assumed that communications are functional when the alarm is generated giving extra time that also facilitates to evacuation process and rescue. If a seismic event occurs and the communication links fail (GSM, GPRS, 3G, 4G, etc.), there are technical possibilities to extend the network of SPs using ad-hoc connections [48] in order to find a SP with internet connection that could relay messages, however it is out of the scope of this paper and it will be developed as future work.

5. Conclusions and future work

Nowadays, smartphone applications can answer questions as what, where, when, and how, about the device's surroundings; and consequently, using different network links e.g. (cell, GPS coordinates, WiFi or Bluetooth) provide information about the smartphone's environment, community problems or natural risks, as in this case, an earthquake. It is impossible to know where and when a seismic event can happen, thus it is known that an earthquake is unpredictable at the epicentre. So, the best way to mitigate damages in infrastructure, assets and even human lives, is the early detection, where a real-time architecture and an efficient communication between actors becomes a requirement.

With the introduction of modern operating systems as Android, iOS, Windows Mobile, etc.; the smartphones are considered versatile devices. The evolution of these devices, and their increasing diffusion, makes possible an amount of types of services, as in this case, this solution, which corresponds to a 3-layered architecture that satisfies the objectives of an Early Warning System in terms of time, scalability, security and adaptability by taking advantage of the new electronic emerging technology boom: the smartphone.

Big part of the success corresponds to these heterogeneous actors (smartphones), all of them forming the Layer-1 of our architecture. Therefore the key point is standardization of the sensor data, and it is achieved by SWE and his component SOS which are used to gather sensor observations in a standard way, so they allow an easy integration in any terminal improving the communication in the whole design. A connection using *World Wide Web* allows a standardization of all this community sensors

Table 3
Sliding window configuration (A, B, C, D, E) comparison.

PASTO—COLOMBIA 2013/02/09				
Max. peak intensity: 3.57 MMI			Max. peak time: 16:47	
	Set Conf. (1,1,1,2,2)	Set Conf. (0.5,1,1,2,1)	Set Conf. (0.3,1,1,2,1)	Set Conf. (0.5,0.5,1,2,1)
# detected peaks	8	10	11	10
MMI Min. detected	2.1802	2.1186	2.0697	2.1186
KWP mean	0.18	0.21	0.37	0.20
Time gained (s)	1	2	2	2
ESMERALDAS—ECUADOR 2012/02/08				
Max. peak intensity: 2.69 MMI			Max. peak time: 50:53	
	Set Conf. (1,1,1,2,2)	Set Conf. (0.5,1,1,2,1)	Set Conf. (0.3,1,1,2,1)	Set Conf. (0.5,0.5,1,2,1)
# detected peaks	3	5	6	6
MMI Min. detected	2.1803	2.1186	2.0496	2.041
KWP mean	0.08	0.25	0.31	0.29
Time gained (s)	1	3	4	3
QUITO—ECUADOR 2011/10/29				
Max. peak intensity: 4.57 MMI			Max. peak time: 55:27	
	Set Conf. (1,1,1,2,2)	Set Conf. (0.5,1,1,2,1)	Set Conf. (0.3,1,1,2,1)	Set Conf. (0.5,0.5,1,2,1)
# detected peaks	3	5	6	6
MMI Min. detected	2.1803	2.1186	2.0496	2.0491
KWP mean	0.16	0.32	0.54	0.28
Time gained (s)	1	3	4	3

could communicate with their SOS (i.e. registering and inserting observations) in real time and secure way. Further, taking into account that the incorporation of a SOS, allows to have thousands of sensors each one with different advantages and limitations resulting in other words in efficiency and accuracy. This provides a modular and scalable architecture design. The Layer-2 is a server, named Intermediate Server, with enough capacity to listen and process the SP's samples, detect a seismic event and, notify to all clients in the covered area through the information collected in SOS. This server implements temporal and spatial analysis not presented in other works promoting in the success of the proposal. The last layer, the Control Centre can manage in a proper way the actual information in order to help the aids-centres to properly distribute their resources (human or monetary). And second, it can help the users to make better post decisions, being that, they are totally unaware of the real situation of the disaster.

To help drive the Internet of Things and complementing the communication regarding early warnings, Message Queue Telemetry Transport has been chosen because of these advantages as his lightweight, and his low power usage, which has been tested getting encouraging results (4.9% in average of battery consume), representing a percentage well below commonly used applications.

Furthermore, the architecture was validated by means past actual data from Ecuador, which is a country in constant seismic risk. Our solution anticipates the maximum seismic-peak in 12 s in the seismic focus; however this time could be greater in further areas from the epicentre. As well the benefits provided could be greater depending on the earthquake's features (when, duration and location). Given the limitations of validation, our first step would be improve the structure of the testing process as [49], so we will be able to ensure better quality with minimal economic investment; and find agreements with centres that have new testing devices, like rooms with earthquake simulators to achieve better validation and improvement of the overall system. As further work, it would be interesting to study more disaster scenarios, considering multiple sensors totally heterogeneous using the same design and coupling the detection process, into the two first layers, to the type of the natural disaster, such as: fires, volcanic eruptions, and many more.

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