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Earthquake Early Warning System (EEWS)

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Abstract - *Natural disasters especially the Earthquakes are catastrophic and cause huge loss of life and widespread destruction of infrastructure in the region surrounding the epicentre. In the recent years, we have seen large causalities and destruction in Gujarat and Nepal. To reduce these losses earthquake early warning system is must. With the advancement of technology particularly in the field of seismic sensors, embedded technology, wireless networks, IoT and cloud computing, it is possible to develop low cost advance earthquake monitoring and warning system using Wireless Sensor Network (WSN).The ability to anticipate and predict the earthquake through scientific means will give the time needed to escape and survive. Two types of waves are generated whenever earthquake occurs namely, P-waves and S-waves. EEWS is based on IoT supported protocols for disaster management. In this paper these protocols are discussed. There are several IoT-based cost effective solutions available in market for earthquake detection, which are also discussed in this paper.*

Key Words: WSN, QCN, MEMS

1. INTRODUCTION

Natural disasters especially the Earthquakes are catastrophic and cause huge loss of life and widespread destruction of infrastructure in the region surrounding the epicenter. Indian subcontinent is prone to earthquakes and the densely populated cities and economic zones that are contributing much to a sustained economic growth would stall the development of the country should these zones stop due to failure of existing infrastructures in the event of a destructive earthquake. In the recent years we have seen large causalities and destruction in Gujarat and Nepal. The recent major earthquake was recorded in Nepal in April 2015, which caused casualty of more than 9,000 people and injured approximately 22,000 persons. Tremors of mild intensity are felt at regular intervals in the Himalayan region.

With the advancement of technology particularly in the field of seismic sensors, embedded technology, Wireless Networks, IOT and cloud computing, it is possible to develop low cost advance earthquake monitoring and warning system using Wireless Sensor Network (WSN) suitable for implementation in developing countries. Thus the ability to anticipate and predict the earthquake through scientific means will give the just time needed to escape and survive. Key to an effective Earthquake Early Warning System (EEWS) is the large scale employment of low cost sensors, highly reliable WSN, Real time analytics and prompt dissemination of alerts to the people and disaster management agencies in the affected region.

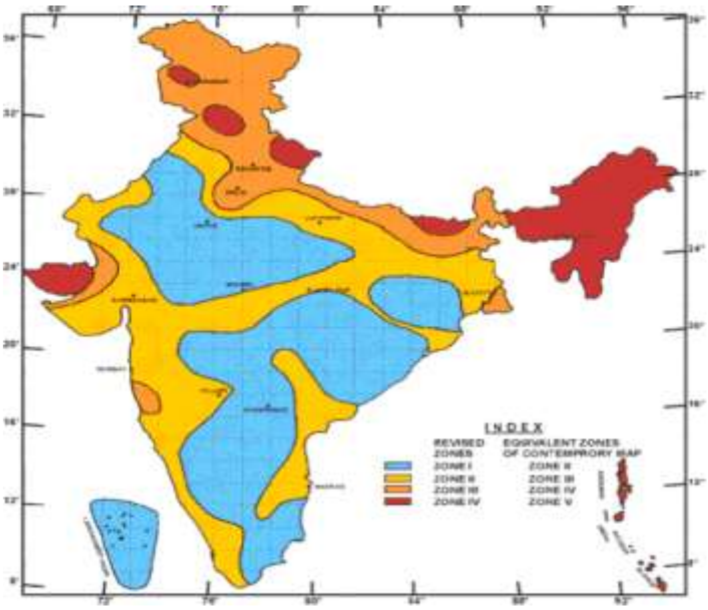

Figure1: The Earthquake Zones of India [17]

2. EARTHQUAKE

2.1 Seismic Waves

There are two types of waves which are generated whenever earth quake occurs. These are P-waves and S-waves[2]. The P-wave is the first wave which travels through the earth's crust and is recorded by the seismometer. It travels faster than the S- wave and the propagation is like that of a sound wave. It causes no or little damage. On the other hand the S-wave which travels at a slow speed like an ocean wave causes extensive damage to the life and property. These secondary waves produce both horizontal and vertical motion of the earth's surface. The duration of time during which the maximum velocities and accelerations are recorded causes the maximum damage to infrastructure. Most of the EEWS are designed to generate alert on the detection of P-waves. This gives some time and opportunity to take reactionary measures to minimize the damage caused by the following S-waves. Strong earthquake near epicenter may cause horizontal and vertical displacements of more than a meter [12].

2.2 Displacement and Frequency

Seismologists use displacement in meters as a measurement whereas engineers use acceleration in m/sec^2 as the unit of earth quake measurement. The range of measurement is very large typically from 1 mm to 1m. The band of frequency is also very large depending upon the nature of waves and intensity. The table below gives the frequency range and the type of seismic wave.

Table 1: Summary of frequency range and type of seismic wave[10]

Frequency band (Hz)	Type of waves
0.00001-0.0001	Earth tides
0.0001-0.001	Free oscillations, earthquakes
0.001-0.01	Surface waves, earthquakes
0.01-0.1	Surface Earth waves, P and S waves, earthquakes with M > 6
0.1-10	P and S waves, earthquakes with M> 2
10-1000	P and S waves, earthquakes, M< 2

3. SEISMOMETER

3.1 Modern electronic seismometers

These seismometers consist of a suspended body of mass which is held relatively stationary with respect to the frame by applying automatic generated negative feedback working in a loop [1]. This feedback loop proportional to the displacement of mass is applied in the form of a magnetic or electrostatic force to bring the mass to the stationary state. The voltage required to produce this force is the seismic measurement produced the seismometer and is digitally available for recording purpose. These instruments measure motions in three axes: i.e. north-south (y-axis), east-west (x-axis), and vertical (z-axis). In one axis instruments, the measurement is done only in the vertical axis because of low noise and provides better detection of motion of seismic waves.

The seismometer consists of electronic sensors, amplifiers, and recording devices. Most instruments cover wide range of frequencies, and are available with frequencies ranging from 500 Hz to 0.00118 Hz (1/500 = 0.002 seconds per cycle, to 1/0.00118 = 850 seconds per cycle). There are three broad ranges of seismometers as tabulated below:

Table 2: Summary of three broad ranges seismometers[11]

Geophones	50 to 750 V/m; For strong seismic detection
Geologic seismographs	1,500 V/m; For local region seismic detection
Teleseismographs	20,000 V/m; For worldwide survey

A professional station may be mounted on bedrock or positioned in deep boreholes. This is to eliminate inaccuracies due to environmental and generated thermal transients, ground noise and tilting of axis from winds and tides. The weak motion sensors are mostly mounted in an insulated enclosure on small buried piers of unreinforced concrete.

3.2 Strong-motion seismometers

A strong-motion seismometer measures acceleration in the three axes [6]. The velocity and position is derived by mathematically integrating the three acceleration outputs. They may be with or without some processing capability. The strong-motion seismometers are comparatively less sensitive but are good enough to be used in interconnected Wireless Sensor Network (WSN) to produce seismic alerts in an EEWS.

4. WIRELESS SENSOR NETWORK AND IOT

WSN is a communication technology whose protocols if chosen judiciously will prove to be the best IOT based EEWS [4]. This WSN can be configured in different topological structures (star, ring, tree, etc.) with smart seismometers having some processing capability. The EEWS network can use either Transmission Control Protocol/Internet Protocol (TCP/IP) or standard Open Systems Interconnection (OSI) models, which are best suited for these types of applications.

4.1 IOT-Supported protocols for EEWS

The IOT for disaster management applications mainly uses protocols which can be differentiated in to seven layers [7] i.e. Infrastructure, discovery, data, communication, semantic, multi-layer Framework, and Security. EEWS protocols have to be carefully selected because each earthquake has different intensity, affects large geographical area and the time period available for seismic signal processing, validating and issuing of alerts is very less. Thus, it is pertinent to consider all related issues while selecting multi-layer framework protocols depending upon the availability of technology and infrastructure in that area. The cost effective, lightweight and low power IOT-based protocols are most appropriate to integrate local low cost seismometers and routers for establishing communications in a reliable and secure way. Since the disastrous region mostly gets cut-off from outside world, employment of physical wired communication links e.g., underground or overhead signal cables, LOS / Tropo antennas, and optical fiber cables is not the optimum solution considering post disaster management.

Table 2: Depiction of the seven layers in IOT protocols

Infrastructure layer
Discovery layer
Data layer
Communication layer
Semantic layer
Multi-layer
Security layer

These seven layers with their available protocols are discussed in following paragraphs.

I. INFRASTRUCTURE LAYER

The protocols enables the software for subsystems interconnection such as IPv6 over Low power Wireless Personal Area Networks (6LowPAN), The Quick User Datagram Protocol (UDP) Internet Connections (QUIC), MicroIP(uIP), Datagram Transport Layer (DTLS), Nano Internet Protocol (NanoIP) and Time Synchronized Mesh Protocol (TSMP).

II. DATA LAYER

These protocols look after machine to machine data exchange functions. The suitable protocols are :- Message Queuing Telemetry Transport for Sensor Networks (MQTT-SN), Constrained Application Protocol (CoAP), Extensible Messaging and Presence Protocol (XMPP), Mihini/M3DA, Data-Distribution Service (DDS), Lightweight Local Automation Protocol (LLAP) and HTTP/2.

III. COMMUNICATION LAYER

The protocols which may be considered for use are :- Worldwide Interoperability for Microwave Access (WiMAX) , Bluetooth, Eddystone, Zigbee, EnOcean, Narrow Band IoT (NB-IoT), Extended Coverage-GSM-IoT(EC-GSMIoT) and Long Range Wide Area Network (LoRaWAN).

IV. DISOVERY LAYER

This protocol carries out the important function of device discovery and configuration. The protocols that can be used are: - Multi-cast Domain Name System (mDNS), Hyper Cat and Universal Plug and Play (UPnP).

V. SEMANTIC LAYER

These protocols ease and simplify the data access to the users. Suitable protocols are: - Sensor Model Language (SensorML), Semantic Sensor Net Ontology-W3C by the World Wide Web Consortium (W3C), Representational state transfer (RESTful) API Modeling Language (RAML), Sensor Markup Language (SENML) and Lemon beat smart Device Language (LsDL).

VI. MULTI-LAYER

These protocols provide multilayer functions to devices and Apps. The protocols that can be considered are: - Alljoyn, IoTivity, IEEE P2413, Thread, OMA Lightweight M2M v1.0 and Weave.

VII. SECURITY

This protocol manages security of devices, data and communications. OTrP and X.509 may considered suitable for EWS applications.

5. IOT-BASED AFFORDABLE AND EFFECTIVE NETWORKS AVAILABLE FOR EEWS

We will now discuss few examples of IoT-based networks (both hardware and cloud-based) for EEWS being used for providing alerts of impending earthquake in high probability zones [8].

5.1 BRINCO [16]

It is an IOT-enabled network which is designed to alert its subscribers about the predicted earthquake or tsunami in personal-aware mode. The network consists of sensor system and data center connected on WSN. The sensor system includes accelerometer, signal processing unit and alarm units. When the sensor senses a seismic vibration, it sends the data to the Brinco Data Center (BDC). The BDC correlates this seismic data with other seismic networks information to decide presence of earthquake P-wave. If the judgment is positive, it activates alarm signals and sends push notifications to its subscribers on smart phone (Android or iOS) or any other networked user device instantly.

Figure 2: Brinco App

5.2 BRCK

This system is designed to be used in poor infrastructures, where 2G communication is still in use. It also sends the perceived seismic data to private cloud service for analysis and justifiable prediction. The sensors have the ability to function on solar energy, hence highly suitable for remote places where power supply is intermittent and availability is not ensured. Smart personal devices are used for alarm notifications.

5.3 GRILLO [19]

It is also an APP based service to provide EEW to its users. The smart phone installed with accelerometer and GPS, whenever detects ground vibration it correlates with its stored vibrational profile of the earthquake. The device is connected with Grillo Sensor Network, which is a proprietary network of Grillo devices (Mexico). As soon as, Grillo receives a seismic data from the smart phone or device it immediately verifies with its own pre-installed sensor network to decide validity of occurrence of seismic wave. Upon successful verification, it produces alert signals to its subscribed users.

Figure 3: Grillo Sensor and App

5.4 MYSHAKE

It also uses an APP where in the sensor data is provided by the subscribers networked in the EEWS. This APP is installed on users Smartphone or device which whenever detects a ground vibration through the device accelerometer, carries out a matching operation with the stored vibrational profile of the earthquake. On successful matching, the information along with the device GPS coordinate (received from the device) is transferred to the Berkeley Seismological Laboratory (BSL) for final correlation/analysis and decision on issue of seismic alert to participating users and other management/ relief organizations.

Figure 4: Shake Alert

6. EARTHQUAKE DISASTER MANAGEMENT SYSTEMS

The usefulness of any earthquake monitoring system depends on its prior detection and timely dissemination of data and alerts before the actual occurrence of earthquake. Two Earthquake Early Warning Systems based on IOT and designed to provide timely alerts through various means including social platform to the general public and related disaster management agencies for pre-established automated responses is discussed below [3].

6.1 Japan Meteorological Agency (JMA)

In Japan, the Earthquake Early Warning (EEW) is primarily issued by the Japan Meteorological Agency (JMA), who also provides guidance as to how to react to them on issue of warning notification. The JMA has two EEW systems: one for providing alerts to the general public and another for the use by the National Meteorological and Hydrological Services. An array of seismometers is installed throughout Japan. Whenever the occurrence a P-wave is sensed by two or more seismometers (Appx 4,235), the main server analyzes and predicts the approximate location of the earthquake's epicenter. The agency notifies effected people in the region through various communication media like TV , radio, Internet and mobile phone network if a strong earthquake of magnitude greater than 5 on Japanese seismic scale is predicted. All seismic data for earthquake more than 3.5 on Richter scale is forwarded to the National Meteorological and Hydrological Services, This is meant for record, research and analytical purposes by the scientific community.

The system is so designed to minimize the after-effects and damage to people and property by alerting people and organizations to take pre planned precautionary measures like evacuation and shutting down of electrical and gas lines in the danger zone before the arrival of its damaging strong

S-waves. It is effectively used by important people intensive places and infrastructure like mass rapid transit systems to slow down or divert routes, power stations to stop generation and distribution and by manufacturing units to halt their production and assembly lines before the damaging earthquake wave hits them.

The time difference between arrival of p and the s waves is few seconds to minute and this is the time window available for evacuation and shutting down of vulnerable services. Hence the placement of sensors, location of data center and type of wireless network is of utmost importance for the system to be affective. The area surrounding epicenter will feel powerful tremors before any warning is issued due to the small time window. The EEWS developed and fielded by JMA has proved its technical viability and usability by its effectiveness whenever earthquake and tsunami has struck Japan.

6.2 The Red Atrapa Sismos[5] (Quake-Catcher Network in Mexico)

The Quake-Catcher Network (QCN) is a modular seismic array consisting of a large number of subscribers who have willingly offered their laptops and personal devices for installation of sensors (MEMS accelerometers) to detect and transfer seismic data to main server. For strong-motion detection, MEMS accelerometers are cost effective solution for EEWS due to its good resolution and near-linear phase and amplitude response. Every MEMS accelerometer embedded In the personal device detect the seismic motion and transfers the data using the Berkeley Open Infrastructure for Network Computing (BOINC, Anderson,2004).The system uses a standard short-term average, long-term average (STLA) algorithm , subscribed computer and sensor unit to detect sudden variation in the acceleration recordings. Whenever a ground tremor signal is detected and analyzed for its positive occurrence, the complete information containing sensor and seismic motion data is communicated to one of the QCN servers. These trigger signals are correlated in time and space, and are then processed by the QCN server to validate the likelihood of an immediate earthquake.

The participant countries in the program include Chile, New Zealand Taiwan, France, and Colombia. Since 2009, Mexico has participated as an autonomous member of the QCN program, referred to locally as the Red Atrapa Sismos (RAS). It started with the installation of ~150 sensors which is increasing due to its success. Mexico is an ideal country for the installation of low-cost accelerometers for real-time earthquake monitoring due to the fact that a large number of moderate to mega intensity earthquakes occur every year along the subduction zone that borders the entire west coast of the country.

The National Seismological Service (Servicio Sismológico Nacional [SSN] array, which consists of 80 broadband stations, is evenly distributed across the country and provides information of low magnitude earthquakes. Even though the resolution of RAS network is limited to earthquakes that detect strong ground motions, the ability of the system to predict high magnitude earthquakes having damaging potential is comparable with SSN. Therefore, EEWS like QCN have high potential usage for a country like India having same or better technological capability.

7. SENSORS

The sensors used in QCN are MEMS accelerometers [9]. These are low cost simple microchips consisting of very small set of force-balance cantilever beams placed inside. A low-level electrical voltage is used to compensate the balance mass weight. QCN uses many types of sensors, some are embedded in personal devices such as laptops/ desk tops, and some mounted on floor and are connected to the devices via USB port.

The QCN sensors measure accelerations between -2g and +2g on three axes. The sampling rate of the sensor is 50 times per second (50Hz). These have higher noise and low digital resolution compared to traditional research-grade seismometers, but their cost is very low suitable for dense deployment in large numbers. However large vibrational noise above the light grey region may be produced due slamming of ventilators, starting of heavy appliances and jumping on floor; Due to these disturbances and noise MEMS may miss up to M3 earthquakes signals.

8. OTHER METHODS FOR EARTHQUAKE DETECTION

There are different other ways which can be used for detecting earthquakes, with a longer warning period[18]. Further studies and research is required to validate these methodologies and develop a reliable and high success alarm rate EEWS.

8.1 Fiber optic cables as seismometers [14]

A team of meteorologists from England in 2006 observed noise in the fiber optic cable which resembled the noise generated from seismic waves. It matched with an earthquake measuring M 6.0 in Italy some 1400 kms away. Similar observations have been noticed in other undersea fiber optical cables. It is reasoned that seismic waves cause micrometric scale changes in the length of fiber optic cable. This change in the travel time to and fro of the data packets in femto seconds can be detected using ultra stable very high grade lasers. Since the P-waves first hit the fiber optical cables, a triangular method can be used to determine epicenter and its depth. More research on this phenomena and development of technique to predict occurrence of P-waves is required to validate the use of fiber optic cable in EEWS.

8.2 Variation in Water Level[13]

A rise of underground water level by 3-15 cm was noticed in China and Russia before the incidence of seismic tremors.

Similar incidents were also noticed in Australia in 1968. The ground water level initially reduces and then increases when an appreciable ground vibration (similar to seismic tremor) is felt. Water is contained in compartments and when the walls crack due to high pressure, the water flows from the higher level to lower level. The high pressure and rapid flow of fluid triggers the earthquake. The remaining seals also get ruptured, and the width of the fault zone increases due to failure of the geometric irregularities at the fault. This process of the water moving in and out of the fault zone continues, thereby decreasing and increasing the water level giving an indication of seismic tremor. Hence, this variation of water level can be used as a reliable method for prediction of earthquake in much advance i.e. 3–10 days before its occurrence.

8.3 Visible and Infrared Imaging [15]

The seismic studies have found that the region around the epicenter experience warm thermal conditions with temperature increasing by 4-6 degree Kelvin. The main causes are the pressure built-up as a result of tectonic activities and the associated degassing at the subsurface which causes variation in thermal signature of the area. This regional warming phenomena before the occurrence of seismic tremor can be detected and analyzed for probable earthquake. A visible and infrared imaging system installed onboard a Leo meteorological satellite can be used for this purpose.

9. CONCLUSION

The present day seismometers are mainly based on detection of P-waves. Future technological advancements in low cost wide band weak motion seismometers, low power long range reliable communication network and improved strong EEW prediction algorithm will definitely improve the EEW time cushion. It will also reduce false alarms and provide wider reach with improved activation plan. Further research in other detection methodologies will provide longer warning period for taking adequate precautionary measures to minimize the damage to negligible.

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