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Earthquake Early Warning and Instrumentation

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ABSTRACT.
Earthquake Early Warning (EEW) was booming in late 1990s after a severe ML7.3 earthquake hit Taiwan, killed more than 2,500 people and cost a loss of 12 billion US Dollars to the society. San Lien Technology Corp have devoted into seismic instrumentation for over 20 years and from 2006, corporation was begun with Yih-min Wu, a former seismologist at Central Weather Bureau (CWB) Taiwan and currently a professor at National Taiwan University (NTU), to develop the first and only low cost network accelerometer embedded with P-wave displacement technology for EEW. The information of P waves was discovered after five years of research from more than 800 earthquake records worldwide. It was found that whenever the faster P-wave moves vertically over 0.5 cm, the upcoming slower S waves would carry destructive energy. The network accelerometer, P-alert, is a palm-size and metal-made tri-axial sensor. It provides P-wave EEW, peak ground acceleration (PGA) and also short time average and long time average ratio (STA/LTA) algorithms. In addition, its Modbus industrial protocol easily makes integration of applications accessible. Thus, P-alert is ideal for mass deployment of a regional earthquake monitoring; moreover, it plays a critical role in a local on-site EEW system which is able to issue warnings or convey signals to attached devices for emergency stops.

Introduction

1:47 a.m., Sept. 21, 1999, a Richter scale magnitude 7.3 earthquake hit Central Taiwan without any pre-warnings (Ma *et al.*, 1999). Most of people in Taiwan were in bed while severe shocks woke them up and terrified all neighborhoods. More than 2,500 residents died and over 8,000 buildings collapsed or damaged during this incident. 90% soil in Central Taiwan reached Central Weather Bureau, Taiwan (CWB) intensity scale level 5 (80 gals, Table. 1), even people in Fu-Chien Province and Hong Kong felt the shake. This earthquake, also known as Chi-chi Earthquake, is the most serious natural disaster for the past 50 years in Taiwan's history.

Earthquake Early Warning (EEW) program developed by Wu is able to determine epicenters of seismic in a shortest time (Chen *et al.*, 2012). With the deployment of seismometers island-wide and the program, in 1999 Chi-Chi Taiwan earthquake, the critical information was determined within 102 seconds, which was a world record at that time (Lin *et al.*, 2012). The important message along with the report (Fig. 1) was given to rescue teams, by which the resources and rescuers could reach to the most damaged locations to save lives.

Table 1. Seismic Intensity Scale, CWB Taiwan (Teng & Lee, 2000)

Intensity		Ground Acceleration (cm/s2,gal)	Effects on People	Effects Indoors	Effects Outdoors
0	Micro	Below 0.8 gal	Not felt.		
1	Very Minor	0.8 ~ 2.5 gal	Felt only by a few people at rest, vibrates slightly.		
2	Minor	2.5 ~ 8.0 gal	Felt by the majority of people. Some awakened from sleeping.	Hanging lamps and objects vibrate slightly.	Standing vehicles vibrate slightly, similar to being passed by a truck, but only lasts for a short time.
3	Light	8.0 ~ 25 gal	Felt by nearly everyone, a few frightened.	Buildings shake; dishes, windows, and doors shake making sounds; hanging objects shake visibly.	Standing vehicles vibrate obviously; electric wires sway gently.
4	Moderate	25 ~ 80 gal	Many people are quite frightened, looking for safe shelter. Most people are awakened from sleep.	Buildings rock noticeably; unstable objects topple over; heavy furniture moves; may cause slight damage.	Felt by drivers; electric wires sway obviously, felt by people walking.
5	Strong	80 ~ 250 gal	Most people are considerably frightened.	Walls crack; heavy furniture may overturn.	Noticeably felt by drivers; some chimneys and large archways topple over.
6	Very Strong	250 ~ 400 gal	People have trouble walking due to violent rocking.	Damage to some buildings; heavy furniture overturns; doors and windows bend.	Drivers have trouble steering; sand and clay blasts occur.
7	Great	400 gal and above	People move with difficulty due to severe rocking.	Severe damage to or collapse of some buildings; almost all furniture moves or falls down.	Landslides and faults rupture occur; railway bend; underground lines break.

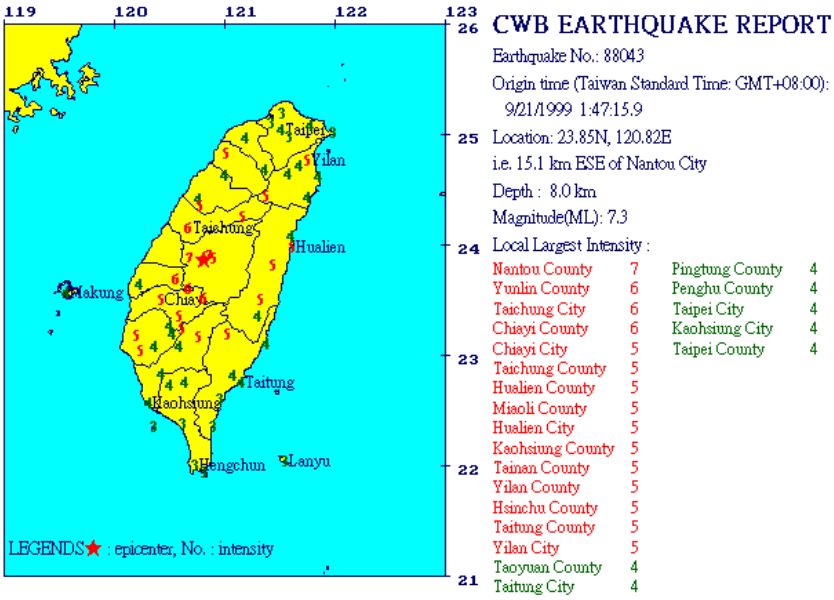

Figure 1. Chi-chi Earthquake Report (Teng & Lee, 2000)

A further research was continued by Wu as the expensive seismometers could only be purchased by government for research purposes but people in Taiwan and the world were not able to benefit from the data they measured. A low-cost EEW model with early warning algorithms was then developed by Wu with the deployment of the important information of P waves and its relation with S waves in more than 800 seismic events worldwide for 5 years. The algorithm developed is named as “P-wave Displacement” algorithm and cooperation is made with San Lien in making the first and only low-cost seismometer – P-alert in Taiwan (Fig. 2).

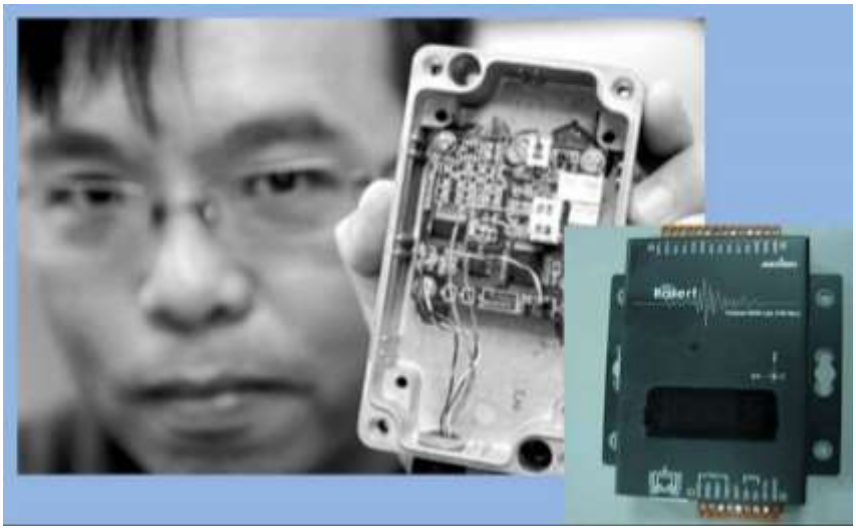

Figure 2. P-alert developed by Wu with cooperation from San Lien

Development of San Lien earthquake early warning system

The early batch of EEW system was tested at CWB and the EEW messages were only sent to some governmental agencies and private companies. This made the EEW messages were very sensitive to the society; the government was unwilling to deliver this information to the public until having it tested thoroughly and the possibility of issuing false alarms was able to be as minimal as it could be. Therefore, the valuable information of earthquake early warning was reluctant to be considered unless users could accept the risk the false alarm brought.

Nevertheless the geological structure of Taiwan limited the development of regional EEW system. The distance from the north and south ends is only 400 km while east and west is less than 160 km. In order to provide estimated local earthquake intensity and countdown seconds to people in different locations, the three elements - the epicenter, magnitude, and depth of an earthquake event have to be obtained first. Nevertheless, the process may take the central server approximately 15 to 18 seconds to determine the three elements. This period would allow a 70-km blind zone at which people are unable to have any pre-warnings of the coming of earthquakes. Only people or facilities out of the blind zone (Fig. 3) will benefit from the system. However, within 70 square km there are many cities, towns or villages along with high-tech factories. Hence, merely relying on regional EEW system cannot be the only options; developing on-site EEW system is necessary.

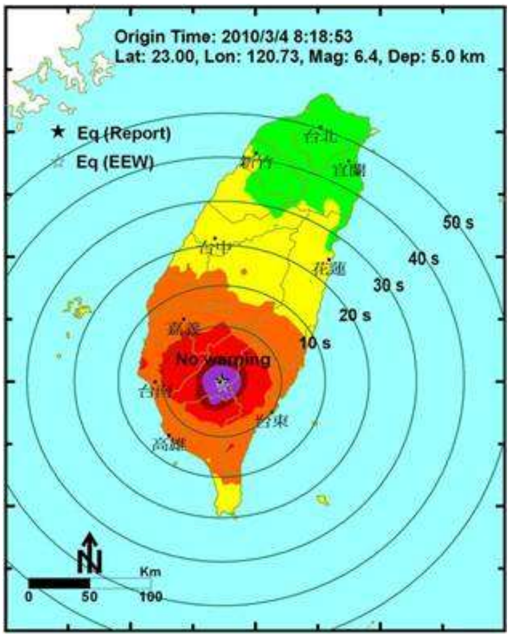

Figure 3. Blind zone (CWB, 2010)

P-alert as shown in Fig. 4 is a lightweight MEMS (Micro Electro Mechanical Systems) network accelerometer with 16-bit resolution. It provides 100 sps (sampling rate per second) in both streaming and record modes. P-alert has two DO (digital outputs) which allow external equipment to be connected directly. In addition, P-alert supports Modbus Protocol connectivity through its RS-232, RS-485 and TCP/IP ports, which offers easy integration to PLC (programmable logistic controller), HMI (Human-Machine Interface) and SCADA (supervisory control and data acquisition). Since its first release to market from 2009, P-alert has been installed more than 800 units around the island of Taiwan. Among them, 600 units are part of Wu's school EEW project which was launched in 2010 and has completed installation island-wide in the end of 2014.

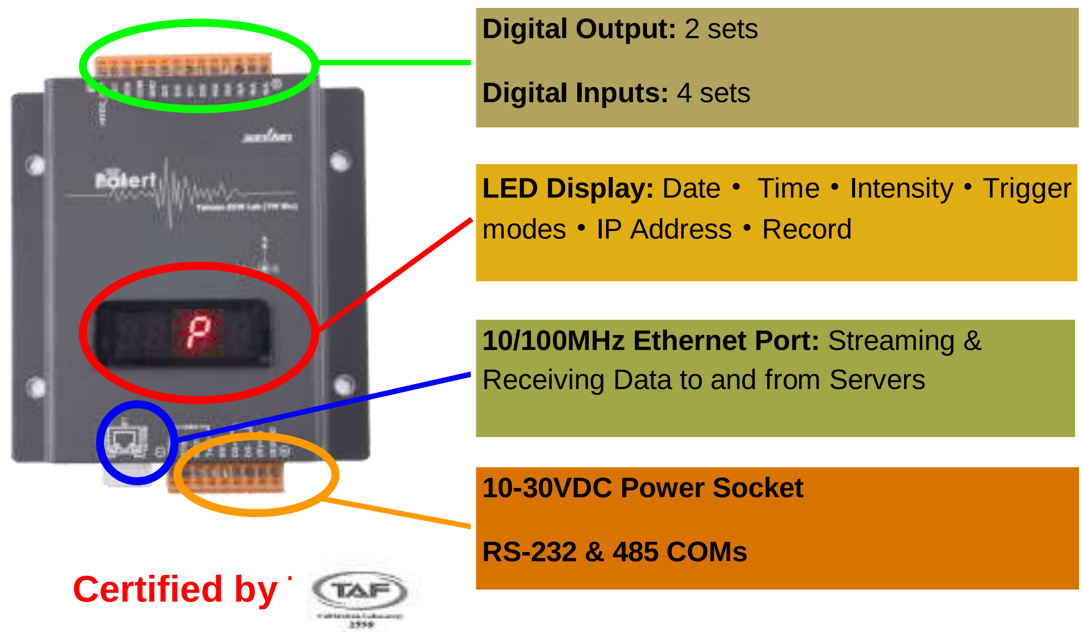

Figure 4. P-alert features

Two violent earthquakes happened in the first half of 2013 gave the system an opportune environment to test its stability and reliability. Within 60 seconds our system was able to generate a preliminary shake map (Fig. 5), giving rescuers and governmental facilities clear target areas which may suffer from severe damages.

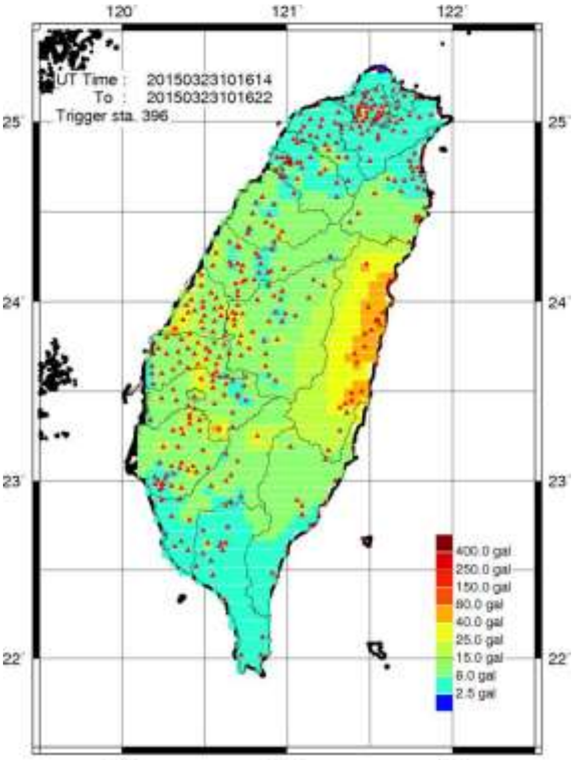

Figure 5. An example of 1-min shake map of P-alert system (NTU EEW team, 2015)

The shake map will continue being updated every minute until the earthquake is over and the data are also transmitted to several universities as well as CWB for evaluation in order to integrate P-alert data into their systems. Due to the rapid sales expansion of P-alert, more inquiries regarding integration of applications have raised in the past year. Before this, system integrators had tried to apply P-alert into their existing systems by PLC (Programmable Logic Controller) or SCADA (Supervisory Control and Data Acquisition); however, incorrect configurations can cause problems while determining emergency warning outputs.

Application of San Lien earthquake early warning system

To avoid false alarms and to convey precise E.E.W. information to users, a main control unit, PX-01 as shown in Fig. 6 has been created. Supporting Modbus TCP/IP Protocol, the PX-01 is designed and developed for on-site EEW system. With a PX-01, three P-alert, and an FTE-D04 seismic warning device or a "plug-n-play" LF-01 Lantern Fish, San Lien On-site Earthquake Early Warning System is formed. Users can also select text scrolling message display devices or integrate with their broadcasting systems to accomplish the full system.

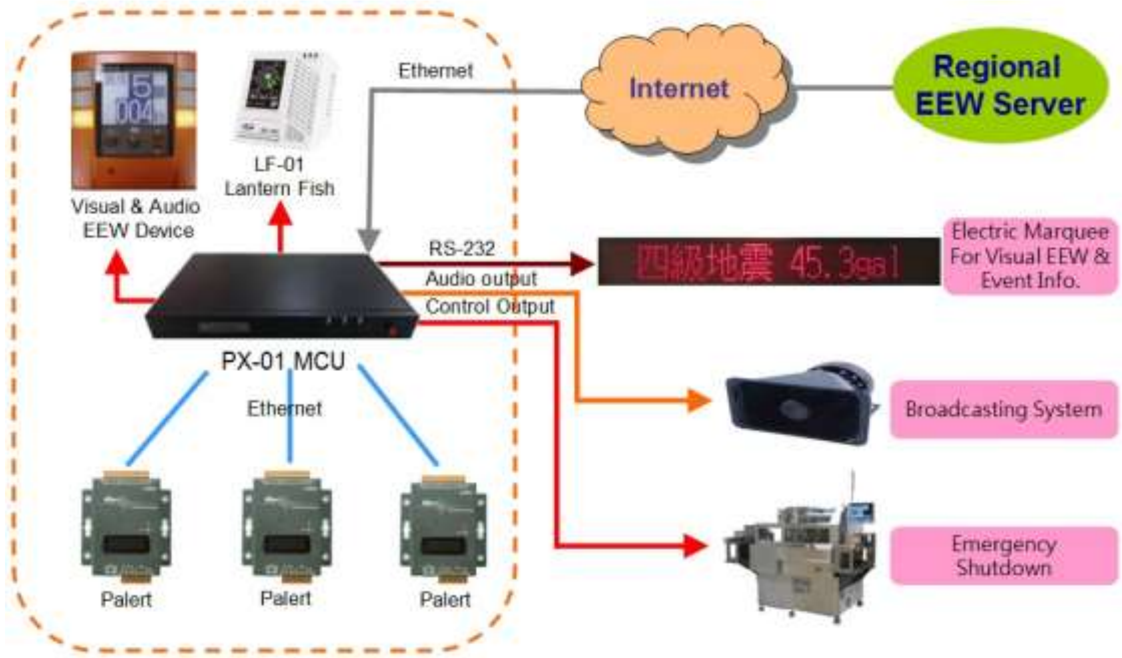

Figure 6. Setting of San Lien on-site EEW System

This system is featured with:

I. 2-out-of-3 EEW algorithm determination.

II. Connecting up to 5 x P-alert and forwarding streaming to 100 clients at most.

III. Provision of event and waveform recording.

IV. Providing minimum 3 relay outputs for multiple purposes.

V. Voice alerts for regional & on-site EEW messages for S-wave countdown and estimated maximum intensity broadcasting.

VI. Modbus TCP/IP emergency door exit control.

VII. Supporting EEW messages outputting to 5 x FTE-D04 and 5 x electronic marquees simultaneously.

VIII. Extension application of tipping bucket rain gauge.

IX. Multi-functional extension application - LF-01 “Lantern Fish”, a plug-n-go desktop Quake Alarm with CO2 & RH/T functions (UDP broadcasting supported).

Moreover, the popular M.Q.T.T. (message queuing telemetry transport) protocol is also a built-in feature of PX-01. M.Q.T.T. is a communication protocol developed by Eurotech and IBM (Stanford-Clark & Wightwick, 2010). It was designed for I.o.T. (Internet of Things) and users can adopt it inside their systems so many of the terminal devices are able to communication to each other via M.Q.T.T (Fig. 7). Since M.Q.T.T. is a cross-platform application and does not require the Internet to convey messages, for high-tech companies or governmental agencies who are very sensitive to information security, M.Q.T.T. is capable of data exchanging through the “Intra-net” and provides faster information transmitting advantage (Benson *et al.*, 2015).

San Lien (PX-01) On-site EEWS is an ideal system to execute emergency shutdowns or evacuation for semiconductor manufacturers, chemical plants, gas line valves, schools, hotels, publics or places where people gather. With the certified TAF lab calibration report for P-alert, this system provides accurate, instant and reliable EEW to fit into various kinds of applications.

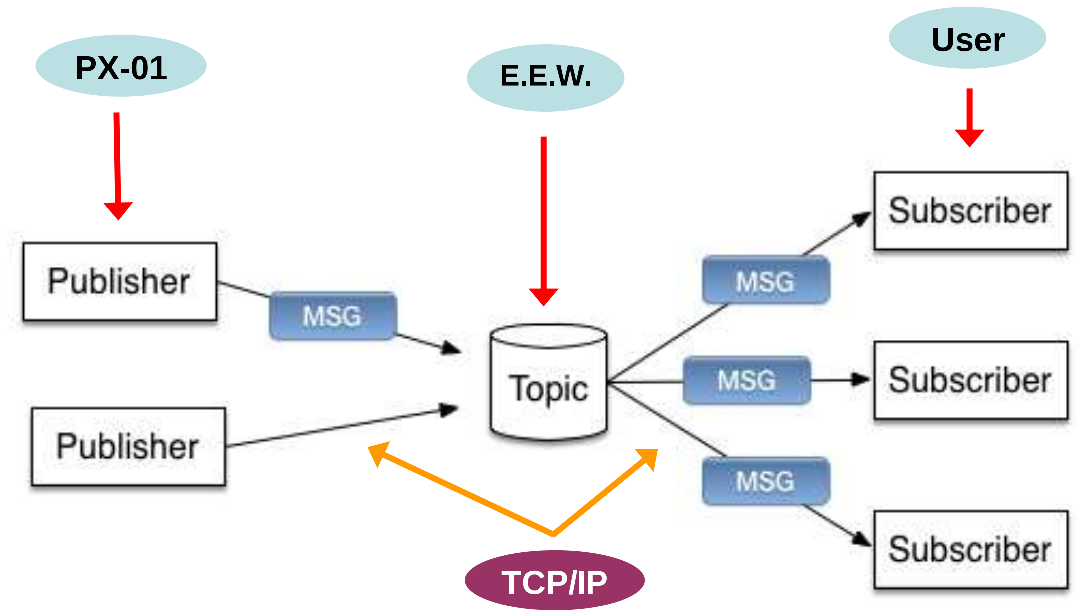

Figure 7. An example of early warning M.Q.T.T. service

Conclusion

After Chi-chi earthquake in 1999, Taiwan's government had required all commercial or residential buildings needed to be shake-proved or were able to stand shake intensity level 7 of CWB scale standard (400 gals, 0.4 G). However, the fears generated by unknown power of seismic activities usually cause unwanted tragedies and accidents such as damage of gas pipelines or oil tank valves which might result into explosion. Therefore, the adoption of on-site EEW system is also playing an important role as that of regional setup as it provides more time for the people to react to the coming earthquakes.

San Lien EEW system had been tested for many years in Taiwan in which the grounds move every six seconds. In addition, the successful export of the entire system to India, China, Korea as well as Indonesia, New Zealand and Solomon Islands has proved the stability and reliability of the system. The most crucial credit of P-alert is of its low setup cost to serve as an economical live-saving system with a high accuracy feedback.

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