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Abstract

Recent years have ushered in tremendous advances in information and communication technologies (ICT) and infrastructures for disaster management. Still, daily news on disasters has been telling us that even people in technologically advanced regions remain ill prepared. Smart and intelligent environments now offer us an increasingly broader spectrum of devices and services for comfort and convenience, safety from intruders, and social connectivity but little or nothing to help us to improve our readiness against killer tornados, major earthquakes, landslides, floods and so on. This paper first describes scenarios based on recent calamities to illustrate the need for enhancing our environments for disaster preparedness. It then describes examples of standard-based cyber-physical devices, systems and applications that can help to minimize loss of lives and damages to property. The paper concludes with opportunities and challenges to make such devices and systems dependable and affordable enough to be used pervasively as parts of future smart living environments.

Keywords Disaster preparedness, cyber-physical devices, CAP-aware devices and systems

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1 Introduction

Experiences in managing disasters have shown time and again that data and information needed to assess situations and support decisions and operations are vital to effective disaster management, especially for preparedness and response phases. This fact has motivated strong messages from opinion leaders urging the harness of information and technology for disaster management [1-3] and the development of disaster management infrastructures, applications and services by countries, inter-governmental bodies, and volunteer organizations. There are now disaster information systems in various stages of being planned and built in Southeast Asia countries and by IGOs such as UNESCAP/WMO Typhoon Committee and UN GDACS (e.g., [4-9]). Open source software communities and social networking services have offered crowdsourcing platforms and tools (e.g., [10-15]) that were found effective, especially in underdeveloped regions, during the crises from recent major disasters.

Many research and advanced development projects in technologically advanced regions are large and integrated. Their primary goal is to make available standards and tools needed to support interoperability of diverse sensor networks and emergency alert systems. As examples, in EU, OSIRIS (Open architecture for Smart and Interoperable networks in Risk management based on In-situ Sensors) [16] and SANY (Sensor Anywhere) [17] aim to make multi-domain, real-time sensor data easy to process and use for managing disaster risks in general. Other EU efforts (e.g., [18, 19]) target methodologies and tools for risk assessment and management of specific types of disasters (e.g., avalanches, debris flows and floods).

In USA, SensorNet [20] and FEMA DMIS (Disaster Management Interoperability Services) [21, 22] aimed to enable autonomous regional and local sensor networks and emergency management systems to function as interoperable parts of a nation-wide public safety infrastructure. DMIS is now superseded by IPAWS-OPEN (Integrated Public Alert and Warning System – Open Platform for Emergency Networks) [23], CAP (Common Alert Protocol) [24] and EDXL-DE (Emergency Data Exchange Language Distribution Element) [25]. OPEN provides services to receive, authenticate and route standard-based messages from alerting authorities to all types of public alert systems, including radio, television, cellular telephones and Internet-based systems. Together with EDXL-DE, the alert message standard CAP supports message exchanges between emergency information systems and public safety organizations. More importantly for our discussions here, CAP enables automatic reports by sensor systems to analysis centers, aggregation and correlation of warnings from multiple sources and automatic processing of alert messages by smart devices and applications.

In addition to disaster management ICT (Information and Communication Technologies) infrastructures and tools, we also have witnessed great advances in the development and deployment of technologies for the predication and detection of killer storms, earthquakes, debris flows, tsunamis, and so on. As examples, today, advanced weather radars and warning decision support systems (e.g., [26, 27]) enable accurate predictions of paths and severities of tornados and hence deliveries of warnings tens of minutes in advance. In developed countries frequented by strong earthquakes (e.g., Taiwan, Japan and parts of USA and Mexico), densely deployed broadband arrays of seismometers and strong seismic motion sensors [28, 29] are networked with computers running advanced auto-location and focal mechanism determination tools (e.g., [30-35]). Systems built on such networks of things can deliver early warnings of earthquakes within seconds after their occurrences, providing receivers of warnings seconds or more before shock waves arrive and ground motion starts.

Despite tremendous technological advances and infrastructure development, we remain ill prepared, not just for devastating events such as 2011 Tohoku earthquake and tsunami and the nuclear accident triggered by them. We are also not well prepared for disasters such as 2011 Joplin MO tornado [36], Virginia earthquake [37] and Seoul Korea flood [38]. Smart and intelligent homes and environments (e.g., [39-41]) now offer us an increasingly broader spectrum of devices, applications and services for our comfort, convenience, and social connectivity. In contrast, there is little or nothing to help us prevent loss of lives, reduce chance of injuries and minimize property and economical losses.

This paper advocates the development and pervasive deployment of cyber-physical devices, systems, services and applications designed to take advantage of the current and future disaster predication and detection capabilities and standard-based alert/warning delivery systems for the purpose of enhancing our preparedness for disasters. When there is no need to be specific, we refer to such devices/systems/services/applications as *intelligent Guards against Disasters,* or *iGaDs* for short. Specifically, each iGaD can authenticate and process standard-conforming disaster warning messages and respond by taking appropriate actions. For sake of concreteness, for the most part of this paper, we assume that alert/warning messages conform to the latest version of Common Alert Protocol [24], and will highlight the capability of an iGaD to respond to CAP messages by saying that it is *CAP-aware*.

As examples of iGaD, when warned by alert messages of earthquakes of a specified strength or stronger, a smart valve shuts down natural gas flow into a condo building to prevent fire and an automatic door controller opens the building doors to ease evacuation. Elevator controllers stop elevators when they reach the closest floor. An application component of the smart environment in hospitals tells surgeons to pause on-going operations, or in supermarkets informs shoppers of relatively safe aisles to be during the quake and so on. As the iGaD part of an on-board vehicular safety system, an earthquake alert device warns the driver of the imminent strong earthquake and may even turn on the hazard flashers, disengages the cruise control or helps the driver to slow down. Smart variable message signs before tunnels and bridges on highways may tell the drivers to slowdown and pull over.

Following this introduction, Section 2 discusses why we need iGaDs and what they can do for us with the help of three future scenarios. Section 3 describes a general architecture of CAP-aware iGaDs and their key components. Section 4 discusses opportunities and challenges in their development, deployment and use. Section 5 summarizes the paper.

2 Future Scenarios

For motivation purposes, the scenarios described below illustrate how iGaDs can help us to be better prepared against disasters similar to 2011 Joplin tornado, Virginia earthquake, and Seoul floods. Such disasters are relatively rare, but still occur too frequently for us not to be well prepared. In regions of the world where supporting ICT infrastructures are sufficiently developed, iGaDs can be made affordable and widely used as tools for prevention of the tremendous losses and chaos summarized by Figure 1.

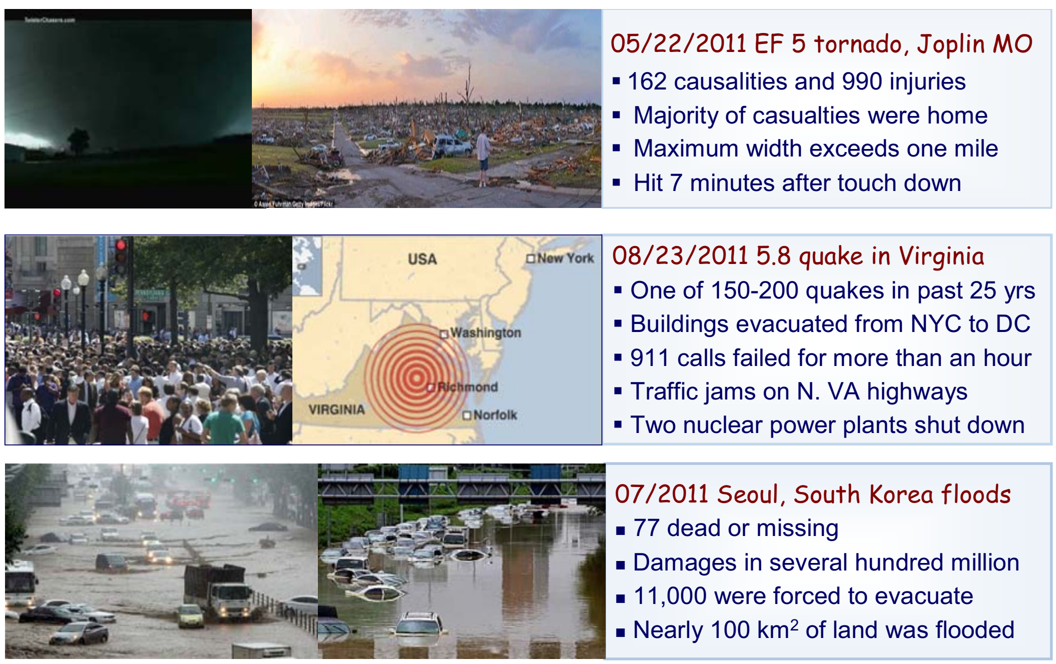

Figure 1 Three 2011 natural disasters [42]

iGaDs for Preparedness Against Killer Tornados The effects of an EF(Enhanced Fujita) 4 or 5 tornado a mile or more wide like the 2011 Joplin tornado can be far more devastating and tragic if it ever hits a more populated part of Tornado Alley. Take Champaign-Urbana (C-U) IL with a population of over 230,000 as an example. The university town is frequented by tornado warnings. In the past, some tornados actually touched down and damaged some house(s). As in

Joplin[1] and many parts of Midwest, a large percentage of houses in C-U, including homes of faculty members and professionals and houses rented to students, do not have basements. A common practice of C-U residents during tornado warnings is to stay on the ground floor of the house, monitoring the storm via TV and radio, and take shelter in an inner closet or bathroom when siren sounds. They do so because experiences over the years tell them that tornados usually leave small inner rooms on the ground floor standing and hence do little or no harm to people hiding inside. As we can see from the top-part of Figure 1, a strong and big tornado can move large buildings off their foundations, flatten the houses completely and kill or seriously injure people inside them. If ever an EF 5 or EF 4 tornado, like the one that struck Joplin, MO, were to hit C-U, the number of casualties and injuries could be in order of thousands.

In addition to a false sense of security, people take shelter at home because outside of working hours, most residents do not have (or do not know of) better places to go. A way to minimize the chance of such tragedies is to provide residents with public shelters and, during dangerous storms, have the shelter entrances marked by light beams that can be seen in rain, hail and darkness. This can be easily done in cities similar to C-U: Steel and concrete university buildings with safe multiple floors underground are scattered throughout the city, within minutes of walk or drive from most homes. Unlike police and fire department buildings, however, many university buildings are locked normally after working hours. iGaDs can be used as tools to make them accessible as shelters automatically during emergencies.

One can envision that in a city or town equipped with them, a smart CAP-aware switch outside each shelter door turns on a bright search light to mark the door when it receives a CAP-conforming message warning of an imminent EF 4 or stronger tornado. In response to the message, an iGaD at each shelter door unlocks the door. Some may turn on additional surveillance cameras to monitor the activities within the building during the emergency. When triggered by a warning message, iGaDs in a smart home may unlock the outside doors and vents to allow equalization of air pressures in and out of the house if and when the tornado hits.

iGaDs for Improved Response to Earthquakes The frightened and confused reactions of people in the mega-regions around Virginia during and immediately after the 2011 5.8 Virginia earthquake remind us that even areas rarely hit by earthquakes need to be well prepared for them. The earthquake led to evacuation of buildings from New York City to Washington DC, failures of 911 calls for more than an hour, traffic jams on highways and chaos in subway stations, and so on. While the earthquake caused no deaths and injuries and relatively little structure damages, the economic losses total near 100 million USD. Much of this loss and rattled nerves of the people can be avoided if the regions were well prepared with not only state-of-the-art early

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[1] According to MSNBC, 87% of homes in Joplin had no basement.

earthquake detection and early warning systems but also well placed iGaDs to take advantage of the warnings. As mentioned in Section 1, CAP-aware iGaDs as parts of smart buildings and environment can warn people via public speaker systems, phones, social media, etc. of the earthquake and instruct them of the best strategies to stay safe. The instructions provided by individual iGaDs can be customized, for example according to the seismic codes of the buildings, furnishing of the workplaces, stores and homes. – For most people in the areas affected by the 2011 Virginia earthquake, it was safer to stay in their buildings than running into streets.

Figure 2 shows a future earthquake scenario to elaborate this point. The scenario can take place in Taiwan where there are more than 1,000 felt earthquakes a year on the average, and there have been 96 catastrophic earthquakes since 1900 according to the statistics provided by Taiwan Central Weather Bureau (CWB). Seismic data from a densely deployed broadband array of seismometers and strong motion sensors sent via RF links enable CWB to determine the focus and magnitude of each earthquake and in case of severe quakes broadcast early warnings to affected areas seconds after the quake occurs. State-of-the-art early earthquake detection and warning systems are also available in Japan, Mexico and parts of USA. The scenario assumes that warning messages conform to CAP and carry sufficient information to guide each CAP-aware iGaD in its determination of whether and when to carry out specified action(s).

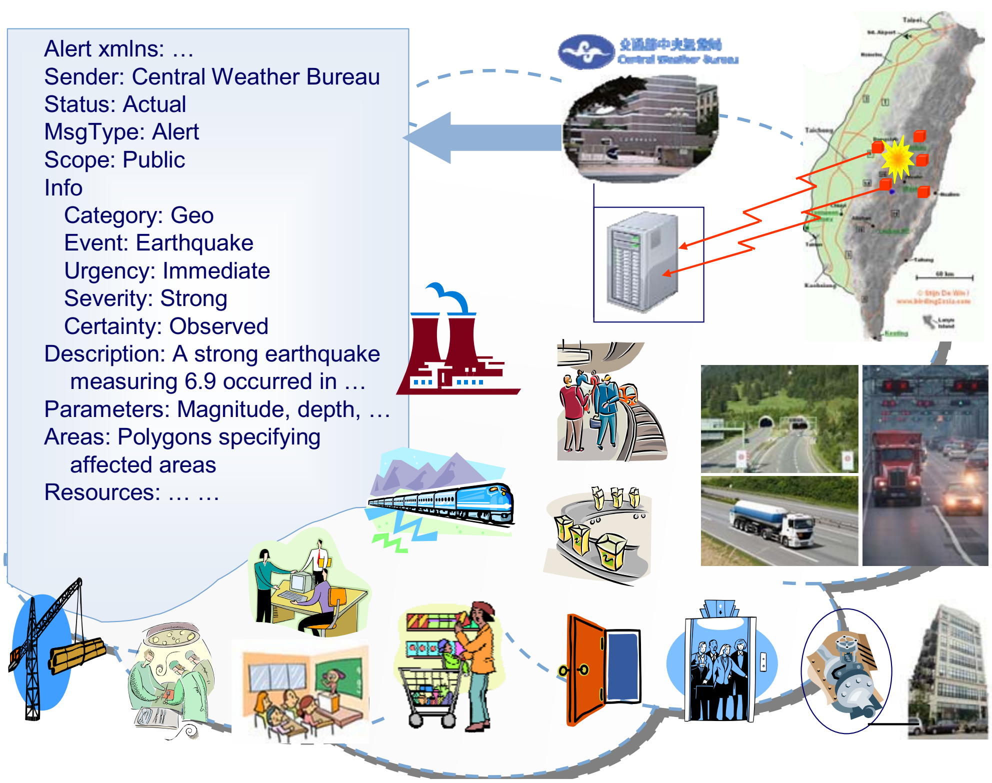

Figure 2 A future earthquake scenario

In addition to usages of smart CAP-aware devices mentioned above and in Section 1 as examples, Figure 2 also shows nuclear power plants, rail and subway trains, and fabrication lines as examples of facilities that can be severely damaged if allowed to continue normal operations during strong earthquakes. Typical safety equipment of power plants can sense local ground vibrations and take appropriate protective actions. The two nuclear power plants in Virginia are examples: During the 2011 5.8 Virginia earthquake [37], their safety equipment triggered the plants' shutdown automatically after local sensors detected ground vibrations twice the maximum strength for which the plants were designed to withstand. A better alternative is to have the region covered by an early earthquake warning system and make the safety equipment CAP-aware. An early earthquake warning message can enable safety equipment to start the shutdown sequence seconds before local ground begins to vibrate.

In earthquake prone regions, big companies operating rail and subway trains and fabrication lines have their own cyber-physical devices and systems for protection against earthquakes. For example, East Japan Rail and Shinkansen (Japan's high-speed train) have tens of seismometers. More than ten seconds before the 2011 Tohoku earthquake struck, one of the seismometers sent an automatic stop signal to the Shinkansen electric power transmission system, triggered the emergency brakes on more than 30 trains running at the time, and thus prevented deaths, injuries and damages from train derailments [43]. Dependable, affordable smart devices designed to respond to CAP-conforming earthquake warning messages generated for and broadcast to all people can provide automation equipment (e.g., automatic pancake machines, printing presses, etc.) operated by small businesses the same kind of protection against earthquakes.

iGaDs for Mitigating City Floods Most of the world efforts (e.g., [19, 44]) on controlling and mitigating floods focus primarily on widespread floods due to multiple events over periods of time causing rivers to overflow. Examples include the devastating 2010-2011 Thailand and Queensland floods [45, 46] and seasonal floods in USA and Europe. State-of-the-art methods and tools for preparedness and response against such floods are not effective for safeguarding ourselves against floods in cities caused by unexpected torrential rain such as the 2-day heavy downpour over Seoul, South Korea in August 2011 [38]. The once in a century rain event caused killer flash floods and landslides and turned city streets and highways into streams and rivers.

Ideally, streets and inner city highways threatened by floods should be closed and directions for detours away from flooded road segments put in place just in time to prevent people and cars from being trapped by water as in the scenes from Seoul shown in the bottom part of Figure 1. Similar scenes played out recently in other cities, including many cities in technologically advanced countries. These cities have not been able to respond promptly enough for many reasons. Among them are that floods in cities are often local; city-wide, even district-wide, rainfall prediction does not provide sufficient information for assessing the threats of flooding along individual streets and roadways; it is too costly to cover the city with surveillance sensors densely enough for assessing flood potentials of individual locations, and the time available to response is short, in order of minutes and hours.

The combined use of crowdsourcing and iGaDs can be an effective solution. People armed with wireless devices and social media services can be used as mobile human sensors [47]. Their eye-witness reports on early signs of flooding in their neighberholds can complement surveillance data from physical sensors. Indeed, past experiences with crowdsourcing information on snowstorms, wildfires, oil spills, and so on (e.g., [48-50]) show that making good use of people and social media is a way to improve short-range weather forecasting (nowcasting) and spatial resolution and timeliness of information needed for situation assessment.

Crowdsourcing information on early signs of floods in a city is considerably easier to implement than crowdsourcing information on severe storms, wildfires and oil spills. Security personals and doormen of commercial and residential buildings, taxi and bus drivers, store keepers and so on with access to phones and Internet are literally everywhere. Even without prior preparation, these people can form a reasonably trustworthy, high quality crowd if they can be activated by a CAP alert message to report conditions around themselves. Today, location-based applications supporting international standards (e.g., GeoSMS [51]) for geotagging messages, photos, etc. are available on an increasingly wider spectrum of devices and platforms. With such applications, it is easy for people to provide the city's emergency operation center (EOC) with location information in standard format along with disaster situation information.

In this scenario, existing variable (electronic) message signs commonly used on roadways to provide travelers with information on traffic and road conditions suffice as tools to divert traffic away from flooded areas. Making them CAP-aware and hence can be written by EOC by sending to them CAP messages during emergencies has some obvious advantages, including putting road closure and detour setup directly under the control of EOC.

One can also envision that in a future city where iGaDs are ubiquitous, all or some of the surveillance cameras outside big buildings for monitoring people and cameras at roadside for capturing traffic violations are CAP-aware smart devices. EOC can selectively activate such devices at selected locations and have them send captured images of local conditions at specified rates and thus acquires additional surveillance coverage during the emergency.

3 General Structure and Key Components

It is evident from the scenarios described above that different types of iGaDs differ significantly in functionality. Moreover, the actions taken by individual iGaDs of the same type may differ widely. Nevertheless, all iGaDs can have similar architecture and key components.

Figure 3 shows a general structure of embedded iGaDs exemplified by the devices mentioned previously in the tornado scenario. By device, we mean here the physical device (e.g., a door or a search light) served by the iGaD. In the block diagram, rectangular boxes represent functional modules, and arrows indicate data and control flows between modules. As the figure shows, each embedded iGaD has a device controller and a CAP message processor. The parts communicate via alarm type and information extracted by the CAP message processor, and device location provided by the device controller. In general, the device controller may import other data (e.g., sensor data) from local sources. To keep the figure simple, we omitted the interfaces to them, as well as the module that provides device location needed by the CAP message processor. A non-embedded iGaD does not have a device driver; in its place, there is one or more disaster management applications running on some platform(s).

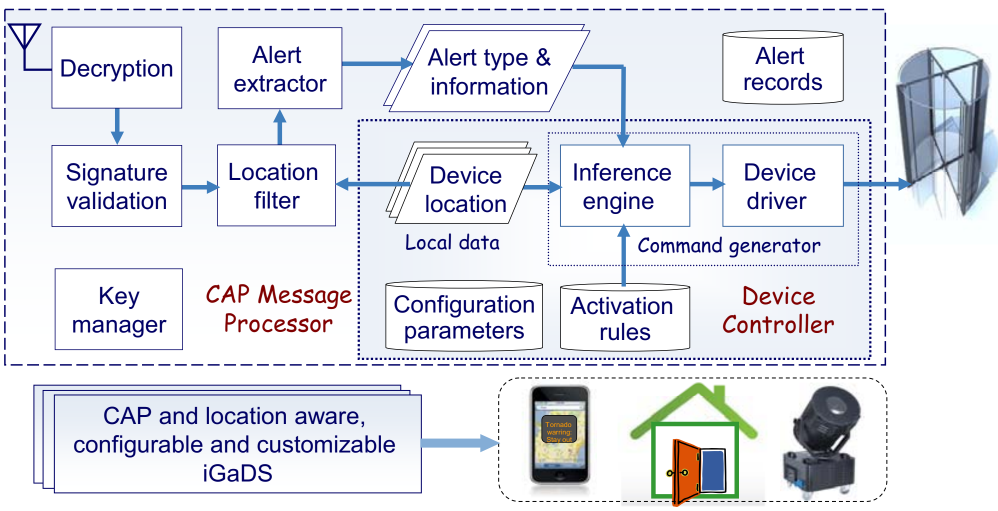

Figure 3 General structure of embedded iGaD

Device Controller The device controller part of an iGaD is both device dependent and installation dependent. Clearly, the command generated by the device controller of an iGaD depends on the type of physical device served by it. By the controller being installation dependent, we mean that the rules governing its generation of the command(s) depend on where and how the physical device is used, as well as specifics about the alert.

As an illustrative example, suppose that the automatic locks for shelter doors and outside doors of homes in an area covered by a tornado warning are identical. So, the commands sent by the controllers to open the locks are identical. The device controller of the iGaD for each shelter door may send an unlock command to the lock immediately upon receipt and processing of the tornado warning message. In contrast, upon receiving the same warning, the controller of the iGaD for the lock of an outside door of a home may wait to issue its unlock command until it senses that the local air pressure has fallen below a threshold.

Such customization can be done by selecting the action activation rules of each controller at installation and maintenance times and by providing the command generator with an inference engine to process the rules. This is why Figure 3 shows that command generator is composed of two parts: The device driver must be tailored to the type of physical device controlled by the iGaD, but the inference engine may be identical for all similar types of devices.

The action activation rules of typical iGaDs of simple devices can be expressed in terms of propositional logic or predicate logic, simple enough to be evaluated by small inference engines such as the ones described in [52, 53]. As examples, suppose that both types of doors should open when warned of a strong earthquake or a severe tornado. The rules specifying the conditions for unlocking them might look like the ones listed below:

(1) `(AlertType == Earthquake) AND (Magnitude >= THRESHOLD_MAGNITUDE)`

(2) `(AlertType == Tornado) AND (Severity >= THRESHOLD_SEVERITY)`

(3) `OutsideAirPressure <= THRESHOLD_RATIO * InsideAirPressure`

The iGaDs of shelter doors would command their locks to open when rules (1) or (2) is true. The iGaDs of the outside doors of homes issue unlock command when rule (1) is true, or rules (2) and (3) are true. Parameters with names in capital letters are configuration parameters. The iGaD used for each door can be further customized according to the construction and age of the building and the door by setting these parameters when the locks are installed.

CAP Message Processor In contrast to the device controller, the CAP message processors for all CAP-aware devices and applications are identical. For the sake of discussion here, it makes sense to assume the general case where each alert element has an enveloped digital signature and is encrypted[2] [24, 54]. As examples mentioned above illustrate, an iGaD once installed, may be in service for years. Over time, many changes are inevitable, including key updates. During each update, a pair of new private/public keys is created and adopted in place of the existing pair. The device must be able to reliably decrypt and validate all alert messages intended for it during and after each key update process, even when some updates are lost. There are many alternative ways to achieve this, including using two pairs of keys, giving keys expiration dates, and so on [55, 56]. The function of the key manager within the CAP message processor is to maintain the keys according to a specified key update protocol (or protocols).

After each alert element is decrypted and authenticated, the location filter discards the alert if the device location is not in any of the polygons and circles listed in the alert element. If the alert covers the device location and has not expired, the alert type, parameters and information are extracted from the message. The extracted values are used as input for the purpose of evaluating the action activation rules of the iGaD and the determination of the action (or actions) to be taken by the device.

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[2] According to revision history, the removal of XML digital encryption within CAP messages was approved on March 2, 2010 [24].

4 Opportunities and Challenges

From illustrative examples on how iGaDs can help us make more effective use of earlier disaster warnings, one can easily envision the potential benefits realizable by deploying a broad spectrum of iGaDs ubiquitously throughout future living environments. Pervasive use of iGaDs clearly means a gigantic new market for smart device manufacturers and mobile application developers. Like many existing safety equipment for homes, factories, vehicles, etc., most iGaDs must be well maintained. They also offer new opportunities to industries that install, upgrade and service them and impose new responsibilities to many oversight agencies and organizations.

There are numerous challenges on the way to make iGaDs ubiquitous and as commonly used as cell phones, GPS devices, social media applications, smart appliances, and so on. Some of the challenges arise from the fact that all iGaDs must be affordable and cost effective, highly dependable, easily configurable and customizable, and adaptable to changes.

Affordability and Cost Effectiveness Some iGaDs are components of low-cost devices (e.g., light switches and gas valves) and therefore, must be even more low-cost and affordable. Some iGaDs are parts of complex safety equipment; they must be cost effective. Standardization is essential for this reason also. We have already seen that CAP-based embedded iGaDs are essentially identical. In particular, alert message processors in all iGaDs can be implemented in hardware and mass produced. It is possible for alert message processors based on a world-wide common standard to be so inexpensive that every cell phone can include one to support disaster preparedness and response applications! Similarly, one can keep the cost of the device controller and CAP-aware applications low by adopting a common architecture with reusable interference engines, device-driver components and a standard interface to alert message processor.

Making it easy to integrate embedded iGaDs with elements of smart homes, buildings and living environment and safety equipment of diverse systems (ranging from elevators, to cruise controller, to automatic pancake machines, to small power plants and so on) is essential to keeping the deployment and maintenance costs of iGaD low. For the same reason, CAP-aware disaster preparedness and response applications must be easy to port and deploy on diverse platforms. Some of them (e.g., applications designed to inform supermarket shoppers where to go during earthquakes and fires) need to be integrated with other applications (e.g., supermarket's inventory tracking system, building sensor surveillance system and local alarm delivery system). This calls for open standards of iGaDs external interfaces. iGaD interface standards must be compatible with existing standards for an extremely broad spectrum of products and systems. Their selection and/or development is a challenging task indeed.

High Dependability Many iGaDs are safety-critical devices or components of safety equipment. Being highly dependable is of critical importance. In general, disaster preparedness applications on phones and other mobile devices, PCs, building management systems, etc. are mission critical and therefore, must function correctly and reliably. From the simple structure depicted in Figure 3, one may conclude that making individual iGaDs dependable is not likely to be technically challenging. Indeed, it surely should not be as challenging as making many medical devices or anti-lock brakes dependable.

Looking at the dependability requirement from a system perspective, however, one sees many challenging issues. As an example, when the iGaD for a shelter door notices that the automatic lock controlled by it fails to open, it should be able to request the iGaD for the light in front of the door to turn off the light. For handling this and other errors and failures, we may want iGaDs to be able to communicate and collaborate. An iGaD may need to process at the same time multiple alerts of different types (e.g., earthquake and severe storm) and the alerts may call for conflicting responses. These seemingly reasonable functionalities can add considerable complexity and make the system as a whole less dependable. How to manage overall system complex to ensure dependability is a challenging problem.

Configurability, Customizability and Adaptability The previous section already elaborated the need for being able to tailor the specific actions to be taken by an embedded iGaD in response to warning messages and the rules governing whether and when it is to take actions to the type of physical device served by it and where and how it is used. Figure 3 suggests that iGaDs can be structured to allow configuration and customization at installation and maintenance times. Many iGaD applications may need to be downloaded and installed in preparation for an imminent calamitous event. Such applications must be portable and easily installed to run on most, if not all, available platforms.

Making configuration and customization possible is not sufficient, however. Such work is typically done by installers, servicemen and end-users, and they are likely to have little or no technical expertise and training. They need tools to help them with the tasks and support standard procedures and best practices to ensure quality of the work.

Again, typical iGaD may be in service for years. During the life time of an iGaD, even the public alert and warning delivery system and message protocol standard(s) may change. Surely, key updates may occur many times. Making all types of iGaD capable of adapting to such changes and technological advances is not likely to be technically and economically feasible. For this reason, support infrastructures, including service and upgrade practices, need to be setup to ensure non-disruptive operations of all existing iGaDs.

5 Summary

This paper advocates the development and pervasive deployment of iGaDs (intelligent guards against disasters). The term collectively refers to smart devices, applications and services that are capable of receiving, authenticating, and processing standard-based disaster warning and response messages from authorized senders and taking appropriate actions to help us stay safe and reduce adverse economic impacts when disasters strike. Recent advances in disaster prediction and detection technologies and ICT support infrastructures have enabled the generation and reliable deliveries of machine-readable early disaster warnings over all communication pathways. The emergence of ubiquitous iGaDs is a natural next step in the advancement of disaster management technologies, as they make disaster warning and response messages not only for human consumption but also for rallying smart things to help.

The previous section pointed out several technical challenges concerning how to make iGaDs affordable; dependable; easy to integrate, configure and customize; and adaptable to changes. We also discussed the critical need of open standards for iGaD reference architecture and key components, as well as standards for interfaces with products and systems and standard-based ICT infrastructures served or relied on by iGaDs. Equally critical are standards and guidelines governing upgrades and changes, service practices, training of installers and service personals, and so on. Developing or selecting standards across industries and governments is a most demanding task, at least in term of stakeholders' time, effort and collaboration. The time to start working on them is now.

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