Early Warning Systems

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An Early Warning System (EWS) is an architecture that integrates monitoring and forecasting subsystems, effective communication technologies, decision-making capabilities, and response activities to reduce the impact of disasters due to hazardous events through the generation and dissemination of accurate and timely warnings.

Keywords: Internet of Things ; early warning systems

1. Introduction

An EWS has the following key elements: (i) risk knowledge and risk assessment, (ii) monitoring of parameters that can enhance or enable predictions and forecasts, (iii) dissemination of timely warnings, and (iv) preparedness to respond to the disaster [1][2]. The United Nations Sendai framework for disaster reduction recommends to substantially increase availability and access to multi-hazard early warning systems by 2030 [3]. In 2020, only 23 out of 195 of the UN countries had a working multi-hazard national EW system. In these countries, 93.63% of the population exposed to natural disaster-related risks was successfully protected through evacuation following the early warning [4], showing the great effectiveness of these systems. The societal impact of a national Early Warning system in terms of risk preparedness and risk mitigation are expected to be extremely relevant. A survey in California from 2016 showed that 88% of the population agreed about the importance of a national Early Warning system for earthquakes [5], and another study showed how such a system on the United States West Coast could reduce the risk of injuries by 50% by enhancing the population preparedness to the event [6][7]. From a cost–benefit standpoint, while a rigorous analysis is required for each use case and it strongly depends on the frequency of the event and the ability of the system to avoid false alarms, employing an EW system can provide great damage reduction, especially when coupled with efficient infrastructures and complementary safety measures. As such, EWSs are useful tools to protect human lives, valuable assets and the financial stability of disaster-prone regions [8]. For example, it has been estimated that a flood forecasting system can reduce up to 35% of annual damages due to floods [9]. The benefits from damage and fatalities reduction thanks to an earthquake warning system could easily repay 1 year of operation of said system [6], and the estimated benefit to cost ratio of a tsunami EWS in the Indian Ocean would be 4:1 [10]. Moreover, according to the Sendai framework, an efficient disaster risk reduction framework requires a multi-hazard approach and inclusive risk-informed decision making based on the open exchange and dissemination of disaggregated data. The use of advanced information and communication technologies could provide the means to make multi-hazard warning systems available in most countries that still do not have a national implementation, thanks to their low deployment costs, and also provide the means for smart and effective alert and information broadcasting [11]. In particular, technologies such as Internet of Things, Cloud Computing, and Artificial Intelligence can assist the monitoring, forecasting and alarm generation aspects of Early Warning (EW) by providing the tools to sense, clean, process, and analyze data coming from the environment.

The Internet of Things (IoT) consists of infrastructures interconnecting connected objects and allowing their management, data mining and the access to the data they generate [12]. It aims at connecting objects, actuators, or sensors to accomplish various tasks, such as environmental monitoring for various customized purposes [13]. A basic and generic IoT architecture includes three levels: (i) the local environment, containing smart objects or sensors that communicate with each other and interact or sense data from the environment; (ii) a transport layer that allows end-nodes from the first layer to communicate with higher layers and infrastructures; and (iii) a storage, data mining, and processing layer, usually implemented in the cloud, and possibly with systems and interfaces to let users access and visualize the data. While Wireless Sensor Networks (WSN) are an essential component in many IoT deployments (providing an interface between the local environment and the users), IoT solutions allow the coexistence of heterogeneous devices, real time applications, data analytic and data storage services, improved security [14], and energy management [15], from which WSNs can benefit. In the context of disaster management and Early Warning systems, the IoT provides the means for widespread environmental monitoring from different data sources, low latency communications and real-time data processing, which enable the generation of accurate and timely warnings in the case of disaster occurrence or forecasting.

2. IoT Architectures for EW Systems

In the following section, researchers introduce a simple IoT architecture that can be used to describe EW systems based on the IoT paradigm. The entry will consider this reference architecture to better describe the reviewed IoT systems in the following sections, and find possible trends.

2.1. Reference Architecture

IoT systems' functions and peculiarities can be described starting from their architectural configuration. As for the most basic IoT solutions [16], a three-layered architecture can be used to describe a generic EW system based on the IoT. As shown in **Figure 1** the common IoT architecture basically consist of a Perception layer, a Communication layer, and an Application layer [17].

Figure 1. Reference IoT architecture.

While specific architectures may introduce or specify new layers and intermediate layers, such as Edge/Fog Layers, Middleware and Interface Layers, a generic and simple architecture can be considered to be one that senses data from the environment, processes it, and/or forwards it to a central server which will then use the current and previously stored data to generate alarms through different methods, such as signal processing, statistical methods, computer vision, or Artificial Intelligence (AI), specifically through the adoption of Machine Learning (ML), and Deep Learning algorithms. Below is a brief description of each layer with its main characteristics.

2.1.1. Perception Layer

The perception layer has the task to sense and collect data from the environment, usually through sensors. Wireless Sensor Networks are widely used in disaster monitoring scenarios: they consist of nodes equipped with sensing units and communication units that can harvest data from the environment and then forward it towards a gateway node that interfaces and communicates with higher layers. WSNs offer benefits such as scalability, dynamic reconfiguration, reliability, small size, low cost, and low energy consumption [16]. Some aspects of a WSN development are particularly important in disaster monitoring or disaster EW scenarios, such as battery life, coverage, and fault tolerance.

The choice of the right sensing unit can be essential in providing a timely and accurate response, and different parameters can contribute differently to a particular environmental hazard. Positioning sensors in certain zones or terrains can be particularly difficult, and while some applications monitor localized events (such as landslides), others might require deployments over large areas (such as river basins in flood EW, or the large geographical regions that can be affected by earthquakes), and this will enhance the cost of the solution and require ad hoc strategies to efficiently cover the entire area to be monitored, for example differentiating between nodes with long and short range coverage capabilities [18] or, for example, with a smart and optimized distribution of the sensors depending on the disaster probability of occurrence [19].

2.1.2. Communication Layer

The communication layer transmits the data acquired and processed by the perception layer to a server, cloud service or application. This layer is responsible for routing, communication between heterogeneous networks, and reliable data transmission. There are different communication technologies that can be used to transmit data, both wireless and wired.

Wireless communication technologies in IoT solutions for EW Systems can be divided in two categories: long range technologies and short range technologies. Low Power Wide Area Network (LPWAN) technologies such as Long Range Wide Area Network (LoRaWAN), SigFox, Narrowband Internet of Things (NB-IoT) and Extended Coverage GSM IoT (EC-GSM-IoT) offer long range and can be further divided into Licensed and Unlicensed, depending on the frequency bands used. LoRaWAN and SigFox use Unlicensed Industrial, Scientific and Medical (ISM) bands, while NB-IoT and Global System for Mobile communications (GSM) use cellular networks and work in licensed spectrum. Cellular networks are widely deployed and they offer reliable services and Quality of Service, but cellular networks can be badly affected by environmental disasters [20][21], which is a critical requirement for the development of EW Systems. Among short range technologies, wireless protocols such as Bluetooth Low Energy (BLE) and Zigbee can offer low-cost solutions with very low power consumption and mesh architectures support [22]. Their main limit is the lack of support for long distance communication, unless the solution makes use of repeaters, which could enhance the costs [23]. The most common wireless communication technologies for EW systems are the following:

- Zigbee: Zigbee is a popular low-cost, low-energy, low-speed protocol built on existing IEEE 802.15.4 protocol and developed by ZigBee Alliance. It works on the 2.4 GHz band and it has data rates from 20 to 250 kbps. Zigbee supports star, mesh and cluster tree topologies, among which mesh connection is more flexible and reliable [24], allowing the WSN to survive node faults and node losses. It has a light weight stack compared to Wi-Fi and Bluetooth and battery life up to 5 years, but relatively short range and low data rates.

- Bluetooth and BLE: Bluetooth is based on the IEEE 802.15.1 standard. The ultra low-power, low-cost version of this standard is Bluetooth Low Energy. Both Bluetooth and BLE operate in the 2.4 GHz ISM band. They have data rates up to 1 Mbps and they use fragmentation to transmit longer data packets [20]. In BLE, there is a trade-off between energy consumption, latency, piconet size, and throughput, but parameters tuning allows BLE to be optimized for different IoT applications [25].

- 6LOWPAN: IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) is a standard defined by the Internet Engineering Task Force to send IPv6 packets over IEEE 802.15.4 or currently also over other protocols such as Bluetooth/BLE. It is widely used for sensors that need to transmit low amounts of data, and it operates on unlicensed bands. The 6LoWPAN group defined the encapsulation and compression mechanisms that allow the IPv6 packets to be carried over the wireless network to allow sensor networks to use IP instead of other proprietary technologies.

- Wi-Fi: Wi-Fi is a widely spread group of wireless technologies under the 802.11 standard. While faster than other IoT-specific standards such as Bluetooth, Wi-Fi devices consume more power than other devices, such as those based on BLE. Wi-Fi HaLow (802.11.ah) is a new Wi-Fi technology that operates in the spectrum below 1 GHz and is specifically designed for IoT use cases by adding low power consumption and long range, which are suitable for this kind of applications.

- LoRaWAN: LoRa is a physical layer technology that uses a proprietary spread spectrum technique and LoRaWAN Medium Access Control protocol is an open source protocol standardized by the LoRa Alliance that runs on top of LoRa physical layer. It works in ISM bands, that is, 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia. LoRa's modulation allows for great performance against interference and different data rates, from 300 bps to 50 kbps. LoRaWAN improves the received messages ratio using re-transmissions, it offers great coverage (10–40 km in rural zones and 1–5km in urban zones [26]) and low costs and long battery life for end-devices. It provides three classes of end devices for different IoT requirements, such as latency or energy consumption.

- EC-GSM-IoT: EC-GSM-IoT re-purposes 200 kHz narrowband carriers from GSM networks and it only requires a software update of the GSM network, without needing additional hardware. Some solutions in the reviewed literature still use GSM and General Packet Radio Service (GPRS) modules for connectivity, but Extended Coverage GSM aims to provide better performance, including better indoor coverage, large scale deployments, reduced complexity and better power consumption compared to old GSM modules and devices [27].

- NB-IoT: NB-IoT is a technology introduced by 3rd Generation Partnership Project that operates in licensed spectrum and reuses existing Long Term Evolution infrastructures. NB-IoT provides high coverage (20 dB stronger than traditional GSM) with a high Maximum Coupling Loss of 164 dB [27], which allows NB-IoT devices to reach underground locations (for example, for locating victims [21]). It has low energy consumption and it improves energy saving mechanisms; network procedures, protocol stack, modulation schemes, and base-band complexity are simplified to reduce the User Equipment complexity and cost. Different kinds of latency can occur during the NB-IoT communication, and latency must be kept below 10 s in real time applications [23].

- 5G: 5G networks will provide further solutions and resources when it comes to cellular/mobile communications. Particularly, Ultra Reliable and Low Latency Communication (URLLC) aims to provide delays below 1 ms and with 99% reliability, making it particularly suitable for use cases such as Earthquake Early Warning, which is strongly characterized by the latency constraint [28].

- EnOcean: EnOcean works in Unlicensed bands, 868 MHz frequency in Europe and 315 MHz frequency in America. EnOcean is not capable to handle ad hoc network topologies as other wireless communication protocols and it has less features than other protocols, but its main focus is to be energy efficient [29], therefore being suitable for disaster management, especially thanks to its energy harvesting feature [20].

- Satellite communications: The use of satellite communications can prove effective when terrestrial communications are down or when the IoT deployment is in geographical areas that are difficult to reach with other means such as cellular communication, for example for a lack of existing infrastructures. There are some providers currently offering services that support satellite IoT, and satellites are also expected to play a relevant role in supporting 5G and IoT systems [30].

Wired technologies can also be used in WSNs and IoT systems. For example, Industrial IoT protocols such as CANOpen have also been used in the reviewed literature to connect devices and sensors that were used in the developed EW systems. Similarly, other wired system such as optic fiber communication can still prove effective for communication, for example in underwater settings. In this context, the aforementioned radio wireless protocols are often not the right choice for communications because of the different propagation scenarios, and instead Underwater Wireless Sensor Networks (UWSN) more often use acoustic communications.

Usually, wireless communications have proved to be the most efficient in disastrous events and emergencies [31], even though both wired and wireless communications are susceptible to failure. Disasters can have a large impact on infrastructures and networks facilities, for example cutting off the affected region in case of antennas, optical fiber links, or overhead cables failures [20]; as such, redundant communication channels should be considered to ensure that working communication links are always available.

2.1.3. Application Layer

The application layer is at the top of the IoT layered architecture. It uses the data received from the communication layer to provide services or operations [16], possibly combining collected data with historical data, and satellite or weather forecasting data from other sources. The application layer implements algorithms to generate and propagate warnings if a disastrous event is imminent; it can provide databases to store old data and current data in real time; it can make predictions and forecasts, and so on. User interfaces can be created on top of the application layer and, in service-oriented-architectures, service management and middleware layers can be interposed between the Application Layer and the Communication layer to act as a bridge between the devices and the applications, and to ensure interoperability [32]. Cloud-based IoT platforms provide almost limitless storage and computational capabilities. There are many existing Cloud platforms that provide different services useful for IoT solutions [33]. Data analytics is an essential part of IoT EW systems, that might have to deal with large amounts of data from different sources, geographic locations and points in time that need to be processed and analyzed. Data analysis can become the bottleneck of an EW system [20], and therefore cloud platforms should be associated with modern EW systems [34]. Cloud computing also comes with problems such as latency when the amount of data to process is too big, but Fog/Edge computing can reduce the weight on the application layer. When dealing with a great number of heterogeneous devices, sensors and data sources, like in EWSs, a semantic approach can also be used to enhance queries and data processing [10].

Fog or, more generally, Edge computing can be implemented between the Communication layer and the Application layer to provide a faster response and better quality than solutions based solely on Cloud computing [16]. While Cloud services provide essential storage and processing capabilities, transmitting big amounts of data from many sensors or data sources can be costly, and processing a lot of raw data in dedicated servers will add a latency that can affect the performance of the EW system. In fog and edge computing, the data from the perception layer is first processed at the network edge (on gateways or even end devices) before transmitting it to higher layers, for example to a cloud service, so that latency and the amount of data to send to the cloud can be reduced. This can also help overcome bandwidth instability [34] (since processing data at the edge can lower the bandwidth consumption [32]) and intermittent network conditions when environmental hazards occur or during the disaster response phase [35]. Moreover, Edge Computing is also suitable for devices with limited battery life [36]. Fog nodes can also implement algorithms to make predictions based on the data collected from the perception layer [19]. It is also possible to embed ML models in Edge devices, but complexity and memory constraints could make it more challenging [32].

2.2. Requirements of an EW System

All IoT solutions have some constraints that need to be taken into account when deploying an IoT system. Early Warning systems need to produce well-timed warnings using data usually obtained from a WSN, which also comes with its own requirements such as limited power consumption and low power communications, high or total end-to-end reliability, and limited delays. Data transmission and processing on higher layers should also be optimized as to not add latency to the system. Therefore, the following requirements can be defined when designing an IoT solution for EW systems:

- Battery life: WSNs deploy sensors that need to last for a long time, especially when they are installed in locations that are hard to reach or difficult terrains that would make replacing the batteries a costly task. Energy budgets should be evaluated for each application, and data acquisitions and transmissions should be optimized to also limit power consumption in critical work conditions such as dark times operations (when solar batteries are not recharged) for sensors equipped with photo-voltaic units, or critical environmental situations that require more measurements and so on. A common energy preserving strategy is to let nodes go into sleep mode when they are not being used; however, communication protocols for WSN should be energy-efficient, minimizing overheads and re-transmissions [37].

- Fault tolerance and reliability: The system should be able to work even if one or more nodes are no longer available or if the network topology changes. Many factors can determine a faulty situation, such as low battery, bad coverage, a node being damaged or destroyed, etc. Since nodes or gateway mobility change the state of the network and complicate the message routing, numerous dedicated WSN routing protocols can be used to take into account these factors [37]. Protocols that support mesh network topology (Zigbee, Bluetooth) are useful because they provide flexibility for the network in case of failure of one or more nodes. Self-reorganizing algorithms and failure prediction are therefore essential to allow the EW system to keep issuing warnings [38]. Moreover, the casing or fabrication of a sensor node should be made so that bad weather conditions, floods, or hurricanes have less impact on it [20].

- Coverage: The geographical regions that need to be covered by an IoT solution for EW systems can be very large, and, as such, the chosen communication protocols must be able to allow long range communication between far nodes and gateways with predetermined rates, latency, packet loss, and other parameters. Some locations might also have blockage, heavy shadowing, or other issues that can compromise radio communications, and therefore a link budget evaluation is essential to understand whether or not communication links will work with the required parameters.

- Latency: EW systems should provide timely warnings, and as such systems should be able to transmit data quickly and the elaboration should not take time. Fog/Edge computing lowers the amount of data to be sent to higher layers, reducing the latency introduced when cleaning, analysing, and processing large amounts of data in the application layer. The choice of the right processing algorithm can also be valuable to reduce latency. Depending on the application, different time constraints could be required, and different communication protocols that are suited for EW can provide short transmission times, from the order of seconds to milliseconds.

Based on the general IoT architecture defined, and on the general requirements for IoT systems, the following sections are going to present peculiarities and solutions for each of the four use cases identified as relevant for the application of EW Systems.

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