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Rapid detection of landslide events using battery-operated long-range wireless tiltmeters

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Abstract

Increasingly, infrastructure assets are affected by landslides and slope instability caused by more intense storms and extreme weather events. Future climate and land cover changes will impact landslide susceptibility, increasing risk over large areas. In recent years, long-range low-power wireless monitoring systems have been deployed for the preventive control of slope instabilities, potential landslides and earthworks that could affect infrastructures. The ability to access measurements from several parameters, at the right sampling frequency, enables analysis of the behaviour and performance of soil, rocks and structures. However, the proper implementation of remedial actions such as evacuations, road closures or allocation of resources, requires immediate alerts. In this paper, we present a method to quickly detect a landslide event through a network of battery-operated, long-range wireless tiltmeters. To analyse data in near-real time and avoid overloading network capacity, the solution is based on edge computing. Tilt measurements collected at 3.9 Hz are compared by a wireless edge sensor with two preset threshold values that define the accepted range for any given axis. This easy-to-deploy solution immediately issues an alert when the tilt exceeds a preset threshold. In the unlikely scenario of multiple tiltmeters detecting an event exactly at the same time, the system-reported latency is under 2 seconds for 10 tiltmeters and under 5 seconds for 25 tiltmeters. The capabilities and limitations of the system are presented, including the results obtained across performance tests and battery life estimations for different scenarios. This paper also outlines an estimated cost of deployment of the wireless solution.

Keywords: Slope Stability, IoT, Edge computing, Wireless, Low-power, Long-range, Real-time, Event Detection, Early Warning System, Tiltmeter, Landslide, Embankment Stability.

1. Introduction

Landslides and slope instabilities triggered by intense rainfall events are a major hazard affecting human settlements and infrastructures worldwide. In Spain, for example, it is estimated that landslides caused losses of about 42 million euros per year from 1990 to 2000 (Ayala et al., 2004), making them the second greatest geohazard in terms of economic loss, after floods. Worldwide, landslides are responsible for more than 17% of all fatalities triggered by natural hazards (Lacasse and Nadim, 2009). Although the future rainfall pattern that may be expected due to climate change is still uncertain, all models predict an increase of the extreme precipitation events across the world, which would raise the occurrence of rainfall triggered landslides and slope instabilities.

In order to identify early signs of slope instabilities and landslide precursors, it is essential to frequently control potential slope failure mechanisms. In most cases, slope control is limited to an inventory of slope instabilities, periodic inspections and historical monitoring of slope movements that have been reported. However, when the risk of instabilities is high, manual or automated monitoring techniques are the best options. The role of landslide monitoring and warning is to gather usable information for avoiding or reducing the impact of landslide activity (Chae et al., 2017).

Landslide and slope stability monitoring techniques can be classified into two main groups depending on the location of the sensors that measure target parameters: a) in-situ, ground-based sensing (Reid et al., 2008) and b) remote sensing (Zhao and Lu, 2019). In-situ sensors are installed above or in the ground, where the unstable slopes are, or in their surroundings. Remote sensing techniques consist of measuring the slope from a distance, which can vary between metres (in a nearby area) or kilometres (using airborne devices or satellites). In contrast to remote sensing, mostly focused on controlling surface deformation on slopes, in-situ in-ground sensors measure targeted parameters related to slope failure mechanisms or precursor movements. Geospatial in-situ surface sensors such as wireless tiltmeters and laser distance meter nodes, similar to remote sensing techniques, mainly measure surface deformation. Surface deformation measurements include precursor movements before a big failure, or a fatal failure itself.

Ground-based sensors have traditionally been measured manually and the information available has been scattered in time and space, so data availability relies on the frequency of site visits. In recent years, and thanks to the application of IoT technologies for the transmission of readings, the fast, automatic acquisition and transmission of data from these monitoring systems is increasingly frequent. Long-range, low-power wireless monitoring systems have been deployed for the preventive control of slope instabilities, potential landslides and earthworks that could affect infrastructures. It is expected that in future long-range IoT wireless technologies and greater social demand for risk management will extend the implementation of these systems thanks to their adaptability, reliability and profitability.

The main groups of in-situ sensors used for preventive control of slope instability measure: a) weather parameters associated to the triggering factors of the landslide/slope instability (e.g. precipitation, temperature, atmospheric pressure, etc; see 8 in Figure 1); b) underground water volume or pressure (see 4 and 10 in Figure 1) and c) in-depth or surface movement (including horizontal and/or vertical displacements; see 3, 6, 7, 9, 11 and 12). These types of sensors are also used to measure the performance of structural elements for slope instability protection, soil-structure interaction (e.g. load in ground anchors, earth pressure against retaining walls, inclination of structural elements, etc) or other relevant parameters for industrial activities (see 2, 5, 13 and 14 in Figure 1).

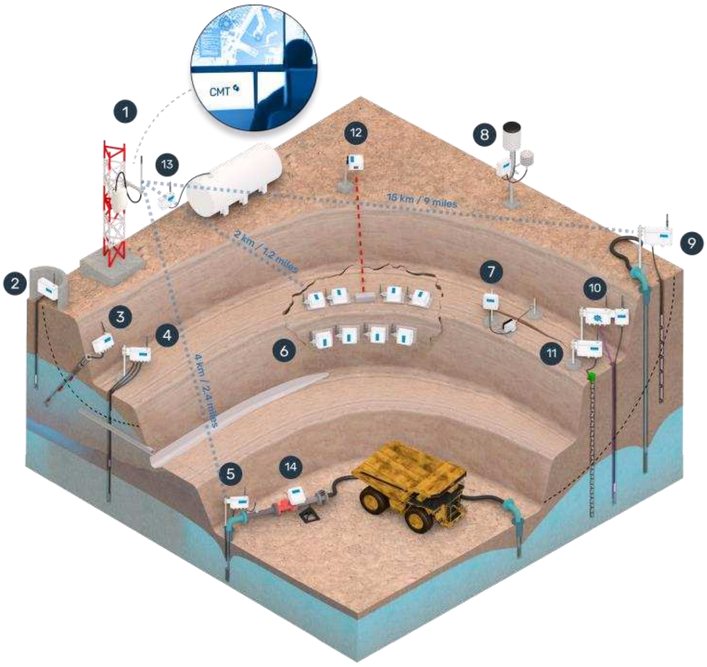


Figure 1: Overview of a long-range, low-power wireless monitoring system based on in-situ ground-based sensors in an open pit mine. 1) Gateway; 2) Water quality probe; 3) Multi-point borehole extensometer; 4) Piezometers; 5) Water level sensor and pressure transmitter at the pipe; 6) Wireless tiltmeters with event detection capabilities; 7) Crack monitoring with a draw wire sensor; 8) Weather sensors; 9) In-place inclinometers; 10) Time domain reflectometry (TDR); 11) ShapeArray (SAA); 12) Laser distance meter and tiltmeter node; 13) Fuel tank level sensor; 14) Water meter.

One of the main advantages of in-situ, ground-based monitoring techniques is the ability to measure in near real-time, which is difficult to achieve using remote sensing techniques. The capability of the monitoring system for near-real time monitoring depends on the velocities of: a) landslide or slope stability phenomena and b) sampling/data transmission/data updates. If a system samples at a frequency similar to or higher than the velocity of the monitored process, the real-time monitoring will only be conditioned by the data transmission and updating velocity. To date, long-range, low-power wireless monitoring systems have provided real-time data for processes such as reading groundwater pressure changes on an hourly basis but find challenging to monitor fast processes (such as the early detection of a rock wall collapse). To achieve high performance in early warning or alarm systems and implement remedial actions such as evacuations, road closures or allocation of resources, the accurate choice of instrumentation is crucial. Key points for a good selection are the life expectancy of sensors and data acquisition and transmission systems, the robustness of the elements, the noise level of sensors and data acquisition systems, and especially the level of real-time data (Michoud et al., 2013).

2. Event detection approach

No standards exist for designing and operating early warning systems (EWS). The design depends on the type of phenomena to be monitored. Many landslide EWS are based on the monitoring of surface and subsurface movements as they show evidence of active deformations. For this, sensors such as crackmeters, inclinometers or extensometers are frequently used. Other EWS are based on meteorological parameters since rainfall or snowmelt are considered common triggering factors for landslides and slope instability. Meteorological stations are key instruments in this case. Some EWS are focused on monitoring changes in groundwater conditions, as these are the direct consequence of rainfall or snowmelt occurrence. In this case, piezometers or soil moisture sensors are the most common (Michoud et al., 2013).

Threshold values are normally based on a combination of sensors, aiming for redundancy and robustness. The calibration of warning thresholds is one of the most delicate processes in the design of a reliable EWS. When thresholds are exceeded, alarm messages are normally sent to operators, who then analyse the data and decide how to proceed. The systems are expected to meet high standards of performance as the actions after an alarm can have important social and safety consequences.

In this paper, we present a method to quickly detect a landslide event, through a network of battery-operated, long-range wireless tiltmeters. Compared to others, this method offers minimal site installation requirements, easy deployment, robustness and ability to operate in adverse weather conditions, and low cost, which allows for its deployment in more areas.

The easy deployment of the solution and the potential for it to be used in different locations is thanks to the use of a long-range, low-power wireless system. Consequently, it is critical to analyse the data in near-real time to avoid overloading the network capacity. Therefore, the solution uses edge computing.

The smart management of data permits acquisition in a non-discrete way, emitting an immediate message when the threshold is exceeded while keeping the energy consumption low thanks to the limited transmission.

Typically (>99% cases) the system reported latency is under 2 seconds for 10 tiltmeters that have simultaneously reached a threshold and under 5 seconds for 25 tiltmeters detecting an event at the same instant in all the tiltmeters. In a typical operation, the probability of successful transmission reached with the implemented techniques is > 99.98%.

2.1 The solution description

The Event Detection Solution (EDS) is composed of:

- Preconfigured wireless tiltmeters running on an operation mode called Event Detection Mode (EDM)
- Gateways for connectivity
- A mobile app for device configuration
- An On-premise or cloud-based network, device and data management software

The solution is a component to be integrated in early warning systems.

In terms of sampling, reporting period and transmission of readings, the EDM simultaneously operates in data exception and periodic reporting approaches as follows:

- Periodic readings in a normal state (see the green circle marked 1 in Figure 2): from 30 minutes to 1 day. The periodic reading captures a baseline measurement during 7.18 seconds. The standard deviation of the set of samples collected during the reading is computed and transmitted with each tilt measurement, enabling the possibility of filtering noisy data.
- Continuous sampling at 3.9 Hz (represented as a line in Figure 2 and with blue circles in the enlarged area).

- When the trigger conditions are met, a message notification is transmitted to the network (see 2 in Figure 2) and sometime after, a reading is transmitted containing the data which triggered the alert (see 3 in Figure 2).

  The alert message transmitted when a threshold value is reached details the exceeded threshold: axes (X, Y, Z) and directions (lower or upper threshold). It also includes the angular amount exceeding the absolute threshold value.

  In the case that the alert conditions are no longer met and after a stoppage time corresponding to 256 consecutive samples -just over a minute- inside the accepted range, an alert off message is transmitted (see 5 in Figure 2).

- Periodic readings in alert state (see 4 in Figure 2): from 30 seconds to 1 day.

  When an event of interest is detected, the node can increase the frequency of the reporting rate, moving from the reporting period in the normal state to the one configured for alert state.

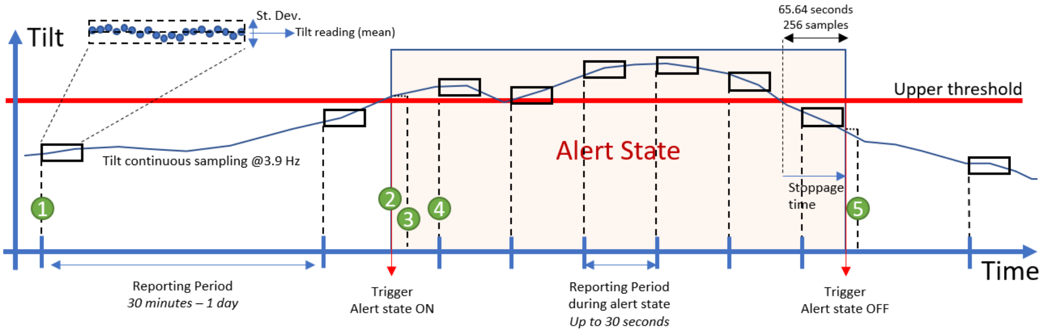


Figure 2: A simplified illustration of an EDM tiltmeter operation. The green circles show the messages transmitted: 1) Normal State Periodic Readings message; 2) Alert Real Time message; 3) Threshold broken - Readings message; 4) Alert State Periodic Readings message; 5) Threshold restored - Readings message.

The triggering algorithm compares the last readings to a set of two absolute threshold values that define the accepted range (threshold included) for any given axis.

Any sample outside this range for any axis will trigger a transmission of an event notification and the activation of the alert state. As an example of this, assuming a progressive movement in the direction of X and with a secondary movement in the direction of Y, one specific tiltmeter will first trigger a transmission when the threshold for X is exceeded, next when the threshold for Y is exceeded and finally when the threshold for the Z axis is exceeded. The tiltmeter will enter the alert state immediately after the first (X axis) threshold is exceeded.

As shown in Figure 3, all the messages transmitted via long range radio are received by one or more gateways connected to the internet or to a private network. These gateways are not only compatible with EDM tiltmeters, but can also provide connectivity to other in-situ sensors (see Figure 1). The software which manages the connectivity is called the Connectivity Management Tool or CMT, and it publishes the data via MQTT for processing by an early warning system. CMT also manages all data and deployed wireless devices and networks and may be cloud-based (CMT Cloud) or on-premise (CMT Edge) when hosted in the gateway.

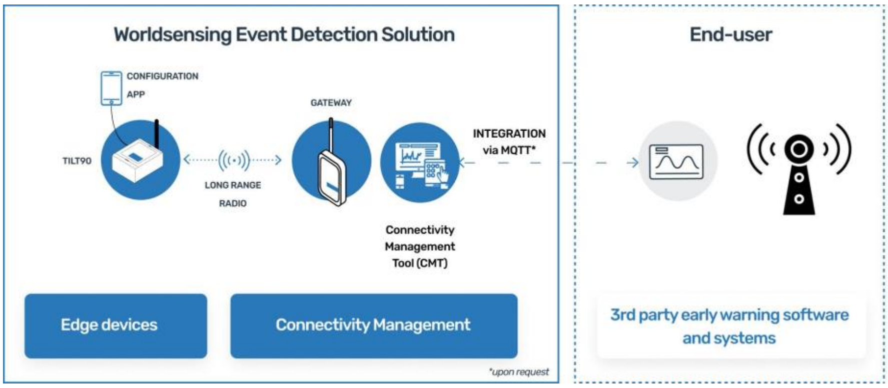


Figure 3: Event detection solution architecture.

The Event Detection Solution is a sensing component to be integrated in early warning systems, combined with other technologies. Third-party software is needed to ingest and process notifications, then trigger a process or action accordingly. Based on the nature of the notification, the software could for example send an email, SMS or automated phone call to an operator, trigger an alarm (siren, lights), or send instructions to devices (road closure, close gate, stop hydraulic pumps in a jacking system or decrease/increase pressure, take a picture/start video recording).

3. Event Detection Mode Specifications

3.1 Sensor's specifications

The Tilt90 wireless sensor is a long-range, low-power wireless edge device. Tilt angles with respect to gravity's direction are calculated from 3-Axis MEMS Accelerometer samples. The measuring range is ± 90° for each of the axes. Finally, the two axes of rotation from the horizontal plane are reported.

To improve the accuracy of the wireless tiltmeters, all the units are individually calibrated.

In terms of weather protection, the wireless tiltmeters are IP68 rated, tested in immersion at 2 m depth for 2 hours. The operating temperature range is wide, from -40°C to 80°C. The size is small; the dimensions of the box (WxLxH) are 100x100x61 mm.

The specifications for the two variants of the wireless tiltmeter operating in EDM are presented in the following table:

	Application:	a. General purpose sensing	b. Railway track monitoring
In periodic readings.	Repeatability:	<0.0003°	<0.0015°
	Offset temperature dependency:	± 0.002°/°C	± 0.005°/°C
In continuous sampling.	Repeatability:	<0.001°	<0.005°
	Peak to peak noise:	<0.006°	<0.034°

Table 1: Wireless tiltmeter configured in the EDM specifications. a) Variant typically used for landslide monitoring (LS-G6-TIL90-X). b) Variant suitable for high vibration environments (LS-G6-TIL90-I) such as installations in railway track beds potentially affected by landslides and slope instabilities; this variant is equipped with an internal antenna.

3.2 Remote device configuration

The set-up configuration of the wireless tiltmeters is done with an Android app called Worldsensing App. Some of the features and functionalities of the Worldsensing App include setting the threshold values to trigger the transmission, selecting the reporting period in normal state, checking the calibration parameters, taking test samples on the field, setting-up of the radio network, and conducting radio signal coverage tests.

The long-range radio system is bidirectional, able to operate remotely, maintain or configure operating tiltmeter parameter values. It can be used to remotely configure thresholds used to trigger the alert transmission and the reporting period in both normal and alert state, and enable or disable the EDM for each channel and automatic time synchronisation.

3.3 Radio Network and transmissions

Radio

The Worldsensing Monitoring Solution uses LoRa for communication. LoRa is one of the available protocols for low-power wide area networks or LPWANs. LoRa technology guarantees long transmission distance, low-power consumption, scalability, reliability and security. The network topology of the system is star (single-gateway network, see a) in Figure 4) or multi-star (multi-gateway network, see b) in Figure 4).

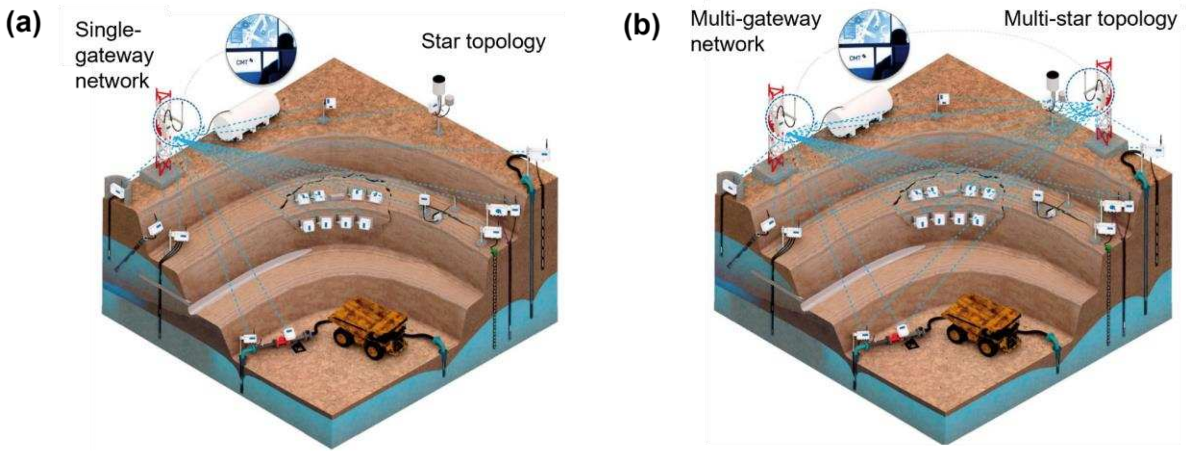


Figure 4: LPWAN Network topologies in an open pit.

The LoRa technology derives from communication concepts used in radar systems and exploits frequency and time diversity and robust coding to ensure high levels of reliability. The modulation, chirp spread spectrum (CSS), is based on transmitting encoded symbols using frequency chirps, spreading the symbol in time and frequency, aiming for very robust immunity against interference in specific frequencies (e.g., subGhz networks) (Reynders and Pollin, 2016).

Because of the combination of CSS and robust coding, LoRa gateways can decode signals even below noise level. This enables LoRa radios to feature long-range communication performance, while still being low power.

The spreading factor (SF), between 7 and 12, impacts the communication performance of LoRa. A higher SF increases the time on air, which increases energy consumption, reduces the data rate and improves communication range. For successful communication, as determined by the SF, the modulation method must correspond between a transmitter and a receiver for a given packet.

To optimize system capacities, the EDM operates in SF7 and under certain conditions can also operate in SF8. The range in this case will be lower than what is achievable for other Worldsensing data loggers, including the wireless tiltmeter that does not operate in EDM, because they can operate in higher SFs. The sensitivity of the receptor gateway in 125 kHz mode varies over the SF being -127 dBm for SF7, -131 dBm for SF9 and -137 dBm for SF11.

Considering the sensitivity and the transmission power of 14 dBm in Europe and 20 dBm in North America, and the experience collected from actual projects, the system can achieve km-range communications as shown in the following table:

	North America 902-928 MHz	Europe 868 MHz
Rural environment - Flat areas. Open sight	7.5 km	6 km
Rural environment - Areas of different elevations.	2 km	1.6 km

Table 2: Range estimates for a wireless tiltmeter in EDM. Radio distance depends on the terrain and installation conditions (height of installation, obstacles, etc.).

Network limits

The solution can manage up to 25 wireless tiltmeters simultaneously transmitting alert messages (an event is detected exactly at the same instant in all the devices).

In most geotechnical and structural scenarios, depending on the distribution of the tiltmeters, it is improbable or even impossible that a group of more than 25 wireless tiltmeters will detect an event simultaneously. In most cases the tiltmeters will cross a threshold successively.

As mentioned above, tiltmeters with EDM can coexist with other wireless data loggers connected to in-situ sensors and with other wireless sensors in the network. The maximum number of end devices connected to the network is subject to the usual recommendations and limitations of the Worldsensing network size, considering the most demanding scenario (e.g. alert state reporting period).

Consequently, depending on the monitoring program and the expected mechanism of failure or deformation pattern, it is possible to increase the quantity of tiltmeters in the network to hundreds of tilts.

3.4 Battery life estimation

For a Tilt90 device operating in EDM, the battery consumption varies depending on the number of samples collected and transmitted and with the environmental conditions. In this mode of operation, not only must the basic reporting period be considered, but also if the node has entered the alert state, how much time it has been in this state, and the reporting period configured for this state.

In a worst case scenario, the following radio settings have been considered for the battery life estimation: EU 868MHz radio configuration, SF9 and, radio transmit power 14 dBm. As the EDM is mainly restricted to SF7, the actual consumption will be lower than the estimates presented below.

The battery life estimates shown in Table 3 have been estimated by Saft with the information provided by Worldsensing and are based on a lifetime mathematical model developed by Saft. Estimates are for two Saft cells: LSH 14 (Li-$SOCl_2$ technology) and LM26500 (Li-MnO_2) spiral, C-size, 3.6 V cells.

Reporting period	Temperature profile	2 LSH 14 cells (year)		2 LM26500 cells (year)	
		Average	Min	Average	Min
30 minutes	Singapore	2.2	2.0	3.1	2.8
	Barcelona	2.4	2.1	3.2	2.8
	Vilnius	2.4	2.2	3.1	2.8
6 hours	Singapore	2.4	2.2	3.5	3.1
	Barcelona	2.6	2.3	3.5	3.1
	Vilnius	2.6	2.4	3.4	3.1

Table 3: Battery expected life duration in years for three different temperature profiles. Consumption varies depending on the events detected, periodic reporting rate and environmental and wireless network conditions.

As shown in Table 3, base consumption from the continuous sampling at 3.9 Hz is the most important contributor to the battery discharge. There is no significant difference in the expected battery lifetime between the 30-minute and the 6-hour reporting periods.

3.5 Device status monitoring

In addition to the sensor data messages, the wireless tiltmeters report and transmit 'health messages'. This type of message is devoted to the health of the wireless sensor, based on parameters such as microcontroller temperature, voltage, quality of the radio link and uptime.

The gateways also publish keep-alive messages through CMT software every 30 seconds, enabling gateway monitoring from third party software. The CMT Cloud platform can also monitor the gateways and nodes and notify any change in the status by email.

4. Laboratory tests

Two system characteristics were mostly tested:

- Latency of alert messages: time between event generation and the delivery of alert messages on the MQTT client.
- Reliability of alert messages: the probability of losing an alert message.

The quantification tests, discussed here, were done in a lab environment. Some field tests were also executed and confirmed that the system performs as expected in a real-world environment.

4.1. Test setup

The test setup consisted of 25 wireless tiltmeters, two gateways, one for the CMT Edge tests and another one for the CMT cloud tests, an MQTT broker running on the cloud and one laptop with an MQTT client for the reception of the alert messages.

All the nodes were screwed to two wooden boards to allow for an easy event generation at the same time on all of them. The event generation was timestamped by pressing a key on a keyboard at the same time as the wooden boards were moved.

Figure 5: Test setup.

Tests with different numbers of nodes were performed. The worst-case scenario results, where events were generated on 25 nodes at the same time, are presented.

The worst-case scenario can impact the latency and reliability of the messages in two ways:

- The radio spectrum is used at the same time for a number of nodes sending several messages, so collisions can happen, and packet loss is a concern. Also, the collision avoidance mechanism implemented may increase the latency of the delivery.
- The software stack must process a high volume of messages in a short period, potentially causing a bottleneck and increasing latency.

Note that this scenario is unlikely in the real world, so the expected performance should be better than the tests.

4.2. Latency

The latency can be divided into two components:

- Radio time: This includes the detection time from the node and the time needed for the first copy of the alert packet to reach the gateway. This time should be the same both in CMT Edge and CMT Cloud.
    - Note that each node will have a different detection time. The sampling rate is 3.9Hz and the samplings are not synchronised across the nodes. This means that the time between the event and the detection could be up to 1 / 3.9 = ~257ms.
- Software time: This includes several layers of software, the radio MAC layer, the application layer and the MQTT layer. In the case of the CMT cloud, it also includes the network time to and from the cloud.

The following figures show the latency of the alert messages for a typical run of an event generated at the same time on 25 nodes both for CMT Edge and CMT Cloud. The Y axis shows time passed from the event generation and the nodes appear in order of message arrival times on the X axis.

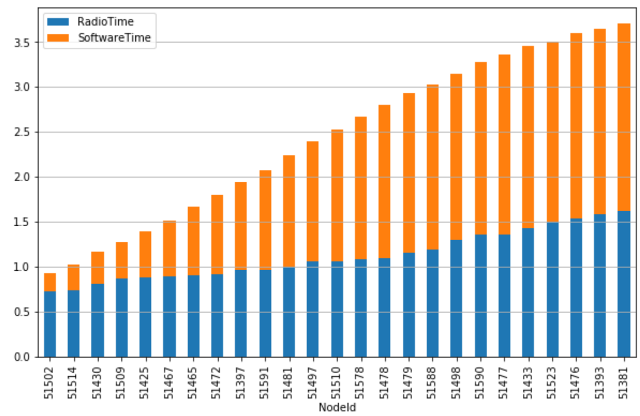


Figure 6: Events generated on 25 nodes at the same time on CMT Edge.

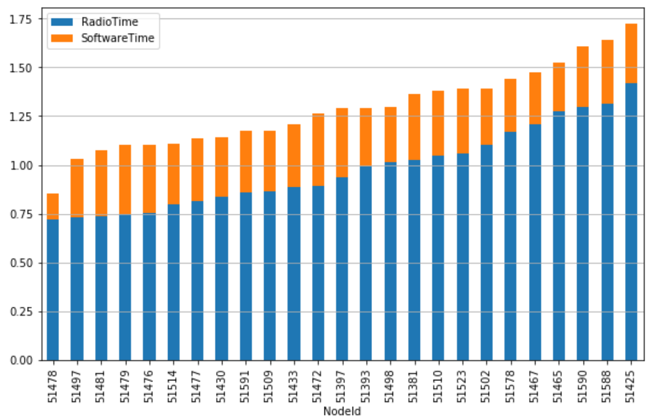


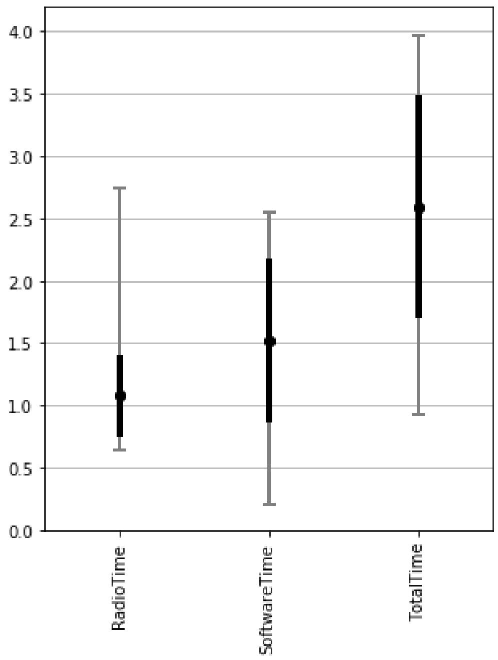
Figure 7: Events generated on 25 nodes at the same time on CMT Cloud.

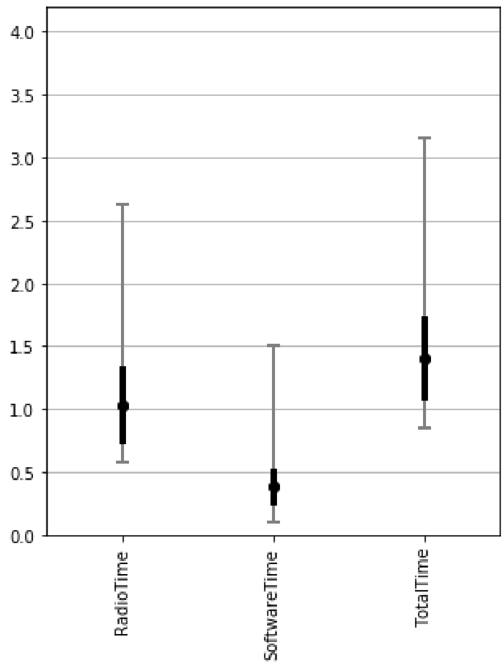
It can be observed that on CMT Edge there is a bottleneck effect on the software time caused by the limited power of the gateway to process the arrival of alert messages. This can be seen as every successive alert message takes more time to process than the last one.

The CMT Cloud solution does not seem to suffer from bottlenecks in the software as it is scaled up to handle a higher number of messages.

The radio time seems to have the same behaviour between both solutions, as expected.

The following figure shows the maximum, minimum, mean and standard deviation of radio and software latencies together with the total latency across all the rounds of tests.





	RadioTime	SoftwareTime	TotalTime
min	0.643087	0.205818	0.931914
max	2.744087	2.552643	3.959205
median	0.980349	1.669055	2.752950
std	0.332742	0.655721	0.890495

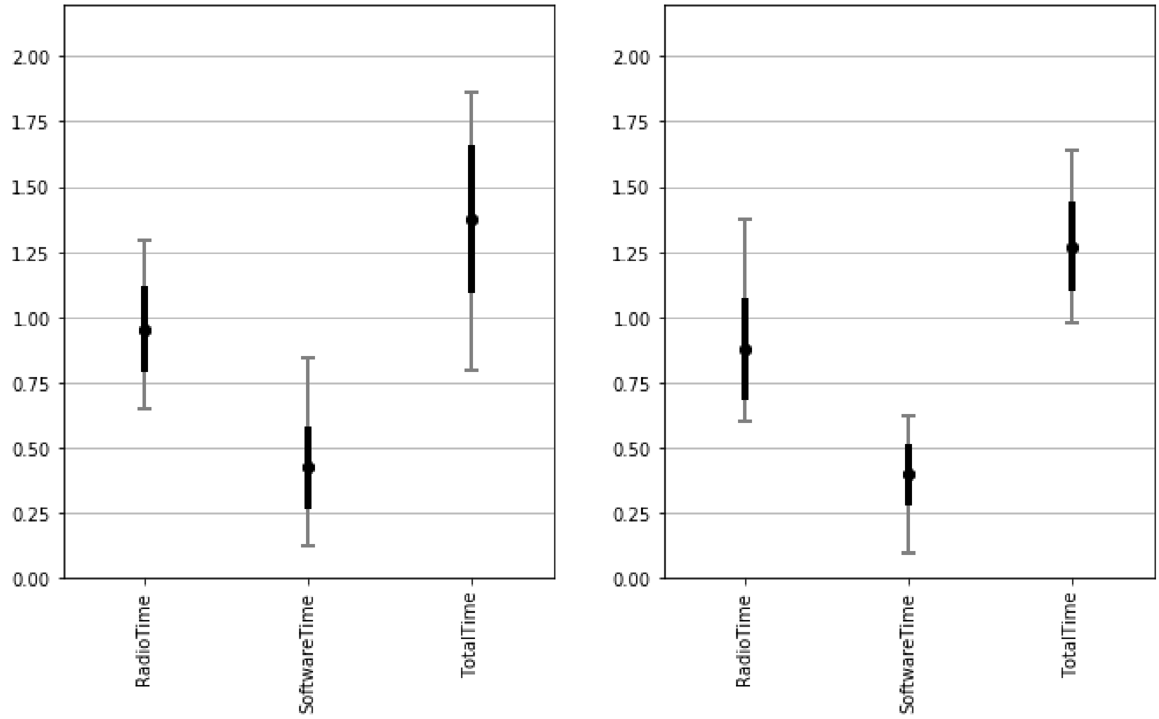
CMT Edge.

	RadioTime	SoftwareTime	TotalTime
min	0.574901	0.103327	0.855024
max	2.624168	1.508466	3.158367
median	0.948538	0.326321	1.352569
std	0.310462	0.152032	0.330664

CMT Cloud.

Figure 8: Variations for radio, software and total latencies generated from 25 nodes at the same time.

As a comparison, one the following figure, the same statistics for 10 nodes are given. The impact of the number of nodes is both on the radio time and the software time on the CMT Edge but mostly on the radio time on the CMT Cloud.



	RadioTime	SoftwareTime	TotalTime
min	0.647101	0.123750	0.794001
max	1.294345	0.842838	1.860720
median	0.924431	0.422988	1.372403
std	0.166824	0.159181	0.284903

CMT Edge.

	RadioTime	SoftwareTime	TotalTime
min	0.599577	0.094328	0.979345
max	1.376054	0.621842	1.638041
median	0.849248	0.342849	1.247356
std	0.195243	0.119123	0.170520

CMT Cloud.

Figure 9: Variations for radio, software and total latencies generated from 10 nodes at the same time.

4.3 Message delivery

To ensure short latency, the delivery of alert messages is performed according to a best-effort strategy with high redundancy. This means every alert message is sent several times through radio and the software layer on the gateway discards the copies. The message delivery tests try to determine the probability of losing a message.

The tests were performed triggering events on several nodes at the same time and checking not only if the messages were received but also the number of redundant messages from each node.

A total of 521 events were triggered (17 rounds with groups of 25 nodes and 4 rounds with groups of 24 nodes due to a configuration error). In all the cases at least one message from all the tiltmeters was received, which makes a 0% message loss in the tests.

When looking at the number of redundant messages, a total of 70.85% of the messages were received. So the probability of losing one redundant message is 0.29 and the probability of losing all the copies, which means missing an alert from a single node, is $1.79*10^{-4}$ or once every 5586 alert messages.

The results depend on the number of nodes that try to send the alert message at the same time, improving with a low number of nodes in the group. With groups of 10 nodes were performed 11 rounds with a result of 9.13 % of redundant messages were lost, which makes the probability of losing an alert from a single node $5*10^{-8}$ or once every 18.9 million alert messages.

Increasing the number of nodes would negatively affect the reliability of the message delivery system and increase the loss of alert messages if all the nodes are triggered at the same time. This could mean some nodes wouldn't be able to send the alert on the first instance even though most would.

5. Field application

5.1. Deployment in Brazil

Tailings dams rank among the largest engineered structures on earth. These typical earth-filled embankments are used to store non-profitable materials in mining operations. The near real time control of slope stability of these structures during their life cycle is of paramount importance not only for safety, but also from an environmental point of view.

Here we present a deployment of the EDS conducted by Tetra Tech in several tailing dams from Mosaic, in Brazil (Leite et al., 2021). In these embankment dams, aside from the standard instrumentation including piezometers, water level sensors, in-place inclinometers, a total station, and interferometric radar, Mosaic installed a surface displacement monitoring system, based on IoT tiltmeters sensors, with EDM to provide high-frequency readings and real time alerts (Figure 10), along sections of 17 tailings dams around 5 cities and 3 states in the south-east and mid-west of Brazil.

Figure 10: Tiltmeters with EDM installed by Tetra Tech in Mosaic tailings storage facilities (TSFs).

The dams have different characteristics, and a consultancy company defined the position and number of tiltmeters for each section (Figure 11). The tiltmeters were installed with two main functions, depending on their location, sacrifice, and reference. The sacrifice sensors are installed on the main dam and are expected to be lost after reporting a failure event. On the other hand, the reference sensors are installed in natural surroundings, and their function is to give a frame behaviour for the critical area movements.

Figure 11: Example of installation scheme.

Data has been collected since the 1st of December 2020 and the monitoring is ongoing nowadays. In most of the locations, the measurements observed indicate a normal behaviour regarding the vertical displacement of the tailings dams monitored. An example is presented in Figure 12 left. In one case, oscillations were observed for one week in one of the tiltmeters, reaching displacements of up to 4 millimetres, whilst the others remained stable. This displacement has been attributed to external interference caused by human intervention in the sensor's proximity and is displayed in Figure 12 (right).

Figure 12: Examples of data from the tiltmeters with EDM installed on the tailings dams in Brazil. Left: normal behaviour; Right: abnormal behaviour.

5.2. Installation best practices and lessons learned from experience

It is important to select an installation method adequate to site conditions and that takes into account the expected mechanism of the landslide and the precision required to detect it.

Wireless tiltmeters can be installed in different ways using mounting brackets and auxiliary elements:

- directly attached to a rock slope,
- attached directly or mounted on a beam attached to retaining structures and/or to buildings potentially affected by landslides,
- inside a precast concrete box to avoid vandalism and/or to improve the quality of the measurements avoiding sun exposure,
- mounted on a pole or stake,
- mounted on a long (e.g. 2 m) pole with a significant length (e.g. 1.5 m) embedded in the ground and properly adhered to measure the tilt or displacement between two points,
- attached to concrete monuments, etc.

In some projects it may be convenient to install the tiltmeter at a certain depth in the ground or in a buried concrete enclosure, to minimize thermal changes. In this case, a suitable antenna cable is required and the LoRa antenna is installed on the surface with the help of, for example, a stake for its support.

In general, the best practices that apply when installing survey prisms and geodetic concrete monuments can also apply to the installation of the wireless tiltmeters. The stability of the elements to which the tiltmeter is attached to is a vital consideration when installing. Depending on the slope conditions it may be necessary to install the concrete base of the supporting element at an adequate depth.

The following are some recommendations to consider when including the Event Detection Solution in a landslide EWS:

- Plan a test bench or develop a numerical model to define proper absolute thresholds. Define the set of conditions that determine the detection of a landslide event (e.g. minimum number of EDM wireless tiltmeters with the trigger conditions met).
- Program the solution considering all the components of the EWS and their integration and compatibility: tiltmeters with EDM, in-situ sensors, other monitoring technologies, early warning software, notification (sending emails, SMS or automated phone call to an operator) and action systems (activation of sirens, lights, road closure, close gate, stop hydraulic pumps in a jacking system or decrease/increase pressure, taking photos or starting video recording).

- Establish procedures to guarantee the operation of the equipment. Install power backups or uninterruptible power supplies for the gateways, ensure the connectivity of the gateways, monitor health and keep-alive messages, install redundant gateways for CMT Cloud architecture, define an action in case of disconnection of a gateway, have a safety stock of equipment, etc.
- Review the location of tiltmeters in the project area. The instruments should cover all the zones that could register a zonal movement in the structure. Identify zones of particular concern and install more devices in these locations. Redundant sensors improve the robustness of the system.
- Plan maintenance of the wireless network including periodic tests of the event detection system.
- Devise remedial actions.

6. Estimated cost

This section outlines an estimated cost of the deployment of the EDS.

For this purpose, an estimated cost for two theoretical examples located in an European country is presented in Table 4. Only the Event Detection Solution component of an EWS has been considered. To estimate the total cost of the EWS, it is necessary to consider all the components and the operation and maintenance cost, not only the Event Detection Solution component.

Variables considered in each example are as follows:

- Example 1: Landslide hazard area in a soil slope that could be controlled with 10 tilt measurement points and a single gateway connected to a CMT Edge private network. It is necessary to drill a 1-meter-deep hole into the ground to guarantee the stability of the tilt measurements. The tiltmeters would be mounted on a 2 m pole on a concrete base.
- Example 2: 2km stretch of mountain railway line with several retaining structures. The total length of the retaining walls is 750 m. The tiltmeters can be easily attached to the structures using a hammer drill, anchor rods, adhesive capsules, and mounting plates. Two gateways would be installed for redundancy (a CMT Cloud multi-gateway architecture). There is mains power for the gateways. The EDM tiltmeters would be installed every 15 m within each retaining wall, so 50 tiltmeters would be required.

Theoretical example	Items considered in the estimation	Estimated cost of the EDS component for 3 years
Landslide hazard area - 10 EDM tiltmeters	10 EDM tiltmeters + brackets + batteries. 1 gateway + CMT Edge software license. 1 solar kit. 10 two-meter length poles. 10 installations including 1 m hole drilled, concrete base and pole mounting.	€29 500 (Cost per EDS control point installed: €2 950)
750 m of retaining structures - 50 EDM tiltmeters	50 EDM tiltmeters + brackets + batteries. 2 gateways + CMT Cloud licences for a period of 3 years. 50 installations. Tilts attached to a retaining structure.	€117 000 (Cost per EDS control point installed: €2 340)

Table 4: The Event Detection Solution component of an EWS cost estimate for two theoretical examples for a period of 3 years. It has not been considered that some elements such as the gateways or the CMT software, can also provide connectivity to other in-situ sensors; their entire cost has been charged to the EDS cost estimate.

7. Conclusions

Rapid detection of early deformation and identification of potential triggering factors are the main objectives of early warning and alarm systems for landslides and slope instabilities. Their high performance is crucial to implement remedial actions such as evacuations, road closures or allocation of resources. In this paper, an innovative method to quickly detect slope instabilities through a network of battery-operated long-range wireless tiltmeters has been developed.

The main benefits of the Event Detection Solution approach are: fast detection, minimal site installation requirements, easy deployment, robustness and the ability to operate in adverse weather conditions, compatibility with in-situ ground-based sensors connected through wireless data loggers to the same wireless monitoring system and inexpensive cost of the solution, allowing its deployment in a scalable way to properly manage risk. The Event Detection Solution uses LoRa network technology, achieving kilometre-range communication. The operation of EDM tiltmeters has been optimised to get more than 2 years of battery life, or 3 years when using Li-MnO_2 batteries.

Laboratory tests have underlined the reliability and the fast response of the solution even in a worst-case scenario. In several rounds of an event affecting 25 tiltmeters simultaneously, the measured latency was less than 5 seconds. The latency is less than 2 seconds for messages from 10 tiltmeters detecting an event at the same instant.

The Event Detection Solution introduced in this paper has been installed by Tetra Tech in 17 tailings dams from Mosaic Brazil for the early detection of any deformation that could affect the stability of embankment dams.

Different installation methods have been introduced, highlighting the importance of selecting a method adequate to specific site conditions and that takes account of expected mechanism of the landslide and the precision required to monitor it. Finally, we have presented a cost estimate and a list of recommendations to consider when incorporating the Event Detection Solution in an early warning system.

The proposed Event Detection Solution has the potential to be a key component in landslide early warning systems that also combine other technologies.

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