



# Design and evaluation of 5G-based architecture supporting data-driven digital twins updating and matching in seismic monitoring

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## Abstract

Digital Twins (DT) models are gaining special attention in the management and maintenance of facilities. The quality of data contained in these models may be enhanced by the use of processed information coming from long-term Structural Health Monitoring (SHM). In this case real time processing and updating in systems using sensor networks for SHM need low latency and reliable communication. This paper presents a solution for exploiting DT models for SHM and early warning solutions improvement. The case study scenario resides within the 5G experimentation in the city of L'Aquila and it exploits a highly adaptable sensor board and a 5G Multi-Access Edge Computing architecture.

**Keywords** Structural health monitoring (SHM) · Earthquake early warning (EEW) · 5G network · Massive machine-type communications (mMTC) · Ultra-reliable and low latency communications (uRLCC) · Multiaccess edge computing (MEC) · MEMS accelerometers

## 1 Introduction

The recent advances in connectivity technologies have brought to the creation of new terms to properly define the possible scenarios. Internet of Everything (IoE) has been recently adopted to indicate a paradigm comprising both previously defined Internet of Things (IoT) and Internet of Humans (IoH) concepts within a variegated scenario where data can be exchanged through Machine to Machine (M2M) or Machine to Humans (M2H). To these paradigms several application domains such as industry 4.0, e-health, smart grids, smart cities, safety and more refer.

This contribution mainly focuses on the application of IoT paradigm, in the urban scenario of the city of L'Aquila (ITALY), that is almost unique, since a reconstruction phase after the strong earthquake that hit the town in 2009, is still an on-going process, Chiarabba et al. (2009). This represents a great opportunity to direct the overall urban design toward

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a “smart city” view, focusing at first toward safety and ecology. In this context, a focus toward Structural Health Monitoring solutions has been seen as an occasion to monitor buildings structures not only for early warning solutions in earthquakes events, but also to control and mitigate service conditions of construction in relations to comfort, energy savings and optimized maintenance. For all these aspects an integrated approach to digital twins designed for multipurpose applications appears to be very attractive. Here, the focus is to evaluate the health of a structure by timely identifying what are the main causes (e.g. deterioration of the material or heavy structural damage) which may affect the use of the structure. Such causes can be induced by different circumstances like manufacturing defects, poor maintenance or exposition to unexpected or extreme events (earthquakes or blasts).

Given the potential advantages, SHM systems have been largely implemented in structures falling in various fields (e.g. civil, aerospace, railway). It is worth noticing that given the 3 main different types of structures (i.e. buildings Dolce et al. (2017), bridges and infrastructures Anastasopoulos et al. (2021), Giordano et al. (2021), Rainieri et al. (2020), cultural heritages Kita et al. (2019), Potenza et al. (2015) and towers Venanzi et al. (2020), Gentile et al. (2016)) different attentions and instructions must be ensured in the phases of monitoring system design.

In the SHM scenario the first important element is a network of sensors that is permanently attached to the structure to be monitored. This network brings an important advantage because it does not require human intervention as Non-Destructive Testing (NDT) procedures commonly provided, Güemes et al. (2020). Sensors may be accelerometers, fiber optics sensors, piezoelectric wafers, microelectromechanical systems (MEMS) and many more.

A second element is given by the communication architecture that is exploited for data exchange between nodes of the network and the data processing unit. Since it has been shown that a major fraction of the overall cost of a traditional SHM system is primarily related to wiring costs, Lynch and Loh (2006), going wireless represents a significant innovation opportunity in SHM field. In this context, the opportunity coming from the choice of the city of L'Aquila as one of the five Italian cities to host a 5G trial, has pushed the exploitation of this communication technology in the SHM field, Antonelli et al. (2018).

Referring to the 5G vision and its three generic objectives to be supported, Shafi et al. (2017), i.e. enhanced Mobile Broad-Band (eMBB), massive Machine-Type Communications (mMTC) and ultra-Reliable and Low Latency Communications (uRLCC), the SHM system can be referred to the mMTC or uRLCC context, depending on the operational scenario. Indeed, the case of data collection and processing from sensors in monitored buildings, considering their large number, can be referred to the mMTC context. Vice versa, during a seismic event or just after it, the use case requires high reliable connectivity and low latency: these features refer to the uRLCC context. It is interesting to evaluate and to experiment the ability of the 5G network to dynamically adapt to the changing scenarios.

Another aspect to be taken into account while conceiving with SHM is the way through which data are processed and exploited to get advantages from the installed sensors network. Starting from the definition of simplified models, the information provided by SHM systems could be used to improve the knowledge of the structural behavior of a building/infrastructure, Gattulli et al. (2021).

This work refers to monitoring and control systems that allow not only to give useful information to detect the damage induced by a catastrophic event, but also to maintain its strength and serviceability during the whole design life, Ceci et al. (2013).

Various vibration control systems have been proposed in literature (i.e., active, passive, and semi active); some of them relying on simple approaches such as PID controllers, others exploiting a dynamical model, which can be difficult to obtain when the structure to be considered is complex, Di Girolamo et al. (2020), Smarra et al. (2020). It is worth noting that if from one hand it is important to have a detailed model structure for applying efficient and reliable evaluating solutions, especially in the case of a catastrophic event, on the other hand special care has to be given to the amount of data that these models eventually require to manage, which sometimes become prohibitive from a practical point of view. For this reason, special attention has to be given to the achievement of the proper trade-off between the simplicity of a model and its ability to faithfully represent the behaviour of a building under certain inputs.

Finally it is important to notice that the sampling intervals need to be tight as it is necessary to be able to quickly react to very rapid external disturbances (e.g., earthquakes). This implies that the dedicated hardware intended for computation must be able to manage the large amount of data coming from the sensors in the structures and compute the control actions in times of the order of milli/microseconds.

This paper presents a 5G-based communication architecture that is able to manage SHM and EEW solutions at the same time, guaranteeing the satisfaction of their different requirements. The opportunity of satisfying very different and sometimes strict applications constraints without the need of using different communication solutions is offered for the first time by the 5G paradigm that thus allows to design multi-functional and multi-purpose scenarios. A case study scenario, based on DT models, is presented in order to validate the stated advantages of the proposed platform.

## 2 Structural health monitoring and earthquake early warning

Structural Health Monitoring is a vital tool to improve the safety and maintainability of critical structures such as bridges and buildings. SHM provides real-time and accurate information about the structural health condition. It is a process of non-destructive evaluations to detect location and extent of damage, calculate the remaining life, and predict upcoming accidents.

The implementation and usefulness of a permanent seismic monitoring systems network installed in public buildings (but also some bridges and a dam) along the Italian territory has been assessed and described in Dolce et al. (2017), where the proposed network, called OSS (acronym of the Italian name “Osservatorio Sismico delle Strutture”) is able to carry on a real-time post-earthquake damage assessment.

In SHM systems one of the main tasks is to detect damage that can influence both global and local structural behavior. About the first task (global) Vibration-Based Monitoring (VBM) is certainly the most widely used. Indeed, a possible variation of the modal characteristics (frequency, shape and damping) could be related to the beginning of a damage since they are in relation with stiffness and mass of a structure, Limongelli and Giordano (2020), Kita et al. (2020).

It is worth highlighting that sometimes daily experimental tests could constitute an alternative to install a monitoring system. In this latter case, if from one side they are easier to be performed (especially when tests are carried out under ambient vibrations), on the other side they are able to supply less information than the ones provided by a permanent monitoring system. In this case the information will be useful to update

forecasting finite element models for carrying out more accurate checks or evaluate the vulnerability of a structure, Diaferio et al. (2015a), Foti (2015), Diaferio et al. (2015b), Foti et al. (2020).

Instead, the second task (local) is easier performed by visual inspection techniques. In recent times, especially due to safety issues of the inspectors (sometimes is very hard to reach inaccessible areas), semi-automatic computer-aided procedures are under development putting together both image processing techniques and robotized systems, Potenza et al. (2020).

VBM systems are traditionally carried out processing accelerometric measurements induced by both ambient vibrations and seismic events using well-known techniques like Frequency, Brincker et al. (2001), or Enhanced, Jacobsen et al. (2008), Domain Decomposition (FDD or EFDD) and Stochastic Subspace Identification Reynders and De Roeck (2008). However, in a recent work, Anastasopoulos et al. (2021), some promising results have been achieved by strain data that are relatively low cost and allow to implement a dense measurement grid. It worth to highlight that the realization of a SHM requires time and considerable economic investments for which could be useful to perform rapid daily experimental dynamic tests for calibrating a forecast numerical model. In Gattulli et al. (2021) thanks to the huge volume of data coming from two-days of experimental campaign on a suspension bridge it has been possible to update both numerical and analytical mechanical model able to well represent the dynamic behavior. Moreover, in the cases of the towers, some predictive formulas have proposed to evaluate the modal characteristics based only on the knowledge of the geometrical features without carrying out dynamic tests, Diaferio et al. (2018). Long-term SHM data need also to be depurated from the effect of the environmental conditions as temperature and humidity, Gentile et al. (2019), Ubertini et al. (2018), Pitilakis et al. (2016). For this reason, data driven methods have found great applicability since they are able to explore the internal characteristics of the raw measured response and deeply detect the damage. Some interesting example are illustrated in Flah et al. (2021), Peng et al. (2021), Kaya and Safak (2015).

Different typologies of monitoring actions (dynamic analysis-oriented monitoring, seismic analysis-oriented monitoring, crack growth-oriented monitoring, environmental- or chemical-oriented monitoring) may have different or conflicting requirements. For example, dynamic analysis-oriented monitoring systems must guarantee a precise measurement synchronization, Krishnamurthy et al. (2008), while this requirement may result less compelling when monitored quantities are slowly variable (e.g. the case of crack growth monitoring). Data gathered are exploited in order to verify the buildings performance over time enabling a continuous evaluation of their safety and the opportunity of planning proper restoration activities to reduce their vulnerability. Sensor networks are able to transmit the measured data to a central data collector in order to process them in a proper way. The ultimate goal of this kind of systems is to build a wide monitoring network with low-cost technologies allowing the development of processes of qualitative analysis and representation of data collected by the sensors (e.g. georeferenced triaxial accelerometer data). The fundamental building blocks of sensor networks for SHM, which determine their performance in terms of reliability, energy consumption and economic issues, are: sensors, microcontrollers and communication interfaces. The latter aspect has seen a lot of research and implementation efforts for exploiting the advantages coming from wireless connections such as greater flexibility and low cost deployment, Lynch and Loh (2006). In general, a lot of sensor networks designs are available for SHM either in form of academic prototypes or

commercial products, all of them constituted by the previously hinted building blocks, see for instance Lynch and Loh (2006), Mustapha et al. (2021), Ostachowicz et al. (2019) and references therein.

This analysis also aims at evaluating the possibility of using this type of low cost distributed systems for the characterization of environmental pressures on the architectural heritage. The building monitoring system is the basis for the implementation of different kind of systems used to protect the health of citizens in case of natural disasters (earthquakes or other catastrophic events). It exploits the ability to constantly track the status of the structures in a timely manner to detect the occurrence of dangerous events and activate, when necessary, proper mechanisms for emergency response. The monitoring systems are used to get an immediate assessment of the safety level of the building, at both global and individual level.

The idea behind Earthquake Early Warning (EEW) is to use the SHM system to detect a seismic event and to propagate a message reporting the event detection (EEW message) to all the buildings that may be damaged by the disaster event. While the seismic detection in the local building can trigger reactive safety actions to compensate the effect of the disaster without any guarantee of effectiveness, the EEW message reception triggers preventive safety actions in the nearby buildings that, if applied with adequate timing, can increase citizens and facilities safety as shown in Fig. 1.

Potential preventive safety actions that can be triggered by EEW include initiation of elevator recall to ground floor procedures, placement of sensitive equipment in safe mode, securing of hazardous materials, halt production lines to reduce damage, unlocking of exit doors, switch on of emergency lights. Earthquake events are normally characterized by the occurrence of body and surface waves. Body waves have lower energy and propagates with a speed between 1.5 and 8 km/s while surface waves propagate with lower speed but, on the other hand, transfer a higher energy with respect to body ones and therefore are more dangerous, Di Stefano et al. (2011). The difference in propagation speed between body and surface waves implies a delay of arrival at different places in the surface that can be effectively utilized to implement preventive safety actions. That being said, once the EEW message is generated, every millisecond spent in the propagation of the message corresponds to an increase of almost 8 m of the radius of the area reached by the earthquake. On the other hand, the reduction of 1 ms of the EEW propagation time corresponds to an increase of 8 m of the area where to implement safety actions. These data stress the importance of exploiting a 5G connection for early warning purposes given the unprecedented low latency level guaranteed by this new generation of networks. At the same time 5G is able to guarantee a proper functioning of the system also under the SHM state. This level of flexibility is due to the *network slicing* concept that is presented in the following section.



Fig. 1 5G EEW system functional scheme

### 3 5G architecture supporting structural health monitoring and earthquake early warning

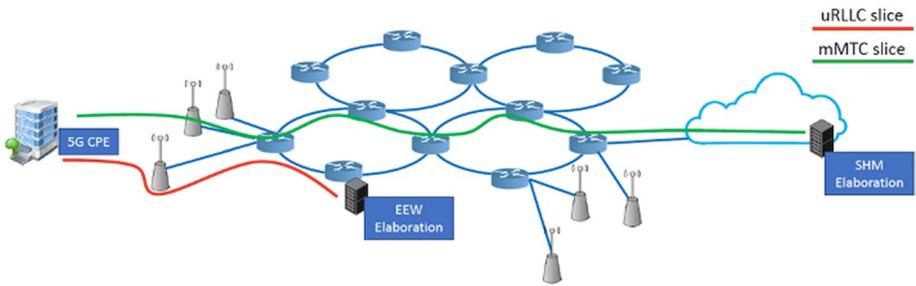
Compared to the previous mobile communications technologies 5G offers an unprecedented level of flexibility to support heterogeneous services. In order to achieve this goal it leverages several enabling technologies and novel network paradigms such as:

- **Software Defined Networking (SDN)** that allows to control via software the behaviour of network elements in order to adapt to different network conditions and to enforce service-specific traffic requirements
- **Network Function Virtualization (NFV)** allows to reproduce the behaviour of traditional hardware-based network functions (switches, routers, firewalls, etc.) via virtualization techniques over general purpose machines. This way, the network can be flexibly reconfigured and service components can be *orchestrated* over different physical locations, i.e. datacenters, to obtain the desired service performance.
- **Network Slicing (NS)** by combining the advantages deriving from SDN and NFV allows to offer to different services virtual *slices* with specific performance tailored to the different services over a common physical infrastructure. The slices are composed by involving the different network segments traversed by the traffic. This includes wireless network, optical transport network, and computation infrastructure.
- **Multi-Access Edge Computing (MEC)** by leveraging NFV, MEC allows to move to the edge computation elements devoted to a specific service. This approach has many advantages: (i) it allows to reduce the latency experienced by the users since reduces the travel of the packets; (ii) reduces the overall traffic into the network thus avoiding congestion for the operator at the price of introducing replicas of elaboration elements at the edge; (iii) it allows to achieve better Quality of Experience for multimedia services.

Parallel to the above described building blocks, 5G introduces novel techniques in the radio segment of the network devoted to offer not only higher throughput, but also higher reliability levels and lower latency depending on the requirements of the specific service.

With respect to the above described SHM and EEW system, one can observe that the two applications are characterized by significantly different requirements. Even if both services are based on the sensing of data performed by the same sensor nodes, the data transmitted for the two applications can be treated differently by the network elements. In fact, the traffic for the SHM can be treated with no particular performance guarantees since it is only devoted to monitoring purpose. On the other hand, the traffic of the EEW application represents a critical traffic with low latency and high reliability requirements since it is devoted to activate safety actions.

In order to fulfill such heterogeneous requirements the adopted 5G network architecture is configured to support two different *network slices*, for the SHM and EEW respectively, as shown in Fig. 2. The EEW slice is configured to schedule the traffic of the EEW with very high priority in the radio segment to achieve low latency; when the packets leave the 5G base station they have to traverse the so called *optical transport* network which is configured to offer protection against failures of physical layer (e.g. fiber cuts); finally the software for the elaboration of the EEW messages is deployed at the edge of the network (thanks to MEC capabilities) in order to obtain a very low latency and can be scaled and replicated to offer higher performance and survivability against disasters. On the other



**Fig. 2** uRLLC and mMTC slices: the red path is intended for EEW traffic while the green one represent the data addressed to a cloud SHM elaboration node

hand the SHM slice is configured to forward the traffic over the physical infrastructures on a best-effort manner and the function responsible for the elaboration of the messages is deployed over a remote cloud which is characterized by higher cost efficiency from the service provider's viewpoint.

## 4 Service development

This Section describes the deployed architecture supporting an experimentation of the designed system for a building belonging to the University of L'Aquila within the 5G trial.

### 4.1 Sensor board design

*SHM-Board v2* has been designed as a highly versatile and high-performance device for real-time SHM of infrastructures or buildings.

Figure 3 shows the device which takes advantage by the experience made in the field with the IMOTE board used in the 5-years continuous structural monitoring of the Basilica of Collemaggio after the 2009 L'Aquila earthquake, Potenza et al. (2015).

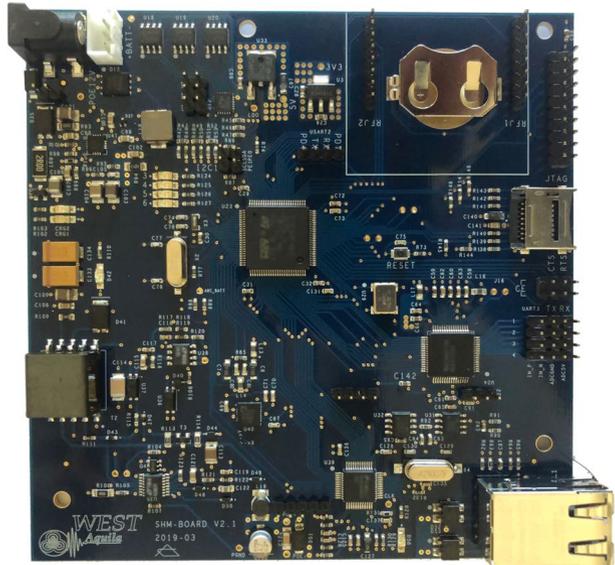
The new *SHM-Board v2* is based on an ultra-low-power micro-controller which offers numerous communication and high-performance interfaces: through its 12-bit ADC, it is connected to a low-noise MEMS accelerometer (Kionix KXR5-2050), mounted directly on the board, that is always active in order to detect accelerations above a configurable threshold.

External low-noise MEMS accelerometers can also be used. *SHM-Board v2* is equipped with 4-channels 24-bit ADC able of sampling at 100Hz and on-board data processing in order to minimize the total amount of data to be transmitted. Two accelerometers, suited for structural health monitoring, were identified and tested.

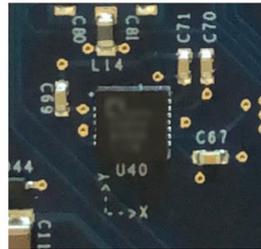
The board has been designed in order to examine the possible adoption of low cost, un-calibrated, MEMS accelerometers for both SHM and EEW scenarios. However, a calibration procedure has been defined for the MEMS accelerometers in order to compare the estimation of the structural response provided by the data processing with and without calibration.

From the communications point of view, *SHM-Board v2* has an Ethernet interface (from which it can be powered via PoE) and other interfaces to connect more peripherals. The board also provides the capability to communicate wirelessly with other nodes of the

**Fig. 3** The sensor board developed for the experimentation



**(a)** SHM Board V2



**(b)** Kionix KXR5-2050

monitoring network through Wireless Meter Bus (Wireless M-Bus) protocol at  $169\text{MHz}$  or  $868\text{MHz}$  that allows communication over long distances and is much less exposed to obstacle attenuation. Also a Narrow Band Internet of things (NB-IoT) or 5G expansion module is available. This flexibility in terms of communication interfaces is the main advantage coming from this dedicated board design.

Finally, *SHM-Board v2* provides the capability to acquire signals from other types of measuring instruments like clino-meters and crack-meters, widely used in the field of Structural Health Monitoring (especially after seismic events that caused serious damages to the buildings). The integrated temperature sensor allows to evaluate the thermal effect on the structure and on the sensor thus allowing to distinguish seasonal variations from real inclinations. The MEMS operating principle guarantees good thermal stability and excellent linearity.

#### 4.2 Architecture supporting the SHM and EEW application

The deployed application has been studied and tested with the limitations of the dedicated communications systems, D'Errico et al. (2019). However, the possibility to leverage an

uRLLC infrastructure unveils tremendous potential benefits on safety of human beings and infrastructures.

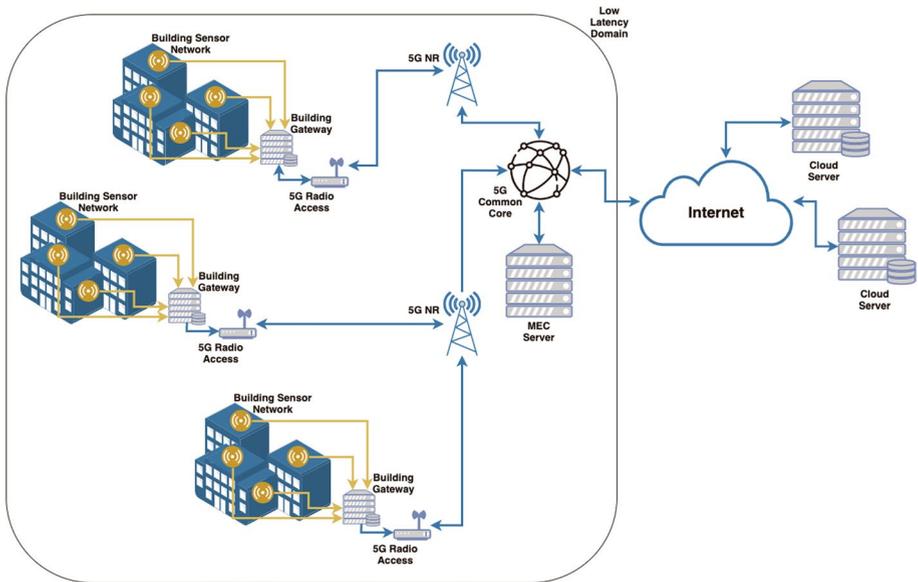
As described in Fig. 4 the deployed service refers to a network of monitored building equipped with the developed sensor boards able to collect accelerometric data used to feed a data driven SHM system and an EEW detection service.

The University of L'Aquila, in collaboration with the municipality, has deployed an experimental network and a MEC elaboration server for the proposed service referring to, at the moment, 5 buildings (3 historical buildings, a RC building, and a base-isolated modern building). Figure 5 shows the location of the buildings in L'Aquila for the pilot experimentation with the *Coppito 1* building, described in Sect. 5, located in "Polo Universitario di Coppito" site.

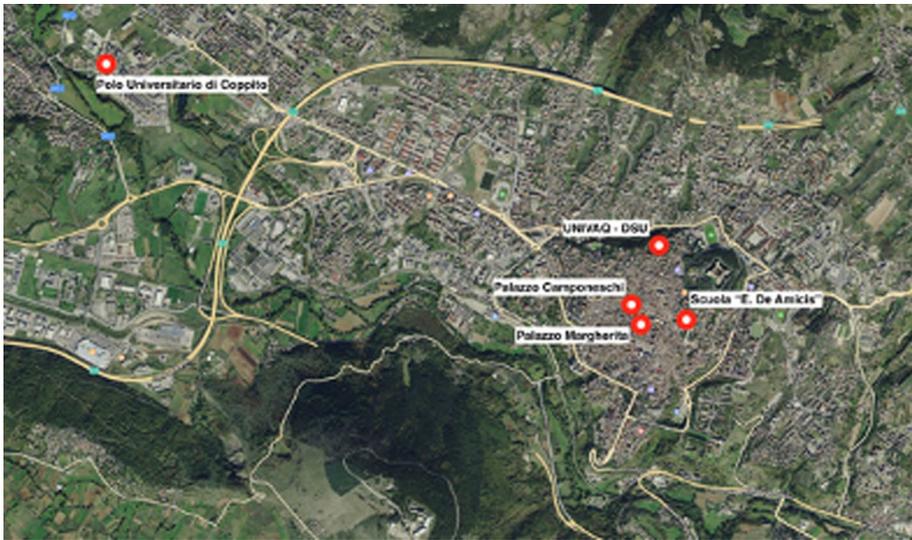
Referring to the first one and considering the scenario described in Fig. 2 the deployed architecture supports the communication within a remote cloud server able to estimate dynamical models for large-scale complex real-life systems via machine learning methodologies, Smarra et al. (2020), De Iuliis et al. (2021), De Iuliis et al. (2021), or continuously update a data-driven model of the monitored building.

Considering the EEW scenario, the idea is to send an early warning message as soon as the P-wave of the earthquake is detected, in order to inform the surrounding areas before the arrival of the possible destructive S-wave. This allows to notify people and surrounding structures for acting in order to preserve severe damages e.g. evacuate dangerous areas, initiate elevator recall procedures to ground floor, halt assembly lines, switch on emergency lights, slow trains and many other possibilities strictly related to the "smartness" of the territory involved.

Trivially, the lower is the time required for the propagation of the warning the higher is the effectiveness of such a system. This is the reason why, for the previously described



**Fig. 4** Deployed IT architecture supporting the structural health monitoring and earthquake early warning application



**Fig. 5** Location of the buildings in L'Aquila for the pilot experimentation

scenario, an application running on a MEC server may receive and process data with a lower latency in order to quickly detect the propagation of a seismic wave.

In both scenarios, the exchange of data is implemented at the application layer through the Message Queue Telemetry Transport (MQTT) protocol based on the use of a broker, designed for the transmission of data according to the publish/subscribe pattern. According to this pattern each building acts as a publisher when sending early warning messages or a monitoring information to the broker. The broker, in turn, sends the collected data to all the interested buildings, them being subscribers at the same time.

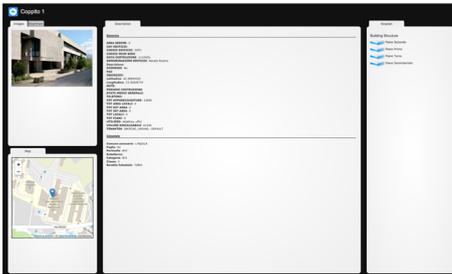
## 5 Case study

The case study is focused on one of the most important buildings belonging to the University of L'Aquila, Ceci et al. (2010). The referenced building for the discussed case study, named “Renato Ricamo” (*Coppito 1*), was built in the 1985. A digital platform, some images of which are shown in Fig. 6, owned by the University of L'Aquila stores a series of information related to the referred building aiming to build a distributed Digital Twin handling also data coming from the monitoring sensors. Figure 7 also shows some aerial view of the study case complex.

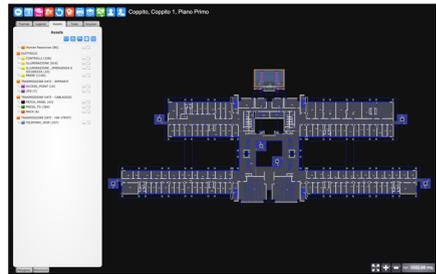
It is composed by six RC (Reinforced Concrete) substructures (C1–C6 in Fig. 8a) separated by seismic joints. Moreover, the first four buildings (C1–C4) are characterized by geometrical regularities, in both plan and elevation, while, on the contrary, the two central structures (C5 and C6) show a higher irregularity. Indeed, even if not well visible in Fig. 8a, they have staggered floors two of which with a central hole. The buildings C1–C4 are developed in elevation through four levels where the vertical structural part is composed by columns and RC walls. The horizontal ones are realized by beams and RC slabs alternated with predalles. Figure 8 also shows the positions of the sensors selected for each

ID	Name	Location	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7	Value 8
101	Asset 1	Location 1	100	100	100	100	100	100	100	100
102	Asset 2	Location 2	200	200	200	200	200	200	200	200
103	Asset 3	Location 3	300	300	300	300	300	300	300	300
104	Asset 4	Location 4	400	400	400	400	400	400	400	400
105	Asset 5	Location 5	500	500	500	500	500	500	500	500
106	Asset 6	Location 6	600	600	600	600	600	600	600	600
107	Asset 7	Location 7	700	700	700	700	700	700	700	700
108	Asset 8	Location 8	800	800	800	800	800	800	800	800
109	Asset 9	Location 9	900	900	900	900	900	900	900	900
110	Asset 10	Location 10	1000	1000	1000	1000	1000	1000	1000	1000

(a) Asset browser



(b) Coppito 1 building summary



(c) Coppito 1 plan

Fig. 6 University platform for digital management of the buildings

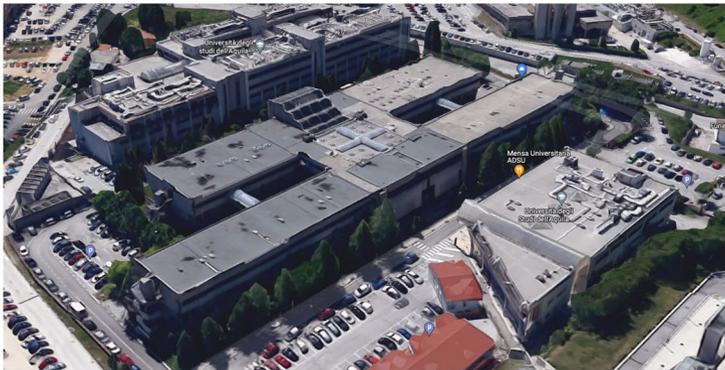
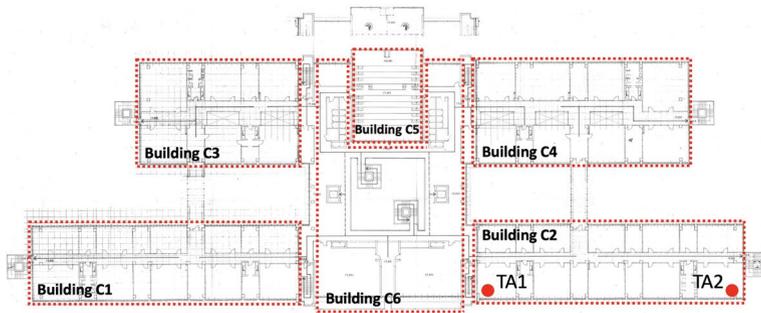
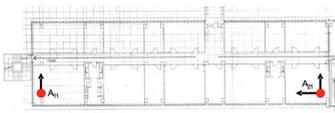


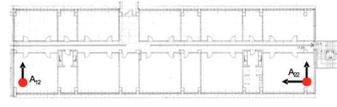
Fig. 7 Aerial view (above) and two lateral view photos (below) of the “Renato Ricamo” buildings



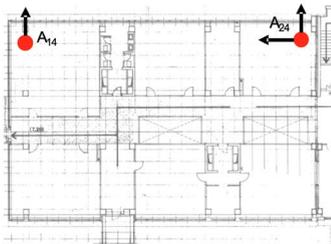
(a) General configuration of the “Renato Ricamo” buildings. TA1 and TA2: position of the tri-axial MEMS accelerometric sensors installed for the building C2 in the last and second-last floor.



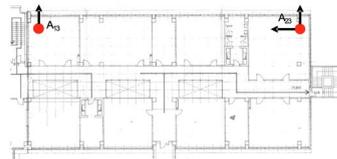
(b) Building C1



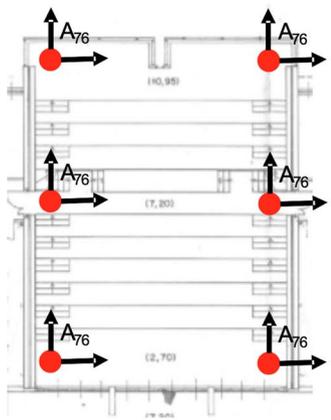
(c) Building C2



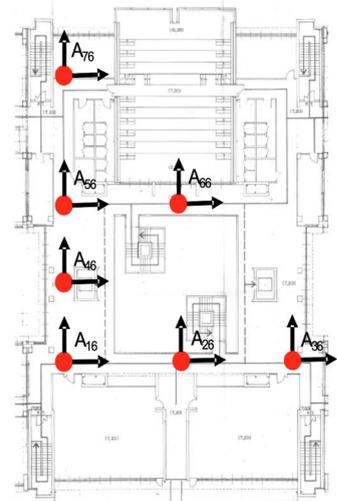
(d) Building C3



(e) Building C4



(f) Building C5



(g) Building C6

Fig. 8 Positions of the sensors selected for each building and elevation

**Table 1** Number of sensors for each building in *Coppito 1*

Building	Sensors/floor	Elevations	Total sensors
C1	2 tri-axial	4	8
C2	2 tri-axial	4	8
C3	2 tri-axial	4	8
C4	2 tri-axial	4	8
C5	6 tri-axial	1	6
C6	7 tri-axial	2	14

**Fig. 9** Deployed sensors for the fourth elevation of C2 building

building and elevation. Finally, Table 1 summarize number of sensors for each building in *Coppito 1*.

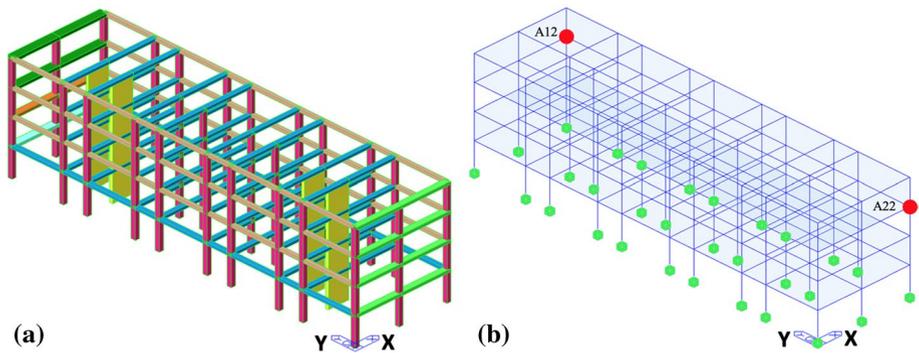
Currently, only four tri-axial MEMS accelerometric sensors have been installed: two in the last and two in the second-last floor of the building C2. They are located on the edges of the building (positions TA1 and TA2 in Fig. 8a) in order to identify the tridimensional dynamic behavior of the structure. Figure 9 reports the deployed sensors for the fourth elevation of C2 building.

MEMS are, in general, economic sensors but highly noisy. For this reason, performing a continuous structural health monitoring using measurements recorded under ambient vibrations is very difficult (for instance with the purpose of following the variation of the modal frequencies due to temperature or humidity). Indeed, the actual configuration, is thought to evaluate the real structural behavior processing recordings obtained under a seismic input. Even though not purely correct, the accelerations induced by low energy earthquakes could be used to approximately identify the main modal features, Potenza et al. (2015). In the following, the building C2 will be taken into account as test bed.

## 5.1 Numerical model

The finite element model of the test bed has been implemented within the environment Midas Gen (v2.2), [44]. Figure 10a highlights the different geometrical properties of the elements varying the colors (8 and 3 different sections for beams and plates, respectively, and listed in the Table 2).

Instead, Fig. 10b shows the type of the boundary conditions applied to all nodes on the base that block all six degrees of freedom. The model is composed by 150 nodes and 389



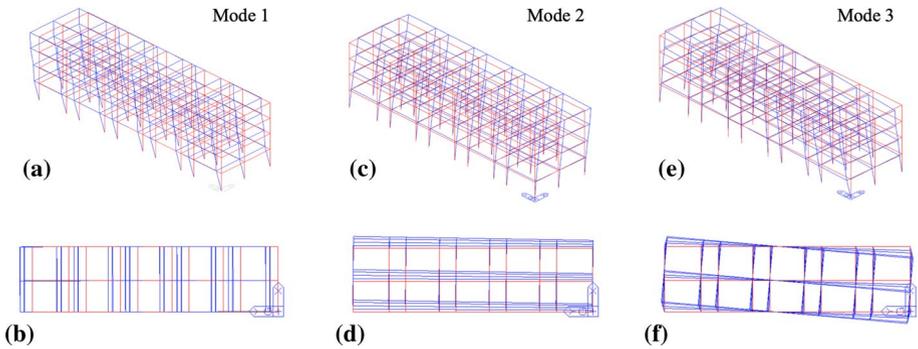
**Fig. 10** Finite element model representative of the structural behavior of *Coppito 1*: **a** different elements typologies, **b** boundary conditions (fixed to the base)

**Table 2** Sections and thickness used in the Finite Element Modelling

Element	Section H (cm)	Section W (cm)	Thickness (cm)	Representativeness
Beam	60	60	–	All columns (constant section for whole height)
Beam	300	40	–	R.C. walls of the stairwells (yellow)
Beam	40	80	–	Transversal elements (light green, X-direction)
Beam	35	105	–	Transversal elements (cyan, X-direction)
Beam	40	60	–	Transversal elements (blue, X-direction)
Beam	40	85	–	Transversal elements (orange, X-direction)
Beam	40	120	–	Transversal elements (dark green, X-direction)
Beam	40	45	–	Transversal elements (light brown, Y-direction)
Plate	–	–	50	Horizontal elements (floors)
Plate	–	–	7	Vertical elements (external R.C. walls)

elements (273 beam and 116 plate). The model shows regularities in both plane and elevation (see Fig. 8a, building C2) as shown by lateral view photos in Fig. 7. The reinforced concrete infills are present only between second and third floor (i.e. second elevation) and between third and fourth floor (i.e. fourth elevation).

It is important to observe that the thickness used for the elements representing the floor (horizontal plates) was of 50cm in order to take into account also the weight of the



**Fig. 11** Numerical modal shapes for the updated model: **a, b** translational in Y-direction (longitudinal); **c, d** translational in X-direction (transversal); **e, f** rotational

non-structural elements (screed, flooring, partitions, machineries, etc...). These latter are not considered in the definition of the elastic modulus for the floor (structural part with a thickness of 20cm) and this is the reason since a reduced value (about an half of the nominal value) has been used. In some sense, such selected value has been applied to taken into account an equivalence of the floor axial stiffness between model and actual structural configuration. Moreover, such elements contribute also to model the floors as infinitely rigid. The masses coming from the floors are automatically inserted in the nodes of the corresponding plate elements proportionally to the influence areas of each nodes.

An elastic-linear constitutive law has been defined for all elements whose parameters have been manually updated based on the information coming from the dynamic tests carried out by the University of L'Aquila Technical Office, [45]. In this last report, it can be found the main modal characteristics (frequencies, modal shapes and dampings) related to all substructures constituting the building of *Coppito 1*. In particular, the ones of the structure *C2* are reported in Table 3. Such parameters have been identified using the software ARTEMIS, Structural Vibration Solutions (2018), through the well-known procedures within implemented: EFDD, Brincker et al. (2001) and Stochastic Subspace Identification - Unweighted Principal Component (SSI-UPC, Peeters and De Roeck (1999)). It was considered reasonable to change only the elastic modulus in order to maintain close, as much as possible, the numerical and experimental modes. The minimization of the difference between the numerical and experimental modal frequencies of the modes mainly involved in the dynamic response has been chosen as objective function for updating the model.

**Table 3** Main modal frequencies and shapes experimentally identified for the building C2 (results found in [45])

Mode	EFDD [Hz]	SSI-UPC [Hz]	Avg. freq. [Hz]	Experimental modal shape
1	2.695	2.704	2.700	translational (longitudinal Y-direction)
2	2.968	2.985	2.977	roto-translational (translational in X-direction)
3	3.802	3.774	3.788	roto-translational (rotational)

**Table 4** Characteristics of the elastic-linear constitutive laws for the updated model

Element	Elastic modulus (initial) (MPa)	Elastic modulus (final) (MPa)	Poisson Coefficient	Specific weight (Kg/m <sup>3</sup> )
Beam	32000	31475	0.2	2500
Columns	32000	31475	0.2	2500
Walls	32000	31475	0.2	2500
Floor	16000	19475	0.2	2600

**Table 5** Comparison between numerical and experimental frequencies (*Coppito 1*, building *C2*)

Mode	Numerical (Hz)	Experimental (Hz)	$\Delta$ (%)
1	2.648	2.700	-1.91
2	2.966	2.977	0.35
3	3.993	3.788	5.41

The corresponding expression related to the first three modes (total participating masses of such three modes: translational X-direction = 81.83%, translational Y-direction = 95.51%, translational Z-direction = 0.09%, rotational X-direction = 0.10%, rotational Y-direction = 0.10%, rotational Z-direction = 86.90%) is shown by equation (1).

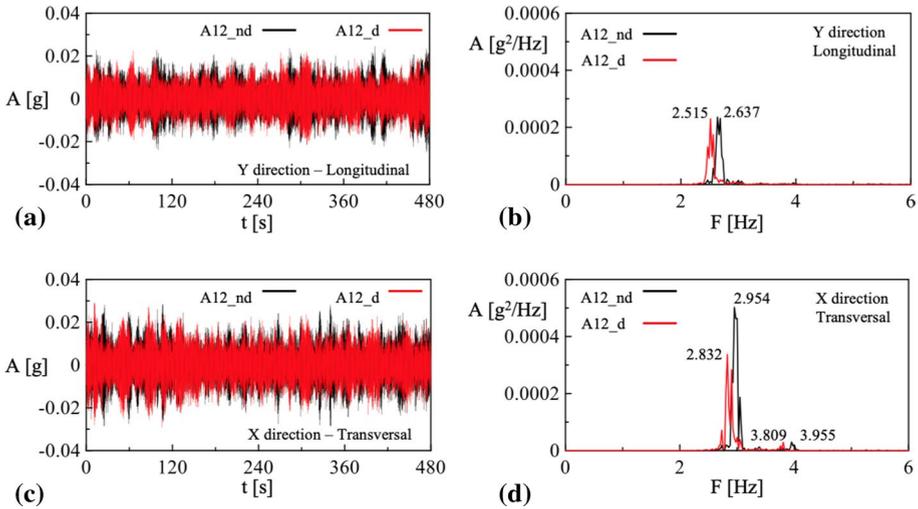
$$F(E) = \min \sum_{i=1}^3 \frac{f_i^{exp} - f_i^{num}}{f_i^{num}} \tag{1}$$

where  $F$  is the objective function depending by the elastic modulus,  $E$ , while  $f_i^{exp}$  and  $f_i^{num}$  are the  $i$ -th experimental and numerical frequencies, respectively. The final parameters are reported in Table 4, where have been reported both initial and updated elastic modulus, while in Fig. 11 the modal shapes related to the updated model are shown.

Table 5 reports a comparison between the numerical and experimental modal frequencies. The first two modes (translational in the X- and Y-direction) are in good agreement showing a percentage difference of -1.91 and 0.35%, respectively. Related to the third one (rotational), a difference slightly higher than the 5% has been found (5.41%) that, in any way, has been retained acceptable. It is worth to highlight that the last choices of the elastic modulus (the only parameters varying), provide also a good agreement between numerical and identified modal shapes: for the last ones refer to the report provided by the University of L'Aquila, University of L'Aquila (2017). The comparison has been carried out only visually.

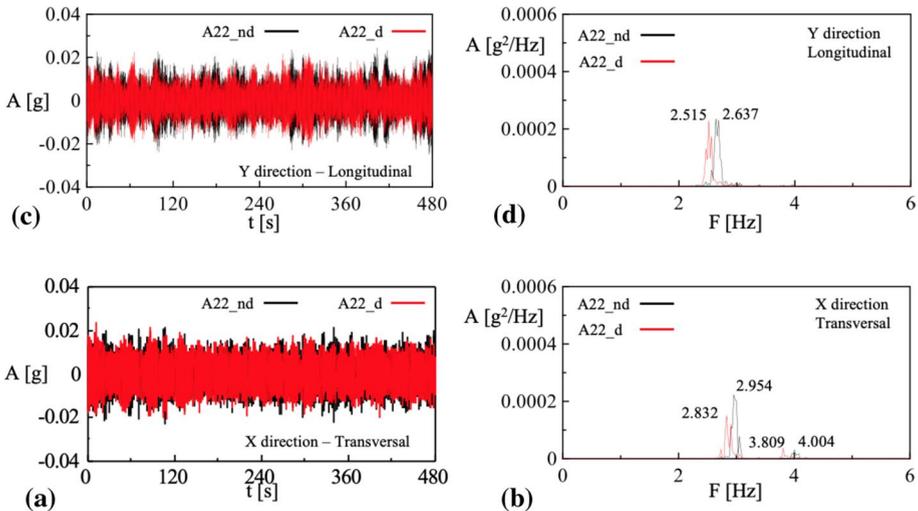
### 5.2 Simulation results

Successively, such numerical model has been used to generate the time histories of a damaged and non-damaged configuration under white noise. The latter has been realized in Simulink through the block "Band-Limited White Noise". The damage has been simply modelled by a reduction of the elastic modulus. This simplification has been assumed in order to make the results more easily manageable and understandable and, above all, to



**Fig. 12** Numerical simulations under white noise related to the nodes A12: **a, c** time histories, **b, d** PSDs; nd = non-damaged, d = damaged

allow a check of the IT system performance. The time histories have been extracted from the nodes positioned in A11 and A12 (see Fig. 10b) and have been reported in Fig. 12a, c and Fig. 13a, c. The effect of the damage is clearly visible when observing the corresponding Power Spectral Densities (PSDs reported in in Fig. 12b, d and Fig. 13b, d). Indeed, the damage affects the modal frequencies producing a reduction especially recognizable on the translation modes. Instead, the rotational mode is poorly identifiable in both damaged and non-damaged configuration.



**Fig. 13** Numerical simulations under white noise related to the node A22: **a, c** time histories, **b, d** PSDs; nd = non-damaged, d = damaged

About the damaged configuration, an approximate reduction of the 10% has been applied to the value of the elastic modulus. Of course, during the processing of real data, coming from a continuous monitoring system, to accurately detect the presence of damage, the main modal characteristics (frequencies and modal shapes) should be identified, purifying the results by the effect of the environmental parameters (e.g., humidity and temperature).

### 5.3 Time series feeding a prototype MATLAB processing application

A prototype application, developed in MATLAB, able to connect through an User Datagram Protocol (UDP) socket with the building gateway, has been used to implement a Machine Learning (ML) based approach for SHM for continuous refining of the model. The time series previously described and representing the building in its elastic condition have been used to evaluate the capability of the deployed application to update the data-driven model obtained from the continuous monitoring of the structure. The same application deployed on MEC nodes of the IT architecture of Sect. 4.2 is able to process the same data near-real time (low latency) and, when they are referred to a damaged structure, to send an alarm to the damaged building.

Some measurements were made on the developed scenarios. The average delay of the network, at application layer, follows a normal distribution with an average value of 2.1ms and a standard deviation of 0.9ms. Sensors data were sent to the edge and remote cloud and delays were assessed. Publish messages were generated every 10ms by the publisher, with MQTT QoS set to zero.

## 6 Conclusions

This contribution has presented a system for Structural Health Monitoring on 5G uRLLC network where data-driven algorithms are applied for data exploitation as well as for early warning systems implementation. Such algorithms can be also used to periodically improve the models as data are collected from sensors by catching new dynamics as structure evolves over time (changes or degradation of certain points of the structure). A real scenario based on a RC structure has been studied. The developed finite element model has been used to generate data referred to health and damaged conditions of the monitored building in order to verify the behaviour of the service. Future works are devoted toward the exploitation of real-time experimental data for service validation. Operational Modal Analysis allowing frequencies identification in the presence of ambient vibrations is currently under evaluation.

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