Structural Health Monitoring and Earthquake Early Warning on 5G uRLLC Network

L. D'Errico, F. Franchi, F. Graziosi, A. Marotta C. Rinaldi
University of L'Aquila,
Piazza Santa Margherita 2, 67100, L'Aquila, Italy
{fabio.franchi; fabio.graziosi; andrea.marotta; claudia.rinaldi}@univaq.it
leonardo.derrico@graduate.univaq.it

M.Boschi, A. Colarieti
WEST Aquila s.r.l.,
S.S. 17 Ovest, 36, 67100, L'Aquila, Italy
{mattia.boschi; andrea.colarieti}@westaquila.com

***Abstract*—This work deals with the development of a permanent structural monitoring system for buildings, based on innovative minimally invasive technologies in order to provide information about the structural behavior under normal conditions and especially in the presence of seismic events. The gathered information will be processed through model based and data based approaches, in order to compare and possibly integrate these techniques. Referring to the 5G vision the SHM system can be considered depending on the operational scenario: in the case of data collection and processing from sensors in monitored buildings, considering the high number of sensors installed, it can refer to the mMTC context. Viceversa, during a seismic event or just after it, the use case requires high reliability connectivity and, sometimes, low latency. Those features refer to the URLL context. It seems interesting to evaluate and experiment the ability of 5G network to dynamically adapt to the changing scenario that this use case can provide. Moreover this paper presents an innovative 5G architecture for Earthquake Early Warning that uses SHM system to detect a seismic event and to propagate a message reporting the event detection to all the buildings that may be damaged by the event.**

***Index Terms*—5G, trial, testbed, IoT, structural health monitoring, uRLLC**

I. Introduction

The mobile access technology is going through a revolutionary change every ten years. Each generation of mobile technology has also provided significant performance enhancements but the success of the Fifth Generation (5G) mobile network is strictly dependent on the creation of a community able to design and develop applications that properly exploit the 5G network potential.

The International Telecommunication Union (ITU) has defined a formal name for 5G as International Mobile Telecommunications IMT-2020, and also defined three typical application scenarios for 5G: Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (uRLLC), and Massive Machine Type Communications (mMTC). eMBB aims at meeting the people's demand for an increasing digital lifestyle, and focuses on services that have high requirements for bandwidth, such as high definition (HD) videos, virtual reality (VR), and augmented reality (AR). uRLLC aims at meeting the expectations for the demanding digital industry and focuses on latency-sensitive services, such as assisted and automated driving, and remote management. mMTC aims at meeting the demands for a further developed digital society and focuses on services that include high requirements for connection density, such as smart city and smart agriculture.

The design of 5G air interface is targeted to have higher transmission rates, faster access, support of larger user density, and better user experience for enhanced eMBB services. Meanwhile, it connects to new vertical industries and new devices, creating new application scenarios such as mMTC and uRLLC services by supporting massive number of devices and enabling mission critical transmissions with ultra high reliability and ultra low latency requirement. [1]

This work deals with the design of a structural health monitoring through 5G Ultra Reliable Low Latency Communications using a full custom node developed in order to support an experimental project ongoing in L'Aquila, Italy [2] and designed to efficiently support long term inclinometer and crackmeter measurements, as well as the characterization of environmental conditions. The node is designed to be battery powered and to carry out a periodic monitoring over a term of two years. The article is structured as follows: Section II briefly summarizes general requirements for a structural health monitoring oriented wireless sensor network, illustrating some significant past case studies, Section III describes hardware and software architecture of the custom developed platform, Section IV presents the 5G architecture used for the validation of the proposed solution and some consideration regarding the capabilities of the 5G network regarding latency and reliability. Finally conclusions are drawn in Section V.

II. Wireless Structural Health Monitoring System

Structural Health Monitoring (SHM) 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 nondestructive evaluations to detect location and extent of damage, calculate the remaining life, and predict upcoming accidents.

Specifically, traditional systems are based on wired grids of sensors and have an high cost, considerable size and poor flexibility. Traditional solutions for structural monitoring of

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buildings are based on wired grids of sensors deployed along a structure. Coaxial cables are one of the most used medium for a reliable transfer of measured data from sensors to a central processing and storage unit; less diffused solutions are based on Ethernet LAN as data collection infrastructure. It has been shown [3] that a major fraction of overall cost of a traditional SHM system is primarily related to wiring costs.

In recent years, the gradual development of wireless sensor networks (WSNs) technology has represented a significant innovation opportunity in SHM field [3]. The use of WSN in structural health monitoring has various significant advantages; first of all, it allows to eliminate connection cables, significantly reducing total system costs. Moreover, wireless nodes have a reduced footprint and visual impact and can therefore be installed in buildings of historical or artistic relevance. Their high flexibility allows the installation in positions for which cable deployment would be complicated (a relevant problem for structures of large dimensions, such as monumental buildings). Furthermore, wireless sensor nodes microcontrollers can be programmed to constantly analyse sensors response and eventually trigger an alarm signals in case of sudden damage detected.

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 [4], while this requirement may result less compelling when monitored quantities are slowly variable (e.g. the case of crack growth monitoring). Indeed, it is possible to identify the following general requirements for a SHM oriented WSN: reliability, reconfigurability, energy efficiency. Reliability is a critical requirement in structural health monitoring application, as measured data are often related to building and people safety. Sensor nodes must be able to correctly report measured data, assuring a good communication quality of service. Energy efficiency is a primary importance requirement in assuring a good operating lifetime for a battery powered sensor node. An high energy efficiency is generally guaranteed by two different actions: design or selection of low power consumption devices (i.e. devices with low active state power consumption and efficient stand-by and sleep modes); adoption of operational strategies oriented to the maximization of low power mode operating time for various blocks (duty-cycling strategy). Other feasible strategies involve power gating (i.e. the use of electronic switches to temporarily disconnect unused hardware blocks), or the exclusion of voltage regulators (i.e. the use of a direct connection of hardware blocks to the battery supply). Silva et al. [5] presented an extensive analysis of the advantages and disadvantages associated with the use of these techniques. This paper aims at implementing a structural monitoring system for public/private buildings, civil infrastructures and also applicable to cultural and architectural heritage, based on solutions able to have full and immediate visibility of the most significant structural parameters that can notice any anomalies and critical issues even in emergency conditions, such as during a seismic event. The project consists in the permanent structural monitoring of buildings and is focused on the creation of a system of observation, based on minimally invasive technologies, sustainable and innovative, so as to provide information about the structural behavior under normal conditions and especially in the presence of seismic events. The large investment of public funds used in the reconstruction of the city of L'Aquila needs an intelligent observatory, able to investigate the effectiveness of the used technologies, especially in relation to their performance over time. The University of L'Aquila has successfully developed and designed a prototype of a system for structural monitoring of an XIII century church, "S. Maria di Collemaggio": a network of wireless sensors equipped with accelerometers, strain gauges and tilt meters has been implemented and actuated. The system has monitored the dynamic behavior of the church during numerous seismic events occurred after the main shock of April 2009 [6]. Today the structural monitoring system is under deployment on various buildings, trying to catch the structural heterogeneity of the urban scenario. This use case may be considered depending on the operational scenario: in the case of data collection and processing from sensors in monitored buildings, considering the high number of sensors installed, it can refer to the mMTC context. Viceversa, during a seismic event or just after it, the use case requires high reliability connectivity and, sometimes, low latency. These features refer to the URLL context. It seems interesting to evaluate and experiment the ability of 5G network to dynamically adapt to the changing scenario that this use case can provide.

III. Prototype Hardware

The use of dynamic measurements either during ambient vibration testing or through permanent structural health monitoring may play an important role in an densely populated area of strategic and monumental structures after the occurrence of a devasting earthquake, such as the case of L'Aquila [7]. In particular, a careful use of different output-only identification procedures may help in extracting the structural signature from low-cost and easy-to-deployed wireless networks of dynamic sensors. This valuable experimental information may significantly increase the general confidence in understanding the real dynamic behavior of the structures which suffered moderate or severe damage due to the seismic action.

In order to achieve adequate level of confidence on the structural dynamic behaviour of the studied buildings a schedule of consequent activities have to be performed: (i) on-site dynamic testing under environmental actions with standard equipments [8] [9] [10] [11]; (ii) finite element modelling based on exhaustive survey and material testing; (iii) definition of SHM-WSN sensor features; (iv) laboratory dynamic testing on test frame in order to validate procedures and wireless monitoring sensors; (v) deployment of structural health monitoring systems with wireless smart sensors; (vi) development and installation by remote programming of modal and damage identification procedures taking into account temperature variation effects.

This paper refers to the implementation of the WSN Structural Helath Monitoring in an URLLC network scenario.

Vibration-based SHM requires sensed data that well represent the physical response of the structure both in amplitude and phase. The measurements must have sample resolution to characterize the structural response and must be recorded with a consistent sample rate that is synchronized with other sensed data from the structure. Thus, the sensor hardware needs a sensor board with high resolution and accurate sampling rates so it has to be designed specifically for SHM applications.

The following types of sensors will be taken into consideration:

- Optic fibre sensors;
- MEMS (Micro Electro-Mechanical Systems);
- Piezoelectric sensors.

Among the smart sensors, fibre optic devices, and in particular those based on Fiber Bragg Grating [12], are successfully used in the monitoring of bridges and buildings of historical and artistic interest. Piezoelectric sensors have been used in various applications for the detection of damage on medium-sized bridges, using both impedance-based methods and acoustic emissions detection [13]. The evolution of MEMS sensors (both low cost commercial and high-performance ones) is extremely interesting. MEMS sensors, in particular accelerometers, have been successfully used for dynamic analysis based on WSNs.

Two hardware configurations of smart sensor nodes are required for the wireless communication and sensing: a gateway node for sending commands and receiving wireless data from the WSN, and the remote nodes. To increase the communication range, both types of nodes are equipped with an antenna which has a communication range of $30m$ and a SMA connector to install an external additional antenna. The gateway node will be connected to the network through a 5G URLLC in order to provide a low latency communication.

The SHM Board has been designed as a highly versatile and high performance structural monitoring board and it will be used as remote node. It consists of an ultra-low-power microcontroller of the STM32L4 family produced by ST Microelectronic, based on the ARM® Cortex®-M4 $80MHz$ core. This microcontroller has numerous communication and high-performance interfaces ($1MB$ Flash memory and $128KB$ of SRAM). The microcontroller, through its $12bit$ ADC, is connected to a MEMS accelerometer (Kionix KXRB5-2050) that is always active and acts as a sentinel in the event of accelerations detected above a certain threshold (this accelerometer is mounted directly on the board).

From the point of view of communications, the SHM board has an Ethernet interface (from which it can be powered via PoE), but also provides the ability to communicate wirelessly with other nodes of the monitoring network; the chosen frequency is $169MHz$ as it allows communication over long distances and is much less exposed to obstacle attenuation.

The Radio Frequency module (W-MBUS $169MHz$), can be used as:

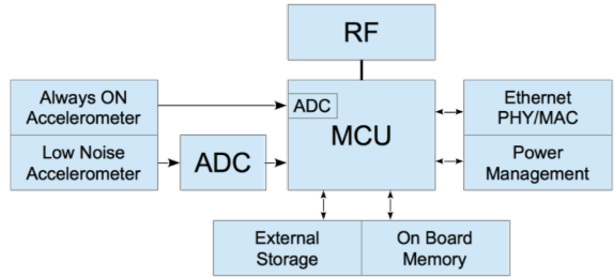

Figure 1. SHM Board Block Scheme

- stand-alone node (equipped with MEMS accelerometer and digital temperature, humidity and brightness sensor);
- MEMS;
- SHM Board's wireless communication module.

Finally, the SHM Board provides the possibility of acquiring signals from two other types of measuring instruments, i.e. inclinometers and strain gauges, which are widely used in the field of structural monitoring (especially after seismic events that cause serious damages to buildings).

Two types of accelerometers are used (i.e. dualaxial and triaxial); the nodes are equipped with a $24bit$ ADC guaranteeing a $100Hz$ sampling rate. Considering the worst-case (nodes with 3-axis accelerometers), the data generated per node will be: 3x24x100 = $7200b/s$ and therefore each node needs a band of about $1KB/s$.

IV. 5G Architecture for SHM & Earthquake Early Warning

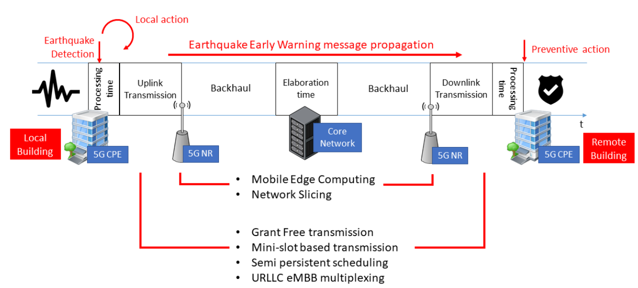

Figure 2. 5G Architecture

Earthquake Early Warning (EEW) in SHM systems represents a challenging application for 5G since it leverages the capability of 5G networks to offer guarantees of packet transmission within a certain latency.

The idea behind 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 buildings that are located in the neighbourhood that, if applied with an adequate timing, can increase citizens and facilities safety.

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 propagates with lower speed but, on the other hand, transfer a higher energy with respect to body ones and therefore are more dangerous. 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 $8m$ of the radius of the area reached by the earthquake. On the other hand, the reduction of $1ms$ of the EEW propagation time corresponds to an increase of $8m$ of the are where to implement safety actions.

The newly defined 5G NR standard targets transmission of relatively small payloads with very low latency ($\leq 1ms$) and high reliability (99.999%) [14], thus, it represents an effective supporting infrastructure for the proposed EEW system.

Fig. 2 shows the segments of the 5G network that the EEW message must traverse from the SHM node that detects the seismic event towards the remote building where to apply a preventive action. Differently from 4G LTE, 5G introduces several degrees of flexibility that can be leveraged to reduce the delay experienced in the EEW system.

Regarding the wireless segment, 5G NR specification introduces some techniques to support URLLC such as [15]

- **Grant Free transmission**: allows to the UEs to transmit without scheduling request;
- **Mini-slot based transmission**: reduces the time transmission interval duration;
- **Semi Persistent Scheduling**: reserves radio resources for URLLC transmission on a periodical base;
- **URLLC eMBB multiplexing**: allows to prioiritize the scheduling of URLLC data;

Parallelly to the enhancements in the radio segment, 5G leverages the novel paradigms of Software Defined Networking and Network Function Virtualization to introduce the possibility of dynamically adapting network resources according to services requirements in a *vertical* manner. On this hand, Network Slicing, i.e. the possibility to provision a virtual set of network resources supporting specific services KPIs represents an effective tool for the support of URLLC application. Furthermore, Mobile Edge Computing, provides the ability to dynamically deploy virtual computation elements at a variable distance from the end user, thus varying the experienced delay basing on targeted performance.

V. Considerations and Conclusions

In this paper some aspects related with structural health monitoring oriented wireless sensor networks has been reviewed. A practical design example has shown how the proposed system can be applied to a real monitoring problem. The EEW in SHM systems is presented in order to leverages the capability of 5G networks to offer guarantees of packet transmission within a certain latency. The idea behind EEW is to use the SHM system to detect a seismic event and to propagate a message reporting the event detection to all the buildings that may be damaged by the event and triggering preventive safety actions in the buildings that are located in the neighbourhood in order to increase citizens and facilities safety. Future developments will be oriented to further investigate the presented technique, implementing the transmissibility method in a real scenario and using a reliable analysis tool to verify its validity. The comparison of theoretical results and real world data-derived results will allow to properly validate the method here presented.

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