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Research Article

An Integrated Approach to the Design of Wireless Sensor Networks for Structural Health Monitoring

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Wireless Sensor Networks are a promising technology for the implementation of Structural Health Monitoring systems, since they allow to increase the diffusion of measurements in the structure and to reduce the sensor deployment effort and the overall costs. In this paper, possible benefits and critical issues related with the use of Wireless Sensor Networks for structural monitoring are analysed, specifically addressing network design strategies oriented to the damage detection problem. A global cost function is defined and used for the definition of possible design methodologies. Among the various approach, the use of an integrated strategy, able to take advantage of a preliminary structural analysis is considered. Moreover, the implementation of a distributed processing is an explored strategy for an overall improvement of system performances. Benefits of this methodology are finally demonstrated through the analysis of a representative case study, the IASC-ASCE benchmark problem.

1. Introduction

Traditional Structural Health Monitoring systems usually consisted in a grid of sensors deployed along a structure, each one communicating through a wired connection with a central processing unit. Data collected by the various sensors were stored in the central unit memory and then postprocessed in order to determine structure's condition and assess a safety level. Progressive developments in sensor integration technology (e.g., the development and spread of MEMS sensors), design of low power circuits, and wireless communications have gradually allowed a wide proliferation of efficient, compact, and cheap wireless devices. This process has encouraged the adoption of wireless sensor networks, which have gradually supplanted wired systems in various application fields [1]. Recently, the use of wireless sensor networks has shown its advantages also in the field of structural health monitoring. In fact, wireless systems are usually less expensive than their wired counterparts and their installation is much simpler (e.g., just think about all the difficulties related to the setup of a wired monitoring system in a monumental building). Nevertheless, there are many challenges related to the practical implementation of a Wireless Sensor Network for Structural Health Monitoring: wireless communication is often less reliable than the wired connection and allowed transmission distances are relatively short; on the other hand, monitored structures could be wide and present a large number of communication obstacles. Finally, sensor nodes are usually battery-powered, so there are very critical constraints in terms of energy availability. This may be particularly critical, because the effectiveness of the analysis is directly linked to the ability in performing measurements over a long period of time. The fundamental problem is then to determine appropriate strategies for network design, usually with the goal of energy consumption minimization. Moreover, there are other issues affecting network global performances and deeply related to the specific application, thus requesting a careful consideration in the design phase. Finally it is appropriate to wonder what are all possible benefits deriving from the availability of a very large number of spatially distributed, processing-capable nodes. Due to the potential enhancements obtained by the

use of Wireless Sensor Network in the development and spread of structural health monitoring systems, the presented work is focusing the attention on two main aspect:

(i) analysis of potential benefits arising from an integrated approach to the design of wireless sensor networks for structural health monitoring, for example, an approach exploiting all the knowledge arising from a preliminary analysis of the structure;

(ii) outlining of possible design strategies, with particular emphasis on the use of distributed processing techniques.

It will be shown how prior knowledge about structure's behaviour and expected structural response could be exploited in the design of a monitoring network. Moreover, the analysis will highlight how a distributed implementation of structural identification techniques could bring advantages in terms of network performances (e.g., by improving energy efficiency).

After a short review of the main concepts related to structural monitoring, the main advantages and disadvantages associated with the use of wireless sensor networks in Structural Health Monitoring will be detailed. Particular emphasis will be put in the analysis of possible processing techniques, specifically reviewing some of the attempts to define distributed processing schemes. An integrated approach to the design will be then analysed and motivated by the definition of a global network cost function and the definition of a possible integrated design strategy. Finally, the usefulness of this approach will be highlighted addressing a well-known case study, the IASC-ASCE benchmark problem.

2. Structural Health Monitoring

Structural Health Monitoring is defined as the process of implementing strategies for damage detection for the infrastructures of mechanical, civil, and aerospace engineering [2]. In this context, structural damage is defined as any general change in the geometry or in material's characteristics of the infrastructure under examination. The key feature of the monitoring action must be the characterization of the system in its normal service condition (i.e., without interrupting normal system's functionality), possibly over a long-time interval.

Restricting the field of observation, the attention is here focused on civil infrastructures monitoring (i.e., monitoring of standard and monumental buildings, bridges, lifelines, etc.). In their normal service condition, these structures will always be subject to environmental action (e.g., wind action) and to human-activity-related forces. As mentioned, monitoring process involves the observation of a structure over an extended period of time, periodically acquiring measures. Data processing allows the synthesis of structural indicators that are somehow representative of structural damage and the successive diagnostic judgement usually derives from a statistical analysis of the obtained parameters. It is usual to consider the following monitoring systems classification (Rytter [3]):

(i) level I system, that is, a system able to detect structural damage when it actually occurs;

(ii) level II system, that is, a system able to detect damage and locate its position within the structure;

(iii) level III system, that is, a system able to detect the damage and give an estimate of its location and intensity;

(iv) level IV system, that is, a system able to estimate the location and extent of the damage and to use this data to determine the state of the overall structure, and therefore its security level.

At the highest levels of Rytter scale corresponds a major detail in structure's condition assessment and, usually, an increase in processing complexity. Processing techniques should therefore be chosen according to the specific requirements of the particular application. In facts, the ultimate goal is not necessarily a complete characterization of the state of the structure and for certain applications a lower level of diagnosis detail may be sufficient. The level of detail required can also differ according to the possible changes in the operational scenario.

Anyhow, regardless of the specific objective of the monitoring action, we can say that the key point is to determine appropriate techniques to extract damage sensitive parameters from measured data. These damage indicators, or features, should

(i) significantly vary when there is evidence of structural damage for a level I system;

(ii) present a significant variation related to the location of the damage for a level II system;

(iii) depend on the extent of damage under a specific law for a level III system.

Finally, for a level IV system, it must exist an appropriate method of statistical analysis that allows the extraction from the assessed indicators of specific information concerning the building, its security level, and the uncertainty of these estimates.

We will now briefly review the main techniques for the determination of the features. As mentioned above, our analysis will focus on a clearly defined scope: building's characterization and monitoring. Furthermore we will consider principally the vibrational analysis approach. It is assumed that the sensors placed along the structure are accelerometers and the measured response is expressed exclusively in terms of acceleration.

2.1. The Traditional Approach: Modal Analysis. The traditional approach for structural health monitoring using measurements of structural response is based on modal identification techniques. The modal parameters, namely the natural frequencies, mode shapes, and damping ratios, are the damage-sensitive features.

Besides the wide use of this technique in the field of civil engineering, the main reason for its wide adoption lies basically in recent years spreading of the so-called output-only analysis. Traditionally, the modal identification requires the measurement of structural response (output) to a known and controlled system of forces (input). Consequently, it was necessary to use appropriate equipment capable of applying such forces on buildings. This approach had relevant implications in terms of system cost, footprint (given the large size of the equipment), and difficulty of running measurements over an extended period of time. Instead, in the case of output-only analysis, we usually try to determine the modal parameters analysing the response to environmental actions (such as wind or traffic), which remain unmeasured as they can be well approximated as white Gaussian noise. This procedure has two obvious advantages: there is no need to use any controlled solicitation equipment and it is possible to characterize the structure under its normal operating conditions (thus fully implementing the basic monitoring principle). For this reason, we often refer to this technique as "operational modal analysis."

Over the years, various techniques for modal structural identification have been developed and recently compared on experimental data [4]. These include

(i) time domain techniques, such as ITD (Ibrahim Time Domain [5]), ERA (Eigensystem Realization Algorithm [6]), Next (Natural Excitation Technique), and SSI (Stochastic Subspace Identification) [7];

(ii) frequency domain techniques, such as BSF (Basic Frequency Domain, also known as the Peak Picking [8]) and FDD (Frequency Domain Decomposition [9], subsequently improved as EFDD, Enhanced Frequency Domain Decomposition [10]);

(iii) time-frequency methods, such as those based on analysis of wavelet transforms [11], Cohen's class transforms [12], and recently EMD (Empirical Mode Decomposition) [13].

The use of modal parameters allows to extract information about structural damage, in different manner as

(i) by analysing changes of natural frequencies in order to detect the occurrence of damage [14];

(ii) by analysing changes in mode shapes in order to locate the position of the damage [15];

(iii) by evaluating changes in flexibility or stiffness or using statistical analysis techniques. Yan et al. [16] analysed all these various methods in details.

As mentioned (and illustrated in [16]) damage detection techniques based on modal parameters represent the "traditional" approach to the problem. This approach could appear convenient when a complete characterization of the structure is strictly required, but, in general, it may present some critical issues. For example, the modal-based identification procedures are almost never completely automatic and often not universal, but rather specifically related to the facility under examination. Moreover these techniques are not efficient in tracing the microdamages that could early occur in the process of damage. Finally, as clearly illustrated by Peeters and Roeck [17], modal parameters variations can be caused both by the presence of damage, whether as a result of changes in environmental conditions.

2.2. Innovative Approaches. The mentioned disadvantages are at the base of recent years increasing interest for all the possible damage detection techniques that are not based on modal analysis. Among the most common approaches can be cited the so called "modern approaches" [16]:

(i) wavelet analysis: it can be shown [18] that the spectrum obtained from wavelet is somewhat directly representative of damage. One of the major advantages of these techniques is that they allow the analysis of nonstationary signals;

(ii) the use of genetic algorithms: it has been demonstrated [19] that the use of genetic algorithms allows detection of structural damage;

(iii) the use of neural networks: this technique has been used several times in the literature, especially for the classification of other features extracted from measurements [20].

Transmissibility analysis [21] also appears particularly interesting, as it has been shown how the extracted feature can provide good results regardless of the type of applied loads.

Moreover, the transmissibility analysis [22–24] or wavelet analysis [25] can also be used for the determination of modal parameters. The adoption of direct feature extraction should not therefore be seen as a limitation, since the extracted parameters are not only indicative of structural damage, but can also enable the global characterization of the structure.

3. Wireless Sensor Networks for Structural Health Monitoring

As stated in Section 2, the primary aim of structural health monitoring is detection, location, and quantification of structural damage according to different strategies: from the analysis of modal parameters to the direct extraction of damage-related features. Wireless sensor networks [26] emerged as a suitable solution for the implementation of monitoring strategies [27]. In fact, the deployment of a wireless system is almost always easier than the installation of its wired counterpart, even in the case of buildings subject to operational constraints and limitations (i.e., buildings of historical or artistic relevance). The use of economic wireless sensors usually allows high-density coverage of a structure with relatively low costs [28]. In addition to the characterization of damage, the system could also be designed with additional goals: for instance the ability to collect a significant amount of data from a very high number of points could allow the development of efficient model updating strategies. Finally, local processing could allow the

introduction of early warning strategies (fundamental in the case of structure at risk of experiencing sudden severe stress, as in the case of earthquakes).

3.1. Network Basic Requirements. The design of a structural monitoring oriented wireless sensor network must necessarily start from the analysis of application requirements. One of the the main problems is that the various analysis techniques usually require the collection of a significant volume of data from sensor nodes, and these data have to be combined in order to extract significant synthetic parameters. This modality heavily impacts on node's energy consumption. Moreover, other analysis requirements can directly influence the design of the network.

In what follows, these problems will be clarified and the main problems in the design of a structural health motoring oriented wireless sensor network will be detailed.

3.1.1. Coverage Requirements. Sensor node's placement is one of the key points to consider in the design of a wireless network [29]. In fact, besides ensuring proper operation and full coverage of the area of interest, the optimal location may have a significant impact on power consumption, propagation delay, and data throughput.

Deployment critical issues clearly emerge where application's proper functioning is highly dependent on node's position. In these cases, application's constraints may be much more important than usual and must be necessarily satisfied. In the case of structural monitoring this problem appears evident: the location of a specific sensor node should be chosen according to the significance of the response at that particular point in relation to structural analysis objectives. Often in the design process, usual WSN metrics must be taken into account only as secondary specifications, with their satisfaction subordinated to analysis needs. So, the design of a structural monitoring oriented wireless sensor networks must firstly consider application's demands [30, 31]. For example, as proposed by Guratzsch [32], an optimized design of sensor nodes deployment could be the one that maximizes the probability of detecting damage. Starting from a finite element model of the structure, appropriate simulations of the possible damage patterns will then make it possible to map an optimal distribution of the nodes along the structure. When the final goal is structural identification, it is possible to adopt a similar criterion, selecting the points that provide the most significant measurements in relation to the parameters to be determined (e.g., mode shapes in the case of modal analysis).

There are several types of algorithms for automatic determination of the optimal nodes position in relation to damage sensitivity. For example, Udwadia and Garba [33] or Lim [34] presented algorithms for optimal placement in relation to the identification and control of the structure. Hiramoto et al. [35] proposed the use of Riccati equation for optimal positioning in relation to vibration control. Tongpadungrod et al. [36] have instead used the principal component analysis to determine performance indicators.

3.1.2. Network Connectivity. Deployment algorithms oriented to structural analysis and damage detection often provide solutions which are nonoptimized, or even not feasible with regard to communication. For example, especially in the case of large structures, there is no guarantee that the positions determined by the algorithms mentioned above will also ensure proper communication between nodes. Although some methods able to take into account both structural analysis and communication requirements have been explored, these approaches are often not feasible. Other strategies, like the use of redundant nodes, must be considered. For example, it is possible to include sensing nodes that are not strictly necessary for the analysis, but arranged in such positions as to ensure proper coverage of the structure. A similar strategy is rather one that involves the use of relay nodes. A technique for relay nodes optimal placement in a wireless sensor network has been presented by Lloyd and Xue [37]. Finally, it is important to consider the case of clustered networks applied to structural monitoring because the partition of the network may be conditioned by the specific application (e.g., a cluster can be associated with a sub-structure). Again the best strategy is to ensure first the satisfaction of application requirements (significant deployment and sectioning in relation to damage analysis and detection) and then optimize other metrics, for example, with an efficient cluster head design and their optimal placement along the structure.

3.1.3. Energy Consumption and Network Lifetime. The reduction of energy consumption is one critical aspect in the design of wireless sensor networks. The sensor nodes are usually battery powered and the amount of available energy is extremely limited. In contrast, wireless sensor networks are often dedicated to tasks such as monitoring of physical phenomena and therefore require a life time as long as possible (it is not uncommon to have to deal with applications that require an operating time of months or even years).

The wireless nodes need often to be installed in hostile or hard-to-reach environments. So, it is not possible to provide an ordinary maintenance operation for battery replacement. Attempts to recover energy through, for example, the use of solar cells have proven to be in general critical. Consequently, one of design's main goals must be energy consumption's minimization.

Each sensor node has different energy consumption characteristics, but, as outlined by Anastasi et al. [38], we can assume as true the following conditions.

(i) In their operative state, radio communication devices dissipate an amount of energy much higher with respect to processing devices. As shown by Pottie and Kaiser [39] transmitting one bit requires the same amount of energy needed to run hundreds of instructions. Consumption could be instead significantly lowered putting the radio device in a sleep state.

(ii) The impact of the sensing blocks on energy consumption varies according to the specific application and it must be managed differently in each particular case.

In the context of structural health monitoring the problem of limited available energy is critical for various reasons. For example, the amount of data to be transmitted can be significant, especially when the monitoring action has to be performed on long-time intervals; moreover, sensor nodes are often placed in not easily accessible locations, so a battery replacement results impractical and expensive.

For monitoring applications, the power consumptions optimization strategies can follow essentially two traditional approaches [38]:

(i) duty-cycling approaches where duty cycle is the time in which radio communication device is active. Since radio is responsible for major energy consumption, strategies to minimize the communication activity should be pursued, leaving the radio chip in the sleep state for most of the time. The strategies usually employed are two and complementary: the control of the topology, that is, the use of a limited number of nodes in a redundant topology and the power control used to obtain the state of sleep in the inactive nodes;

(ii) data-driven approaches that consists essentially in data-reduction techniques chosen according to the specific application. The basic principle is still taking advantage of the fact that a local data processing carried out by single nodes would result in low consumption than that required to transmit the same data. The used techniques are usually in-network processing, or a data aggregation performed before transmission, data compression, or the use of techniques of data prediction.

3.2. Additional Possible Requirements. There are also other requirements, mostly aimed at ensuring network robustness, or particularly critical only for specific applications; in what follows we briefly review some of them.

3.2.1. Synchronization Protocols. Different nodes may have different trigger moments and therefore, the initial timestamp of acquired data acquired can be different for different sensors. Moreover, all the possible errors due to different clock misalignment and drifts must be considered [40].

Synchronization may constitute a critical issue for some of the reviewed structural monitoring techniques, while it can be less critical for others. For example, it has been proven how a synchronization lack could compromise the correct estimate of mode shapes, while it is less critical for natural frequency and damping ratios determination [41].

The problem of synchronization between nodes in a wireless sensor network has been object of extensive research over the years and various synchronization techniques have been developed. Basically, the majority of techniques try to use communication between neighbouring nodes to align differences between local clocks. For example, RBS (Reference Broadcast Synchronization), FTSP (Flooding Time Synchronization Protocol) and TPSN (Timing-Sync Protocol for Sensor Networks) are widely used synchronization techniques. The latter has proved particularly suitable in the context of structural health monitoring [42].

3.2.2. Fault Tolerance and Robustness. Usually, structural monitoring networks should provide good fault tolerance, at least in relation to the following possible fault causes:

(i) running out of batteries, because the observation interval should be the longest possible;

(ii) possible sensing units malfunction: if data is not properly detected it is possible to obtain a false positive damage detection;

(iii) damage due to a violent stress, because events such as earthquakes are extremely significant in the life of a building, and it is therefore necessary to ensure proper functioning of the system so that we can study the behavior in those particular stress conditions.

Some of the classical strategies [43] to achieve good fault tolerance in wireless networks are not immediately applicable in the case of structural health monitoring: for example, a possible method of fault prevention is to design network topology in order to ensure maximum connectivity. As mentioned, however, in the monitoring networks, sensors location is generally conditioned by the constraints of application. In this case it is necessary to jointly consider application and fault tolerance requirements, or insert appropriate redundant nodes. Fault detection can help prevent possible false positives in damage detection applications. In this regard, Chan et al. [44] have detailed some preliminary studies on possible strategies to improve the reliability of a system for damage detection in relation to possible fault, putting in place appropriate detection strategies.

3.2.3. Real-Time Constraints. Actually, real-time processing is rarely considered as a requirement of current sensor networks for structural health monitoring, but is rather one of the most interesting research topics in this area. It bears mentioning it for two main reasons:

(i) it is an essential requirement in Early Warning oriented applications;

(ii) distributed processing architecture allows in some cases a local damage diagnosis. This fact, and the progressive advancements in processing hardware (e.g., the spread of application specific processor for wireless sensor networks) makes obtaining real-time damage detection a very next feature goal.

3.3. Distributed Architecture for Structural Health Monitoring. The problems highlighted clearly emphasize the need to determine an optimal strategy for the design of sensor networks oriented monitoring, that is, strategies able to take into account the principal highlighted issues. As mentioned, one of the problems lies in the conflicting demands between two aspects: analysis requirements and efficiency of the network. In facts, while a detailed analysis of the structure would require the collection of all data from various sensors, optimization of consumption would require to minimize the time intervals in which nodes operate and above all to minimize data communication.

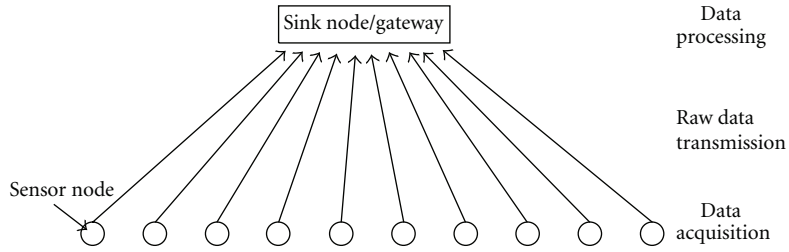

Figure 1: Traditional centralized architecture for data aggregation-based structural monitoring.

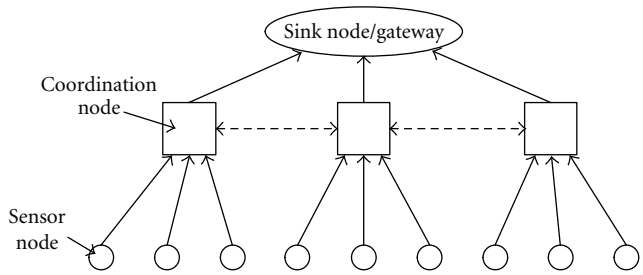

Figure 2: Distributed computing strategy for damage detection.

In recent years the attempt to overcome this problem has led to an increasing interest towards the use of distributed processing schemes. This approach can be critical for an efficient design, so it is appropriate to summarize the main available techniques.

Early structural health monitoring oriented wireless sensor networks suffered from this contradiction in a clear manner. In fact, the architectures used were centralized, with a single node to act as a sink for the various leaf nodes, instead devoted to the measurement of structural response in the significant points (Figure 1).

In this scenario, each sensor nodes must communicate with the sink, each time transferring the data acquired in a time window of interest. Since the size of the acquired data can be very large, this architecture is highly inefficient in terms of consumption, since it requires a massive use of radio communication unit. This architecture appears biased towards the needs of the application and takes little account instead of the optimization of communications. This is reflected in many of the first implementations in the context of wireless structural health monitoring and is basically tied to the fact that wireless systems were used as a simple cable replacement.

The need for a change in paradigm has emerged quickly, leading to a rethinking of the architecture used. As we saw in Section 2, the basic objective of monitoring is to characterize the structural damage, or more generally the state of the structure. It is therefore natural to consider the possibility of implementing an in-network processing or distributed processing within the network. For example, we might look for a convenient way to ensure that the single node may arrive to an estimate of the modal parameters before the transmission phase, thus processing only local acquired data. This approach, which basically responds to the data-driven philosophy, appears efficient provided that

$$E_{\text{raw}}^{p} + E_{\text{info}}^{\text{tx}} \leq E_{\text{raw}}^{\text{tx}}, \tag{1}$$

where E_{raw}^{p} it is the energy needed for raw data processing, $E_{\text{info}}^{\text{tx}}$ it is the energy needed for local processing of raw data and $E_{\text{info}}^{\text{tx}}$ it is the energy needed for the transmission of processed data. As mentioned, this condition can be assumed as true for common off-the-shelf sensor nodes. Network optimization could then pass via a review of the techniques mentioned in Section 2 in optic of a distributed processing across the network.

One of the first significant contributions in this direction is the one presented by Gao et al. with the introduction of Distributed Computing Strategy [45]. Assuming that the damage is inherently a local phenomenon and given the high density of sensors required to detect the damage, they have proposed to overcome the problem of low efficiency of centralized architectures by introducing the clustered architecture as shown in Figure 2.

The analytical method used is one of those classified as "traditional": a combination of distributed modal analysis (performed using the NExT/ERA techniques) and use of the flexibility matrix to estimate the damage. The obtained results have already shown the potentiality of the distributed approach.

In the context of modal analysis it is interesting to examine the strategy of distributed computing developed by Zimmerman et al. [46] (Figure 3). The technique of analysis considered in that case was the simple peak picking: assuming that the structure is excited by a white Gaussian noise, the Fourier transform of the single node measured response corresponds to the frequency response of the structure for that node. Since response's peaks are located in correspondence to the natural frequencies, local analysis of the calculated spectral profile can lead to a fairly accurate estimate of natural frequencies themselves. This estimate can be improved by analysing the global information obtained by all the nodes.

The technique is simple but it indeed allows the determination of natural frequencies and can also be used for damage detection. In fact, as mentioned in Section 2, changes in natural frequencies may indicate the occurrence of structural damage.

The same article also illustrates a distributed version of the Frequency Domain Decomposition. In that case it

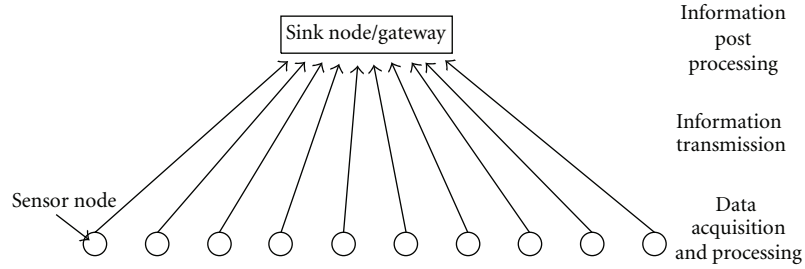

Figure 3: Decentralized architecture for peak picking-based modal analysis.

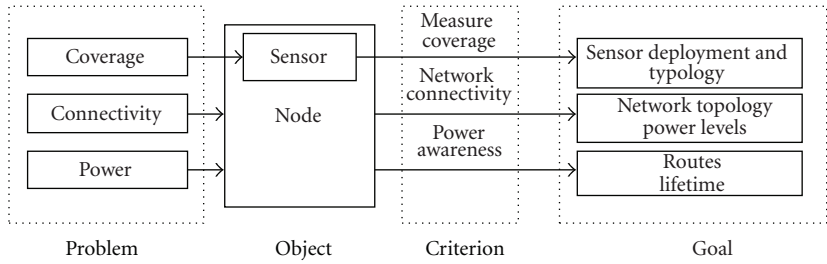

Figure 4: Different approaches in the design of a Wireless Sensor Network.

was shown that by using the measured data from a pair of sensors, it is possible to obtain an accurate estimate of the mode shapes. This approach, based on the calculation of "local" mode shapes, has been further developed by Sim [47] introducing the concept of overlapping clusters of sensors for the determination of the local mode shapes using the NExT/ERA technique (the method is still valid with techniques such as Frequency Domain Decomposition and Stochastic Subspace Identification).

This technique, however, do not reduce the amount of data to be transmitted, which may even increase compared to the previous case. Zimmermann and Lynch [48] have introduced a market-based approach to network topology formation. The goal was basically overcoming the previous case problems and obtaining of a more flexible system.

Modal analysis has however other several disadvantages, starting from the difficulties associated with full automation. It may therefore be convenient to use "modern" techniques, not based on modal analysis. For example, Gun et al. [49] presented a distributed approach for damage detection based on wavelet analysis. Worden et al. [50] have presented a technique based on the use of the transmissibility for the detection of structural damage in plate structures. Toivola and Hollménn [51], have instead presented a statistical technique for the selection of features. Canales et al. [52] have proposed an approach based on local transmissibility analysis for the detection of the damage.

The latter case is of particular interest because the analysis technique is local and each sensor node can independently analyse the result and make local decisions about the level of danger. In a distributed scenario, each node may be suitably programmed to behave differently depending on of the different position or react differently to an event.

4. An Integrated Approach to the Design of a Wireless Sensor Network for Structural Health Monitoring

The results obtained from the preliminary study of a structure and the eventually realized model can be exploited in the design of a wireless sensor network for structural health monitoring. This section will detail and justify this "integrated" approach.

The problem of wireless sensor networks design has been addressed in several studies. Depending on the problem's formulation, three different approaches can be distinguished.

Coverage Problem. The main goal is to determine sensor deployment location, given some coverage quality constraint.

Connectivity Problem. The main goal is to determine a network topology and node's transmission power level, given some network connectivity constraint.

Power Awareness Problem. The main goal is usually to determine transmission routes, given some network lifetime constraint.

In general, design choices will usually arise from compromises between these various needs; for example, as already mentioned, network lifetime depends on the energy stored in node's batteries. The reduction of transmission power level can certainly increase lifetime, but at the cost of a lesser connectivity.

Coverage, connectivity, and lifetime are the main problems to be addressed in the design of a sensor network (Figure 4). A good coverage requires a suitable number of

sensors, sufficient to detect the response of a given set of targets. A good connectivity requires that each nodes must be able to communicate with its nearest sink node, given a certain transmission power level. Network lifetime should be the maximum possible, given node's power consumption and transmission power.

It should be noted that there are several possible definitions for the lifetime of a network. For example, a feasible indicator is the total number of operations that the network is able to complete since at least one node stops to operate. Alternatively, it is possible to consider the relationship between node's total amount of available energy and its average energy consumption per time unit.

Furthermore, since radio transmission predominantly affects node's power consumption, an alternative indicator is the volume of data that the node can transmit before battery exhaustion.

A good coverage is essential for a Structural Health Monitoring Sensor Network: the main goal of monitoring action is in fact to measure a sufficient pool of information, in order to capture the structural signature.

It will be also important to ensure a good network lifetime: as pointed out, sensor nodes could be often installed in remote places, so replacing batteries would be a difficult and expensive task.

Other possible requirements, like fault tolerance and measurement synchronization, are here considered as second-order specifications.

It could be useful to evaluate the quality of a wireless sensor network oriented to structural health monitoring defining the following cost function:

$$C = C_{\text{cov}} + C_{\text{con}} + C_{\text{lt}}, \tag{2}$$

with C_{cov} *coverage cost*, C_{con} *connectivity cost*, and C_{lt} *lifetime cost*.

Both coverage cost and connectivity cost depend on the number of nodes of the network: the first by the number of sensor nodes N_s, and the second by the total number of nodes N (supposing the presence of N_r relay nodes, it will be $N = N_s + N_r$). Sink nodes are excluded from the calculation, mainly because they usually have not stringent constraints in terms of power consumption.

Regarding the coverage problem, the sensor deployment can be driven by an expert interpretation of the dominant behaviour characterizing the structural response, often supported by numerical simulations. In particular, useful suggestions about the number, type, and placement of sensors can follow from geometric, static, and dynamic analysis, with major attention to assess a minimal sufficient number of sensors, still able to extract the information of interest. For structural health monitoring purposes, key considerations are specifically oriented to limit the points to be monitored. They regard, for instance

(i) the nature and position of the external constraints, connecting some structural elements to the ground, which may completely or partially fix the degrees of freedom of the constrained nodes;

(ii) the stiffness distribution, which may suggest reasonable assumption about the extension and bending flexibility of mono- and bidimensional elements;

(iii) the mass distribution, which may enable an efficient reduction in the number of dynamically active degrees of freedom, based on the dominant inertial forces.

On the other hand, different considerations tend to augment the measurement points, in order to capture critical aspects of the structural response, worth to be monitored. Preliminary linear and nonlinear analyses may reveal

(i) the presence of internal resonances between the natural frequencies, which may activate relevant phenomena of energy transfer between the resonant modes;

(ii) the presence of nodes (fixed points) in the shape of the dominant natural modes;

(iii) the localization and hybridization of modes, which may concentrate high dynamic accelerations and stresses in one or more structural regions;

(iv) the development of high-amplitude oscillations in slender elements.

A general point to be considered is that a meaningful representation of the structural response is composed of both global (e.g., the natural frequencies) and local information (e.g., the components of natural modes). Global information is naturally redundant, since it can be usually extracted by several sensors. Local information may require instead a certain amount of redundancy to compensate the eventual failure of single node. Therefore, it is always convenient to plan a small increment of sensors with respect to the minimal sufficient set. In principle, these additional sensors should be considered separately in terms of costs, since, being redundant, they can be required to satisfy reduced performance levels.

The coverage cost C_{cov} can be expressed as follows:

$$C_{\text{cov}} = \gamma_n \sum_{i=1}^{N_n} c_{ni} + \gamma_m \sum_{i=1}^{N_m} c_{mi}, \tag{3}$$

where N_n is the minimum and sufficient number of sensor nodes needed for the specific structural analysis and N_m is the number of redundant sensor nodes needed to obtain a good coverage robustness (clearly, $N_s = N_n + N_m$). Two cost indicators, c_{ni} and c_{mi}, represent the cost per sensor node, respectively, for core sensor nodes and redundant sensor nodes. This indicators depend on sensor node typology and performances (and therefore also with the economic cost), as well as the installation costs. Finally, the γ coefficients, here and in the following, represent weighting factors ($\gamma \preceq 1$).

Network connectivity will depend on two main aspects:

(i) the ability of each node to communicate with at least its nearest sink node: this ability depends on network architecture, routing strategy, and transmission power levels;

(ii) the possibility of satisfying connectivity requirements including a certain number of relay nodes.

A virtuous integration among the needs of the structural health monitoring process and the improvement of the wireless network performance can be based on the actual possibility to harmonize the hierarchical network organization with the hierarchical structural scheme of the monitored object. In this respect, a smart cluster design strategy of the network nodes can be based on the recognition of different substructures, characterized by a limited number of significant degrees of freedom. Typical exampling cases are represented by clusters of all the nodes placed on structural element groups affected by internal rigidity constrains (as the horizontal planes of pseudo three-dimensional frame models in concrete structures, or the macroelements in three-dimensional models of masonry structures).

The connectivity cost function c_{con} can be expressed in the following way:

$$c_{\text{con}} = \gamma_c \sum_{i=1}^{N_c} c_{ci} + \gamma_r \sum_{i=1}^{N_r} c_{ri}. \tag{4}$$

In the previous relation N_c represents the total number of links, while c_{ci} is the architectural cost (i.e., the cost related to the existence of a connection between two nodes, given a certain power transmission). As outlined, this cost strongly depends on chosen network topologies and routing strategies. Without loss of generality, this cost can be modelled as an increasing function of the distance between two sensor nodes d_i:

$$c_{ci} = \alpha_{ci} d_i^{\beta}. \tag{5}$$

The fixed β coefficient models possible radio channel attenuation factor. The global cost is an increasing function of the number of links: this is strictly true for traditional networks, not for innovative approaches based on the use of network coding techniques [53]. If architectural solutions do not allow the desired network connectivity a choice could be to increase transmission power level, for example, for the problematic (isolated) nodes. In general, this is not a particularly good choice, since it greatly impacts power consumption. As mentioned, an alternative is instead the insertion of N_r relay nodes, each at the cost of c_{ri}.

Network lifetime, as mentioned earlier, is primarily related to node's energy consumption. A feasible indicator is the following:

$$c_{\text{lt}} = \gamma_0 \sum_{i=1}^{N_n+N_m} c_{0i} + \gamma_v \sum_{i=1}^{N_n+N_m+N_r} c_{vi}. \tag{6}$$

The relation takes into account two main factors:

(i) the fixed cost c_{0i} related to acquisition and data processing. If nodes can be put in a sleep state, it is possible to consider the following formulation:

$$c_{0i} = c_{0i}^{\text{run}} + c_{0i}^{\text{sleep}} \tag{7}$$

with $c_{0i}^{\text{sleep}} \ll c_{0i}^{\text{run}}$.

(ii) a cost related to the volume of data to be transmitted:

$$c_{vi} = \alpha_i^{\text{meas}} \alpha_i^{\text{proc}} c_{ui}, \tag{8}$$

where c_{vi} represents the transmission cost per data volume unit. As mentioned, energy consumption is an increasing function of transmitted data volume. One possible choice in order to increase network lifetime could be the adequate selection of measured data. For example, a sampling frequency reduction or the selection of only one axis of a 3D accelerometer can reduce the total amount of data. The α_i^{meas} factor represents this reduction. Similarly, the α_i^{proc} factor represents the possible dimension reduction resulting from a distributed processing.

Data volume, and thus the c_{ui} cost, can be directly related to the distance d_i: in fact, considering, for example, the *first-order radio model*:

$$\begin{aligned} R_i &= \epsilon_{\text{elec}} v, \\ T_i &= \epsilon_{\text{elec}} v + \epsilon_{\text{amp}} d_i^2 v, \end{aligned} \tag{9}$$

where R_i and T_i are, respectively, transmission and receive power, while d_i is still the distance between two generic sensor nodes and v_i the volume of data to be transmitted. The factors ϵ_{elec} and ϵ_{amp} are, respectively, the energy needed for transmission or reception of a single bit and the energy consumption per transmitted bit of transmission amplifier.

Analogously to the connectivity-related cost c_{ci}, even this cost depends on link's distance, but while the former indicator defines the cost related to a certain level of connectivity (e.g., a certain network topology), the second defines the cost related to information transfer on the available network.

The definition of the C cost function allows to outline a possible design strategy specifically calibrated on the requirements of a structural health monitoring application. As outlined, the three components of the defined global cost are not independent. The weighting factors can thus be chosen so as to give an importance to one of the specific aspects, in fact orienting the design action. As mentioned, coverage is the most important requirement in the design of a structural health monitoring system. So, a possible strategy consists in assigning to γ_n the maximum value and than proceeds with the following steps:

(1) definition of the minimum number of sensor and their positions along the structure by means of a preliminary structural analysis and modelling action;

(2) definition of the number of redundant sensor N_m, starting again from structural considerations;

(3) definition of the network architecture and routing strategy, given a certain transmission power level and coverage requirements;

(4) connectivity verification and possible insertion of relay nodes;

(5) data selection and processing distribution in order to satisfy network lifetime requirements.

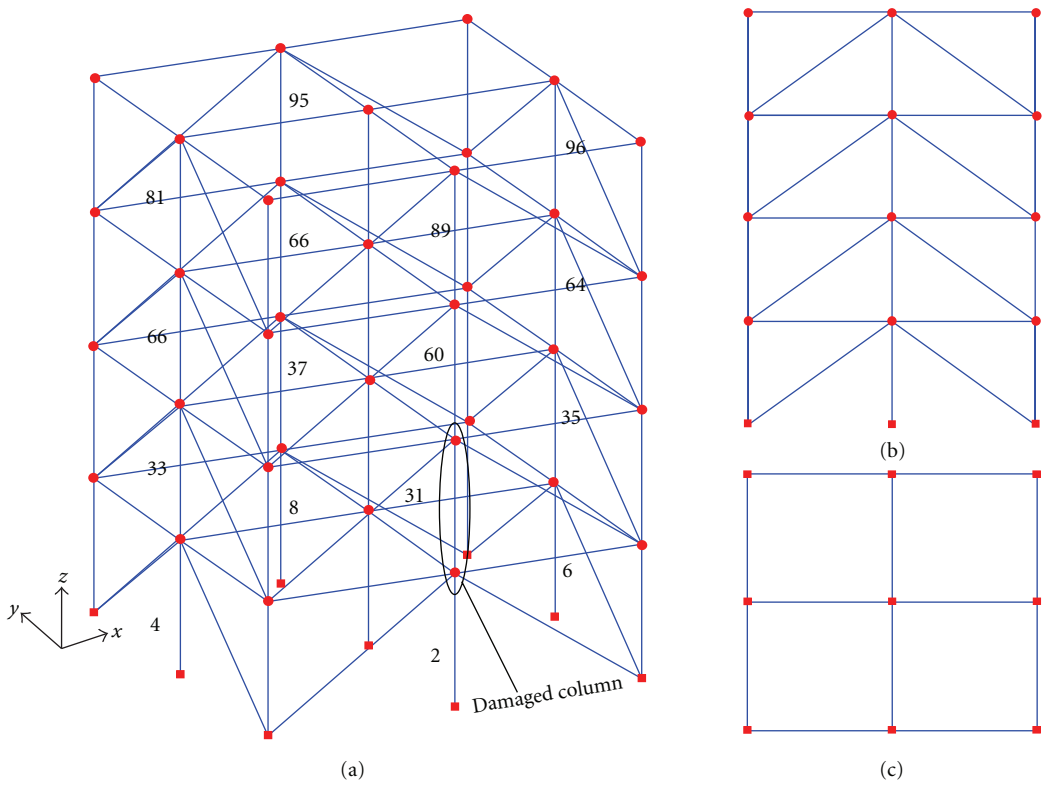

Figure 5: IASC-ASCE benchmark structure model.

As already mentioned, network lifetime is influenced not only by the amount of transmitted data but also by the transmitting power. For this reason, if the lifetime requirement is not satisfied by means of step 5, it will be necessary to reconsider the architectural choices. One possible strategy is the reduction of transmission power level, possibly adding additional relays to maintain connectivity.

To conclude, it must be remarked that the proposed strategy allows a certain flexibility, since it can be adapted to satisfy different purposes of the monitoring process, as well as to exalt the network potential. In fact, the design problem solution can be uniquely determined at different steps. In general, structural considerations (steps 1, 2) may leave the sensor deployment open to alternative solutions, different in their individual topology, but substantially equivalent in terms of measure coverage. Therefore, the connectivity and/or power awareness requirements (steps 4, 5) become determinant as discriminating criteria. This common situation is highly stressed in advanced networks, equipped with distributed processing capacities, oriented to peculiar structural purposes within the structural health monitoring field (experimental modal analysis, damage identification, model updating, and early warning). In this case, a proper tuning of the cost weights may transfer the strategy focus from the information measure (dominant coverage problem) to the information processing (dominant power problem). The exampling case study presented in the following section illustrates how the power cost ends up to discriminate between two network topologies with similar coverage costs, when a three-dimensional frame structure is monitored for damage identification purposes.

5. Integrated Design Example for a 3D Frame Structure

The *IASC-ASCE* benchmark problem is here used to demonstrate the main features of the proposed methodology in a well-known case study.

The problem, formulated in 1999 under the umbrella of IASC (*International Association for Structural Control*) and ASCE (*American Society of Civil Engineering*) deals with a four-story, two-bay by two-bay steel frame (see Figure 5).

The numerical model, here used for demonstration purposes, has been constructed through the Finite Element Method (FEM) using 132 beam elements. Classical assumptions, such as the rigid m-plane behaviour of each floor is used to derive a reduced-order model, following a methodology clearly explained in [4, 54].

In the benchmark problem, displacements along the x-y axes as well as rotations with respect to the vertical axis in each floor were constrained to be dependent on the central mode. Rotations with respect to the x and y axes were allowed at all nodes. Consequently, the application of the reduction procedure gives the equation:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{M}\mathbf{R}\ddot{\mathbf{u}}_g, \tag{10}$$

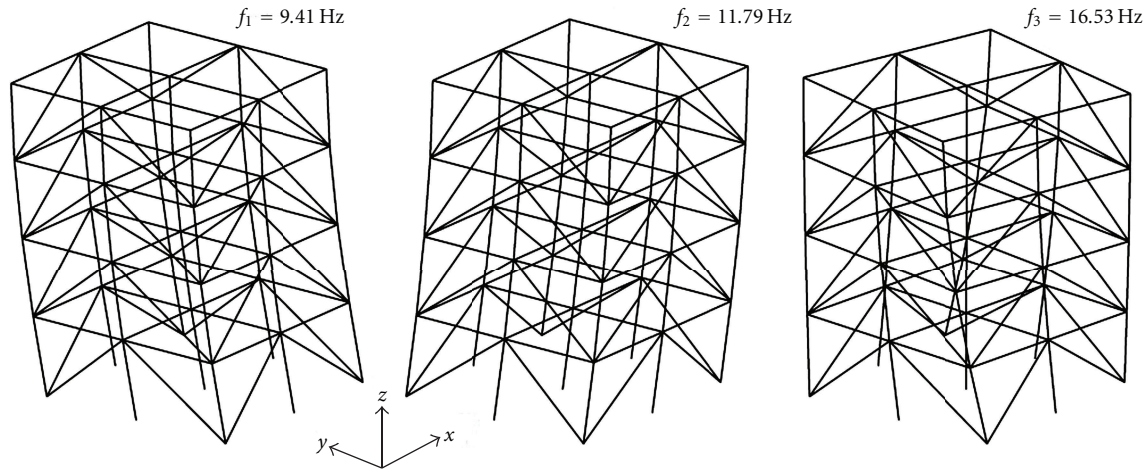

Figure 6: First 3 mode shapes of the frame structure.

where **u** is the displacement vector describing the active 88 DOFs and **M** and **K** are the mass and stiffness matrices; **R** is the rigid matrix which allows to simulate the ambient disturbance responses as generated by the $\ddot{\mathbf{u}}_g$ ground motion acceleration vector containing the two horizontal components in the x and y directions as well as a rotation with respect to the z axis. Finally, the damping matrix **C** is obtained such that a damping ratio of 1% is introduced in the six lowest modes, while the three excitation components are three bandwidth limited, statistically independent, and normally distributed random inputs. Figure 6 shows the first 3 mode shapes of the frame structure.

The simulation of the structural response consists of 6 min inputs from which data are obtained at a frequency of 200 Hz. A damage pattern can be also simulated as stiffness reduction of a given element.

The plain design strategy for the wireless network tends to realize the necessary and sufficient coverage, maintaining a minimal measurement redundancy. According to the same structural considerations which justify the pseudo three-dimensional model of the frame, three independent components of motion (plus 1 redundant, dependent on the others) should be measured for each floor plane ($N_n = 12$, $N_m = 4$, considering monodimensional accelerometers for simplicity). It can be supposed that connectivity reasons, related to the transmitter features, the frame dimensions and the environmental conditions, require the addiction of one relay node for each floor ($N_r = 4$). The consequent topology of the network is referred to as WSN_1 in the following and is illustrated in Figure 7(a).

Each floor is equipped with three mono-dimensional sensors (or equivalently a three-dimensional sensor with triple cost) in the central node, and two eccentric nodes (the redundant sensor and the redundant relay, with reduced functions and reduced cost). Since this topology is able to wholly characterize the global structural response of the frame, it is expected that the WSN_1 may well-perform for most of the structural monitoring purposes. For instance, all the modal components would be captured during experimental modal analyses, typically finalized to modal identification or model updating.

Nonetheless, the benchmark problem refers to a particular structural monitoring purpose, relying on the damage identification in columns. Moreover, an advanced wireless network might feature a distributed processing potential to be exploited. The key question to be addressed is whether and how the proposed design strategy can evaluate the cost-based convenience of a different network topology, taking into account the possibilities of the process distribution to smart nodes.

To give general consistency on the network design, a reasonable assumption is that an efficient damage identification technique can be based on the comparison between the experimental response measured at the column upper and lower node (u_i and u_j, resp.). These considerations allow to detail most of the processing costs in the WSN_1. Aiming to distribute the processing effort, two smart central nodes P_i (measuring x_i, y_i, θ_i) and P_j (measuring x_j, y_j, θ_j), placed in the ith and jth adjacent floors, respectively, are requested to locally perform the following information processing:

(i) P_i: reconstruct, the experimental response u_i from x_i, y_i, θ_i (operation O_i),

(ii) P_j: reconstruct, the experimental response u_j from x_j, y_j, θ_j (operation O_j),

(iii) P_i or P_j: compare the experimental response u_i and u_j (operation O_{ij}), that is, each pair of smart nodes is charged of three local processing operations for each column. Assigning conventionally the elementary costs to the related power expense (see Table 1), and following the algebra of the previous section, the final cost of the WSN_1 can be evaluated as $C_{\text{WSN}_1} = 5800$). It is worth noting that this evaluation follows from a conventional assignment of the individual cost weights, explicitly oriented to reward the minimal sufficient network topology, characterized by a small number of sensors (high γ_n values).

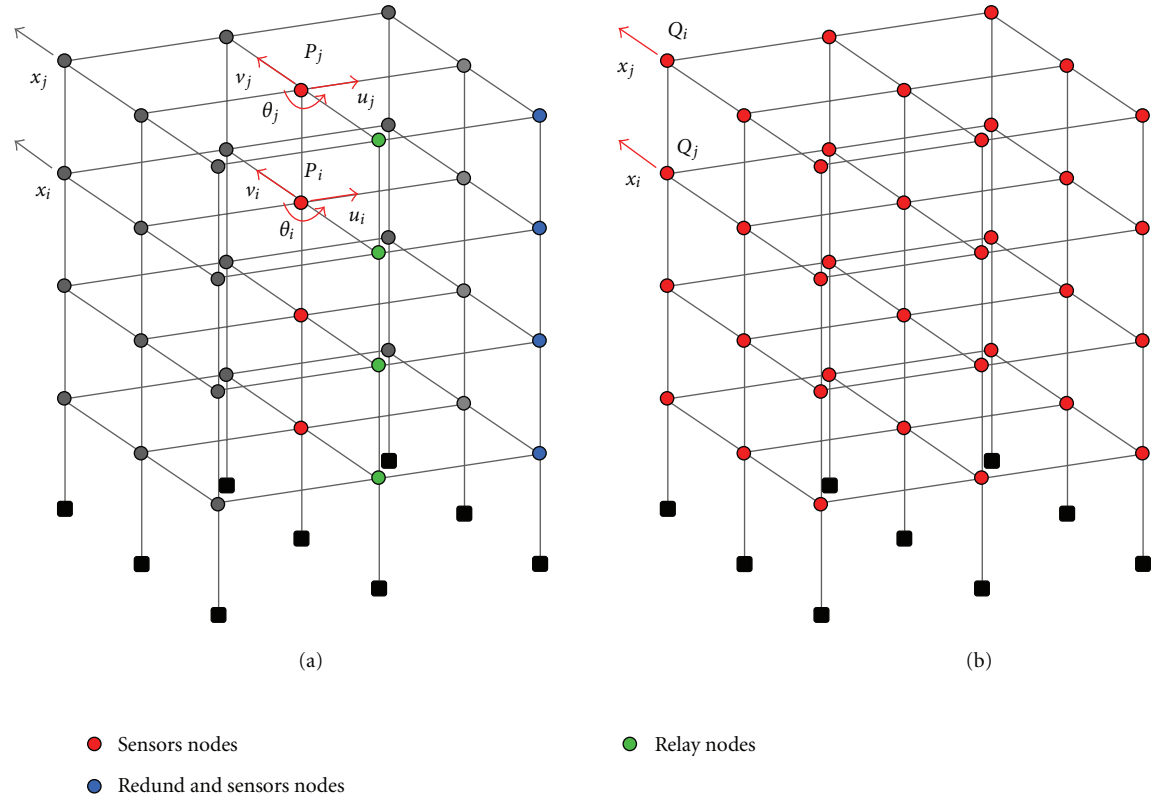

Figure 7: Wireless Sensor Networks for column damage identification in the IASC-ASCE benchmark frame: (a) WSN_1, (b) WSN_2.

Table 1: Values of the weighting factors, unitary costs, and coefficients in the cost function.

WSN_1			WSN_2		
Weighting factors	Unitary costs	Coefficients	Weighting factors	Unitary costs	Coefficients
$\gamma_n = 1.0$	$c_{ni} = 100$	—	$\gamma_n = 0.5$	$c_{ni} = 100$	—
$\gamma_m = 1.0$	$c_{mi} = 100$	—	$\gamma_m = 0.5$	$c_{mi} = 100$	—
$\gamma_c = 0.7$	$c_{ci} = 40$	$\alpha_{ci} = 1.0$	$\gamma_c = 0.6$	$c_{ci} = 40$	$\alpha_{ci} = 1.0$
$\gamma_r = 0.7$	$c_{ri} = 70$	—	$\gamma_r = 0.7$	$c_{ri} = 70$	—
$\gamma_0 = 0.5$	$c_{0i} = 60$	—	$\gamma_0 = 0.5$	$c_{0i} = 60$	—
$\gamma_v = 0.9$	$c_{ui} = 80$	$\alpha_i^{\text{meas}}\alpha_i^{\text{proc}} = 1.0$	$\gamma_v = 0.9$	$c_{ui} = 80$	$\alpha_i^{\text{meas}}\alpha_i^{\text{proc}} = 1/3$

Combining both structural considerations and damage identification purposes, a second network WSN_2 can be considered (Figure 7(b)), adopting a diffuse node deployment, finalized to have a sensor in each beam-column joint ($N_n = 36$). Due to the high sensor density, additional sensors or relay nodes are supposed unnecessary ($N_n = N_r = 0$). Under the previous hypotheses about the processing distribution on smart nodes, each couple of eccentric nodes Q_i (measuring u_i) and Q_j (measuring u_j), is requested to locally perform a single information processing:

(i) Q_i or Q_j: compares the experimental response u_i and u_j (operation O_{ij})

that is, each pair of smart nodes is charged of one local processing operation only. The sensor deployment and link scheme need to be accompanied by a proper routing strategy, which is supposed to support this particular behaviour. As before, the final cost of the WSN_2 can be evaluated. With respect to WSN_1, the WSN_2 definitely consists of a larger number of nodes, each one performing a lower number of operations. The consequent major difference in terms of cost is not a significant reduction of the data volumes to be transmitted (which reduces of only one fourth), but the actual possibility of a more efficient routing strategy in the transmission. To quantify this advantage, an $\alpha_i^{\text{meas}}\alpha_i^{\text{proc}}$ coefficient less than unit has to be applied, inversely proportional to the square of the data volume per single transmission.

Therefore, it is easy to verify that WSN_2 is a better solution (i.e., is less expensive than WSN_1)

(i) if the designer can somehow reduce the individual node cost, or equivalently wants to strongly penalize the minimal network topology (low γ_n values);

(ii) if the designer must consider high processing costs, large amount of data volumes, or equivalently wants to award an efficient processing distribution (high γ_v values).

In the particular case study, according to first approach, the WSN_2 has been adopted for the damage identification purposes, as it becomes less expensive than the WSN_1 ($C_{WSN_2} = 3384$) when the sensor cost weight is reduced to one half.

To illustrate the WSN_2 effectiveness with respect to a particular damage identification procedure a possible response-based implementation is proposed. Given the sensors s_i and s_j, the transmissibility is defined as

$$T_{ij}(f) = \frac{u_i(f)}{u_j(f)}, \tag{11}$$

where u_i, u_j are Fourier transform of the displacement response at i and j nodes under the ground motion input due to ambient disturbances. Transmissibility magnitude among the selected nodes can be approximated by the following relation:

$$\left|T_{ij}(f)\right| = \sqrt{\frac{G_{ii}(f)}{G_{jj}(f)}}, \tag{12}$$

where G_{ii} and G_{jj} are the estimated power spectral density of the structural responses measured at nodes i and j. In the possible implementations, an estimate of power spectral density can be pursued using Welch's method [55], which is basically an improved version of the periodogram-based power spectral density estimation. In Welch's method, measured signal is divided in overlapping segments and each segment is then windowed. The average of the periodogram calculated from each segment is a good estimate of the needed power spectral density. The use of Welch's method can significantly reduce the contribution of noise and is therefore widely used in embedded applications.

Supposing that the goal is to detect columns damages, an intuitive choice may be to consider, for all the frame storeys, the transmissibility calculated between pairs of sensors positioned at both ends of each frontage middle columns. As reported, all the columns of the structure are oriented to have higher bending flexibility in the x direction. Without introducing normalization, we can then assume frontages as single reference substructures (i.e., single scenarios for parameter comparison and classification).

Assuming that the structure is not initially damaged, the previous algorithm would lead to the calculation of baseline transmissibility. Damage detection should intuitively be based on the analysis of variations with respect to the baseline. In the successive measurement cycles a node will have then to calculate an updated transmissibility, searching for evident variations.

The ASCE tool is here used for the generation of a $T = 800$ s sequence of acceleration at all the $N = 16$ sensor nodes deployed along the structure. Obtained structural data, we used the Welch method to estimate the power spectral density of each response, using $N_w = 8$ segment and an Hamming window. We assumed the direct ratio between the power spectral density at two nodes as estimate of the relative trasmissibility.

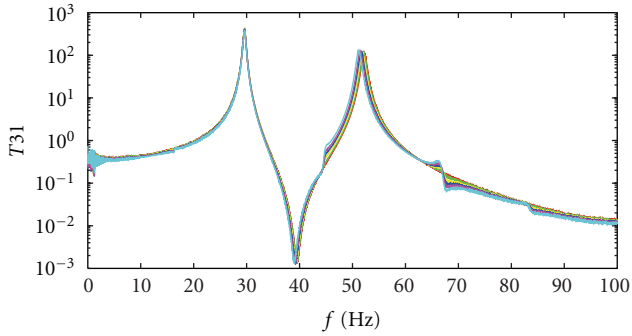

Figure 8: Transmissibility evaluated on column 31 for different damage intensity.

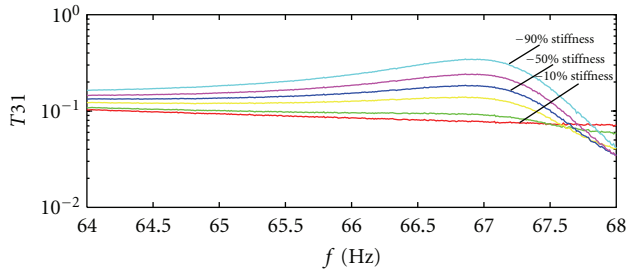

Figure 9: Detail of transmissibility T31 for different damage intensity.

Figures 8 and 9 show the variations of the transmissibility calculated at different frequencies between nodes at the ends of element 31 in which the damage is concentrated and simulated as a loss of element's stiffness. The different transmissibility functions are drawn for different damage intensity, with the decrease in stiffness varying from 10% to 90% of the normal conditions.

The effects of damage on the transmissibility among other nodes have been investigated and as example the functions related to columns 37 and 60 are reported in Figures 10 and 11.

The use of local information through the evaluation of the transmissibility functions can be demonstrated still efficient with respect to a more global analysis if an efficient damage indicator is introduced. This indicator could in fact become a synthetic damage-sensitive feature. There are various ways to extract a synthetic feature. For example Johnson and Adams [56] used the following indicator:

$$\mathrm{DI} = \frac{\left|\sum_f 1 - \left(T_{ij}^u(f)/T_{ij}^d(f)\right)\right|}{n}. \tag{13}$$

Table 2: DI versus EDI for $x - z$ response at various columns.

Stiffness Reduction	Columns						Columns					
	31	37	60	66	89	95	31	37	60	66	89	95
10%	0.011	0.013	0.012	0.009	0.003	0.008	5.633	5.744	5.160	5.382	5.192	4.922
30%	0.044	0.054	0.051	0.024	0.001	0.041	7.331	7.415	6.591	6.949	6.446	6.111
50%	0.075	0.092	0.087	0.029	0.008	0.076	7.895	7.919	7.167	7.603	6.906	6.543
70%	0.112	0.142	0.128	0.030	0.025	0.123	8.263	8.191	7.603	8.106	7.199	6.840
90%	0.182	0.236	0.196	0.026	0.065	0.212	8.425	8.311	8.060	8.659	7.431	7.081
Index	DI						EDI					

Table 3: DI versus EDI for $y - z$ response at various columns.

Stiffness Reduction	Columns						Columns					
	35	33	64	62	93	91	35	33	64	62	93	91
10%	0.691	0.066	0.028	0.001	0.006	0.003	4.792	4.696	4.018	4.368	3.997	4.125
30%	0.204	0.142	0.455	0.055	0.024	0.006	6.236	6.017	4.898	5.507	4.901	5.124
50%	0.232	0.129	5.810	0.116	0.042	0.005	6.901	6.601	5.254	6.017	5.272	5.564
70%	0.253	0.104	0.269	0.186	0.063	0.001	7.443	7.054	5.516	6.442	5.568	5.934
90%	0.271	0.074	0.066	0.292	0.097	0.013	8.073	7.556	5.809	6.927	5.921	6.365
Index	DI						EDI					

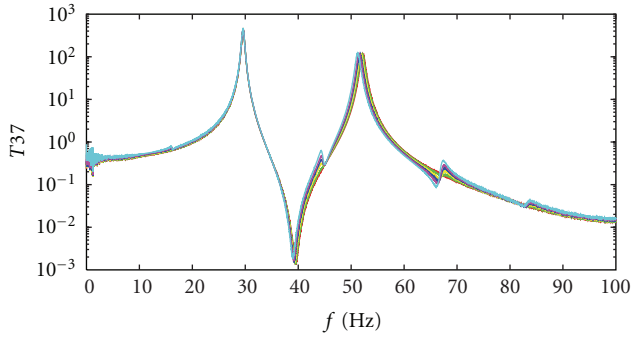

Figure 10: Transmissibility evaluated on column 37 for different damage intensity.

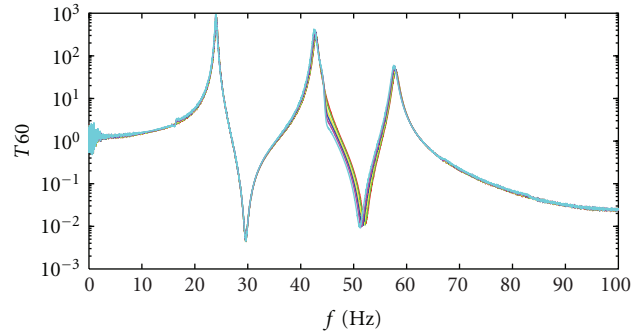

Figure 11: Transmissibility evaluated on column 60 for different damage intensity.

Here, a possible improvement of the technique is proposed introducing the damage feature index DF as

$$\mathrm{DF}(f) = \left| \log\left(1 - \frac{T_{ij}^{u}(f)}{T_{ij}^{d}(f)}\right)\right|. \tag{14}$$

Then, the enhanced damage index (EDI)

$$\mathrm{EDI} = \frac{10}{\frac{1}{n}\sum_{f} \mathrm{DF}(f)} \tag{15}$$

is proposed as a synthetic indicator, easily implementable in wireless sensor networks.

In Tables 2 and 3 we have reported all the values assumed by the EDI indicator, evaluated for all the selected node couples, when a damage is introduced again on the element 31 and progressively increased (T_i indicates transmissibility for column i). As mentioned, it is convenient to separately evaluate different sides.

It should be noted that the EDI indicator is effectively sensitive to damage, provided that we consider different columns characteristics. In fact, considering the single frontages, we have a significant variation of the indicator when damage is introduced. Moreover, the highest value is relative to sensor couple positioned at the extremities of the damaged element, for all the examined cases and the indicator value increases with the the damage intensity augmentation.

We have obtained similar results applying damages in other positions, concluding that in the analysis of singular frontages the proposed procedure can effectively locally diagnose the occurrence of a damage.

6. Conclusion and Future Developments

In this paper many of the critical aspects related with structural health monitoring oriented wireless sensor networks design have been reviewed. The analyses have allowed the definition of a cost function useful for the assessment of a deterministic criterion to compare different network solutions.

The cost function can be adapted to alternately reward or penalize the network coverage, connectivity, and power expense, depending either on expert designer choices or particular project constrains. According to cost-saving purposes, it has been evidenced how an original, dedicated algorithm for the network design can actually take advantage of a number of preliminary structural characterizations of the object to be monitored, implementing a socalled integrated design strategy. It has been shown how an integrated design could be able to simultaneously satisfy different target balances among application, communication, and energy requirements and could represent an interesting starting point towards an overall efficiency and sustainability improvement.

A practical design example has shown how the proposed design methodology can be applied to a real monitoring problem. A damage detection strategy has been outlined and successfully applied to the exampling case of a benchmark frame structure, introducing among other things a novel damage indicator, the enhanced damage index. It has been shown how this indicator can be useful in columns damage detection.

Future developments will be oriented to further investigate the presented technique, implementing the transmissibility method in a real scenario and using a reliable statistical 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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