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D 1.4.2: CONCEPTUAL FRAMEWORK FOR APPLICATION OF DIGITAL MONITORING SYSTEM

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1. Intro

The main goal of the deliverable D1.4.2 is to present a conceptual framework for implementing a digital monitoring systems for bridges in Central Europe.

This deliverable is an output of the Activity 1.4 of the BIM4CE project, that aims to derive a meta study and a conceptual framework to approach innovative methods that will be applied in digital monitoring systems for BHM (Bridge Health Monitoring) purposes.

2. Long term digital bridge monitoring system

One of the main goals of the BIM4CE project is to design a long-term digital monitoring system for bridges in Central Europe. The long-term phase of the BHM system aims at assessing the loss of capacity of the bridge over time, as a consequence of the normal degradation of the structures. The purpose of the long-term monitoring is to guarantee serviceability, safety, sustainability of the bridge, and low operational cost.

The development of modern information and communication system, signal processing technology, Internet, and structural analysis significantly advances the application and improvement of the BHM systems. Despite these advancements, there still exist big challenges, which need to be addressed in the future, such as the improvement of the accuracy of a sensory system, high-frequency and accurate data sampling and synchronisation, data mining and knowledge discovery, diagnostic methods, the analysis and modeling of the Big Data for decision making on maintenance and management.

From a logical standpoint the BHM framework is composed of fundamental building blocks (or subsystems) reported in Figure 1.

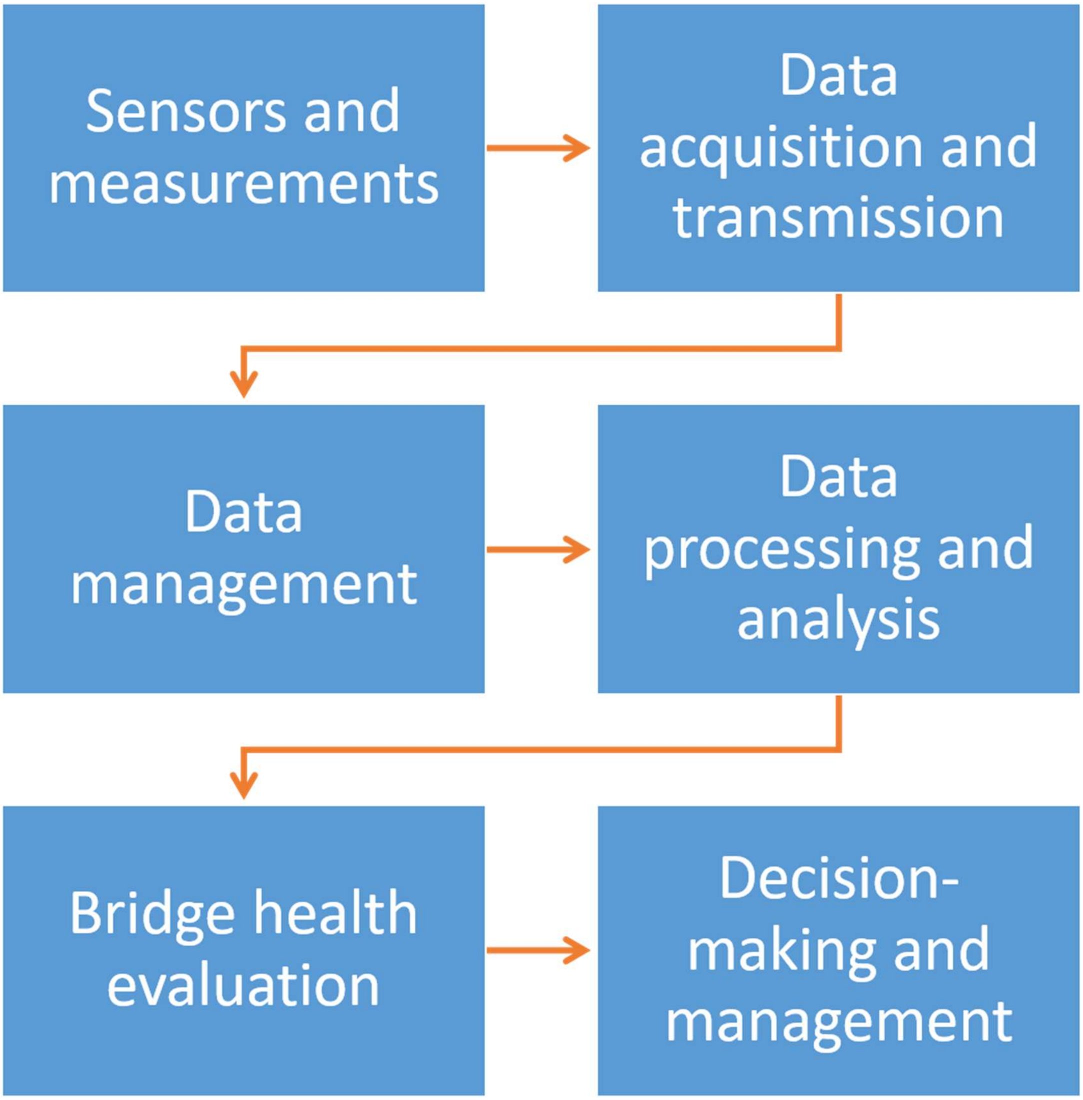


Figure 1: Subsytems of BHM framework.

The function of each subsystem can be summarized as follows:

- **Sensors and measurements**: utilized for sensing the information of the working environment of a bridge and various factors that affect the safety of the bridge, such as wind speed and wind direction, environmental temperature and humidity, traffic loads, vibrations, displacements, strains, etc;
- **Data acquisition and transmission**: the information acquired by sensors is sampled and transmitted;
- **Data management**: receives and stores the observed data;
- **Data processing and analysis**: used to process and analyze the obtained data to make them available in an optimized way for further elaboration;
- **Bridge Health evaluation**: includes algorithms and methodologies for evaluation and assess the condition of the bridge;
- **Decision**-making and analysis: utilized by bridge managers to make decisions about the target bridge, such as maintenance, repair, strengthening or reconstruction.

A SHM framework including the aforementioned subsystem is envisaged to:

1. obtain numerous field data that can be utilized for leading-edge research;
2. provide real-time information for safety assessment;
3. provide information for prioritizing bridge maintenance and repair;
4. detect anomalies in loading, response, deterioration and damage to ensure structural operation safety;
5. validate design assumptions and parameters that allow for improved design specifications and guidelines.

3. The conceptual framework architecture

The architecture of the conceptual framework can be represented with an IoT (Internet of Things) scheme composed of three main layers:

- Sensing layer: utilized to acquire measurements for sensing the information of the working environment of a bridge and various factors that affect the safety of the bridge;
- Communication layer: includes the communication and data protocols used to transmit the data sampled by sensors to the service data center:
- Application Layer: the layer where data are collected, stored, and analysed.

The architecture of the IoT system defining the conceptual framework of the bridge monitoring system is shown in Figure (sensing layer) and Figure 3 (communication and application layers).

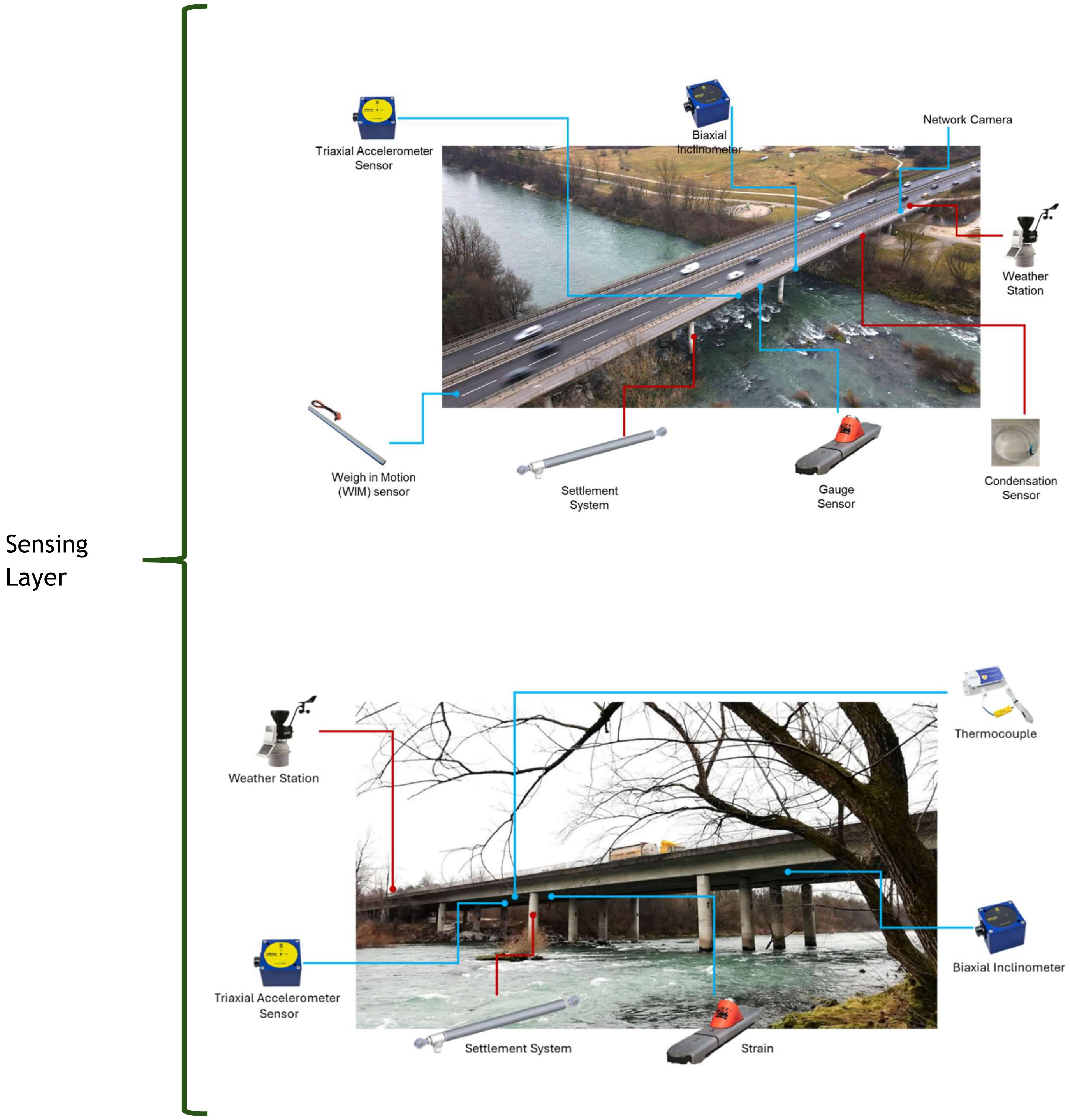


Figure 2: Sensing layer of the conceptual framework architecture.

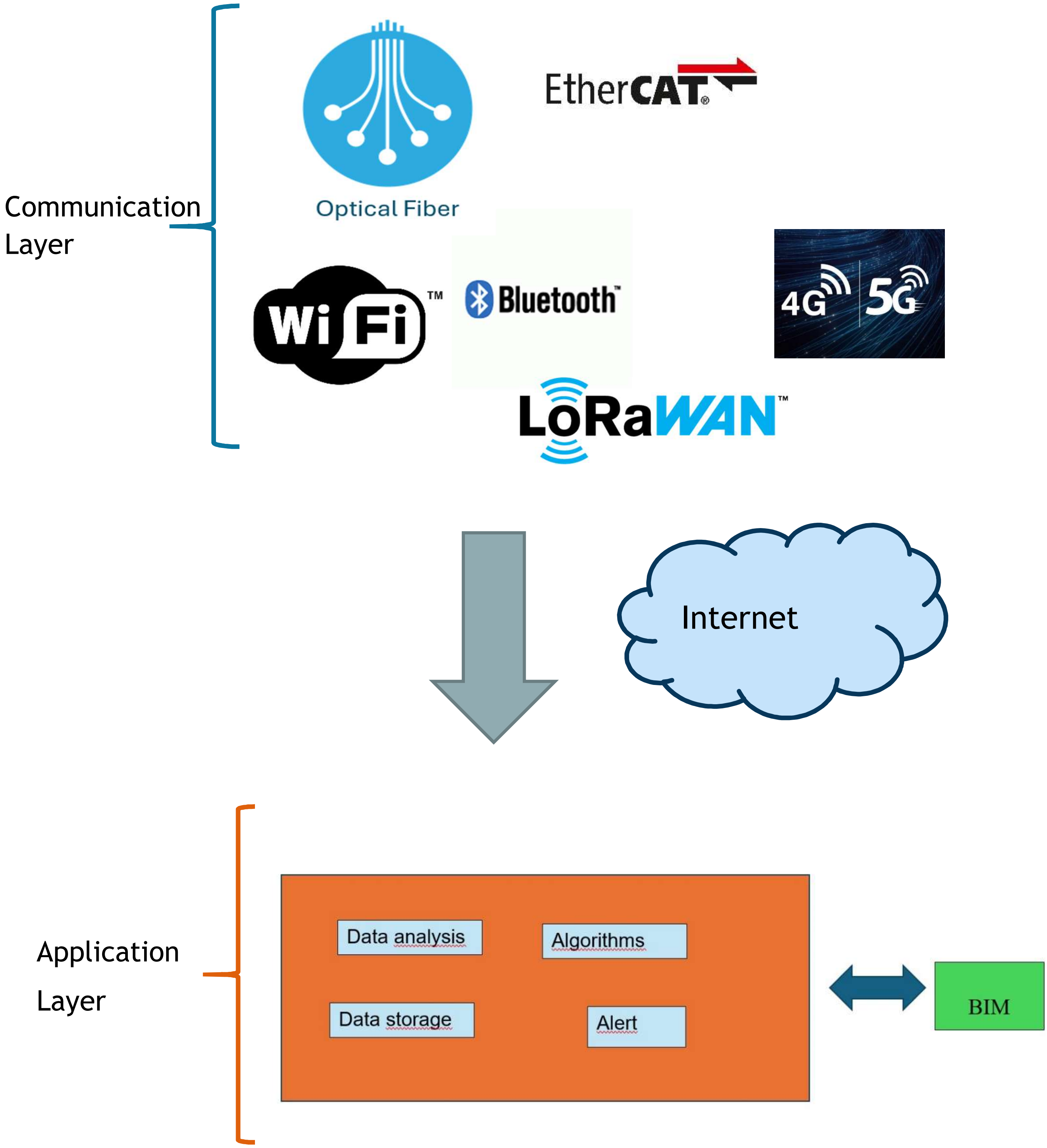


Figure 3: Communication and application layers of the conceptual framework architecture.

4. The sensing layer

The sensing layer is the section of the IoT framework that is responsible for the acquisition of measurements by sensors. The interfaces with the communication layer includes technological solutions of various types as will be illustrated in depth in the following section 5 dedicated to it.

As defined in the final output of Deliverable 1.3.1 [1], the choice of pilot sites is based on the desirable characteristics reported in the following table:

Item	Description
Bridge types	Slab bridges
	Girder bridges
Material	Reinforced/Prestressed Concrete
Span length	Between 6 m and 40 m
Deck thickness	Up to 80 cm (slab bridges)
	Up to 250 cm (beam/deck combination)
Number of lanes	Up to four
Other parameters	No skew Smooth approach Road surface in a good condition

Table 1: Desirable characteristics of bridges for demonstration purposes

For this reason, the Slovenian Tomacevo Bridge has been selected for showing the sensing layer of the conceptual framework architecture in Figure . The position of the sensors along the bridge is shown considering the same Tomacevo bridge from the observation points: from the high and from the side.

4.1. Sensor nodes

The main elements of the sensing layer are the sensor nodes. Each sensor node consists of transceiver, power supply, processor, memory and sensors. The overall architecture of a sensor node is shown in Figure .

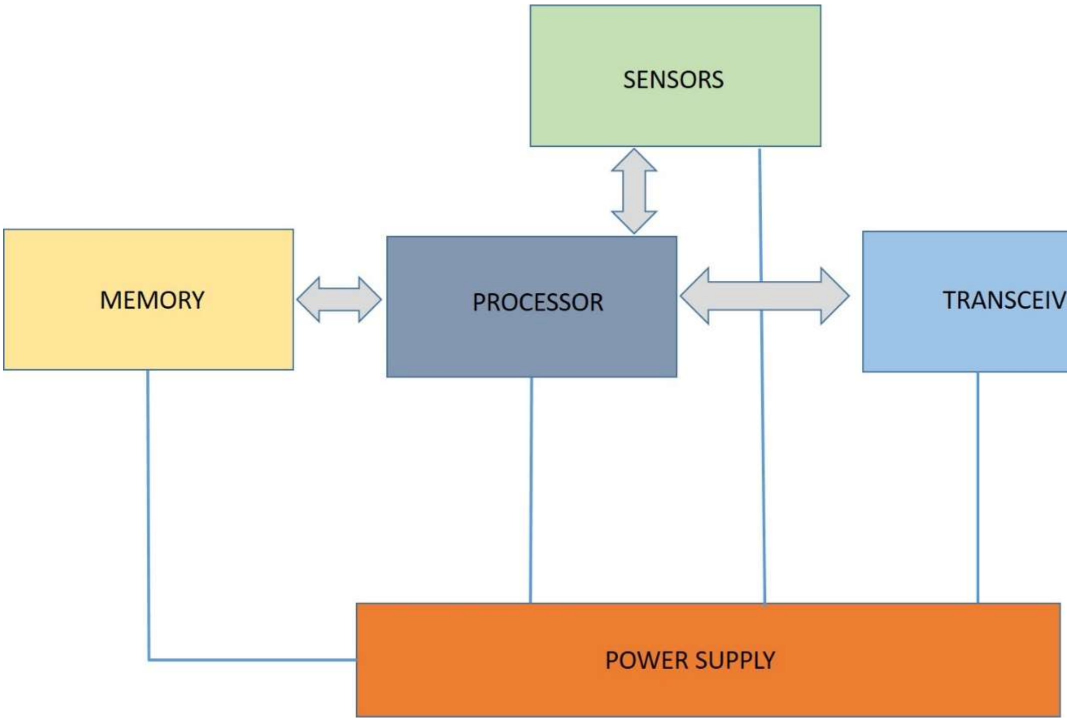


Figure 4: Schematic diagram of sensor node

In more detail, the elements constituting a sensor node are:

- **Power Supply**: The power supply unit of the sensor node is responsible for providing power to all other components in the sensor node. It could be rechargeable with renewable sources (i.e. solar energy) and consist of batteries or it need electrical power supply from the power network.
- **Processor**: is the CPU of the sensor node. It is an embedded system, usually a microcontroller.
- **Sensors**: they sense the surrounding environment and inform the controller about the phenomenon being observed. These sensors can be divided into active and passive sensors. Sensors measure the physical quantity, convert it to digital data, and give it to the controller.
- **Transceiver**: transmit and receive data to and from the communicating media. It can be wired or wireless, as we will see in Chapter Five.
- **Memory**: Sensor nodes will have programmable Flash memory and RAM in most cases.

In a sensor node, the energy requested to the power supply system mainly depends on the consumption of the active sensors and the transceiver. Over the last few years, there has also been a tendency to increase the intelligence on board the sensor node (intelligence on-the-edge); this is a further factor to take into consideration when sizing the power supply system.

4.2. Sensors

The main sensors shown in the sensing layer scheme of the conceptual framework (Figure) are defined in Deliverable 1.2.1 [2] of the BIM4CE project. The diagram is showing the position of sensor installation.

The table below summarizes the types of sensors based on the type of bridge monitoring, the position, and recommendations:

Dynamic monitoring		
Sensor Type	**Position**	**Recommendations**
Triaxial accelerometer on slab	Girder/Slab	Min. 2 per span (left & right side); best 6 per span (if higher mode shapes are of interest)
Triaxial accelerometer on pier or abutment	Pier/Abutment	1 per element - best at the top
Strain sensor	Beam/Deck	Place at location of higher strains (generally at midspan); in girder-type bridges min one per girder; in slab-type bridges min 3 per span
Weigh-in-motion sensors	Beam/Deck	2 axle-detection sensors and 1 weighing sensor per traffic lane; more weighing sensors if transverse distribution of loads is significant
Static monitoring		
Sensor type	**Position**	
Biaxial inclinometer on deck	Beam/Deck	Place near supports: in girder-type bridges min 2 per girder; in slab-type bridges min 6 per span
Biaxial inclinometer on pier or abutment	Pier/Abutment	1 per element - best at the top
Longitudinal displacement sensor	Support/Restraint device	At expansion joints (min. 1), at bearings (min.1)
Transverse displacement sensor	Support/Restraint device	Min 1 per abutment/ pier cap
Strain sensor	Beam/Deck	Place at location of higher strains (generally at midspan); in girder-type bridges min one per girder; in slab-type bridges min 3 per span
Environmental monitoring		
Sensor type	**Position**	
Printable flexible temperature sensor	Beam/Deck/Pier	Min. 1 sensor in shaded position; recommendations for printable sensors will be elaborated within the project.
Condensation sensor	Beam/Deck	Min. 1 per traffic lane at location of larger sags (midspan); place additional at vulnerable zones and/or near prestressed tendons
Weather station	Deck top surface/Top of abutment	One for the whole bridge
Printable moisture sensors under the moisture insulation layer	Deck, under the moisture insulation layer	Strips of sensors near locations of drainage devices; recommendations will be elaborated within the project.
Printable pressure sensor based on piezoelectric effect or capacitive measurement	Deck, in pavement	Transverse strip of sensors crossing all lanes at two longitudinal positions; recommendations will be elaborated within the project.

Table 2: Sensors summary based on the type of bridge monitoring

4.3. Network cameras

As discussed in previous sections, sensors are fundamental for the structural monitoring of the bridge. However, in the conceptual framework, it is important to consider the use of network cameras for traffic monitoring. This is due to the fact the estimation of vehicle loads is a rising research hotspot in bridge structure health monitoring and computer vision-based approaches, coupled with Weigh-in-Motion (WIM) sensors measuremnts, are promising ways for vehicle tracking on bridges. The main goals of the use of IP cameras in the bridge monitoring context are:

- identify heavy vehicles, if complemented with WIM;
- have real-time awareness of the temporal-spacial occupation of vehicles along the bridge
- identify correlations between traffic conditions detected through computer vision and data detected by sensors

The computer vision-based vehicle detection approaches could obtain the temporal–spatial distribution of vehicle loads in the field of a single camera which covers a limited portion of the whole bridge. When the visual fields of multiple cameras are not continuous, the shapes of the same vehicle in video frames of different cameras will be quite different, and it is very important to apply the re-identification technique of vehicles and avoid having an overlapped visual filed.

Historically, IP cameras were used to stream video in real-time to a service center where the processing took place. This required high bandwidth availability in the telecommunications networks on which these videos travel. However, in recent years, thanks to the availability of embedded boards with high computing power, the trend has been to move the algorithms and intelligence on board IP cameras (on-the-edge). This allows us to send only the processing results that require lower bandwidth occupation and can also travel on IoT wireless networks, which will be described in the section dedicated to the communication layer of the framework.

Such cameras for traffic monitoring are not able to measure the actual weight of the vehicles. Therefore, an important application in the bridge monitoring system is to analyze the correlation between cameras monitoring and WIM sensors, enabling the possibility of measuring the dynamic weight of passing by units.

Finally, it is important to remember that the use of network cameras usually requires the availability of an electrical power supply system at their installation points.

5. The communication layer

The communication layer is the part of the framework that deals with protocols and technologies used to transmit the measurements acquired by sensors to a central server. For that, a wired connection or a wireless connection can be used. The choice of the communication depends on certain aspects:

- The availability of a wired connection along the bridge;
- The availability of power supply along the bridge;
- The simplicity of connecting new sensors with wired systems;
- The needs in terms of bandwidth and data rate for the sensor nodes.

If there is availability of wired communication technologies along the bridge, these ones must be favoured in the choice, on condition that the sensors to be installed can be easily connected with them.

Wireless networks are to be favoured if the bridge does not have telecommunication infrastructure.

In both types of connection must be guaranteed that the central server can be reached via the Internet network, i.e. via what from a telecommunications point of view is defined as TCP/IP protocol suite.

5.1. Wired networks

The most diffused wired infrastructures are the optical fiber networks (more simply optical networks) and EtherCAT communication protocols. In the next two paragraphs they will be analysed both.

5.1.1. Optical network

An optical network is a type of data communication network equipped which uses optical fiber cables as the primary communication medium for converting and passing data as light pulses between sender and receiver nodes.

Optical networks have three important elements: capacity, range and speed. The optical network is one of the fastest communication networks.

Unlike copper based networks, the light pulses of an optical network may be transported quite a distance until the pulses are regenerated through an optical repeater device. After a signal is delivered to a destination network, it is converted into an electrical signal through an optical receiver device and sent to a recipient node.

Moreover, an optical network is less affected to external inference and attenuation and can achieve substantially higher bandwidth speeds than copper networks.

An optical network is basically composed of the following elements, as depicted in Figure 5:

- Stations: Stations in an optical network serve as the source and destination of the information being transmitted and received. Stations are those devices that are used by the users of the network. For example, a computer or any sensing device in a bridge monitoring system.
- Trunk: A trunk is a transmission line i.e., an optical fiber cable in order to transmit the optical signal. A network is composed of one or multiple trunks for signal transmission over large distances.

- Node: Node acts as a hub for multiple transmission lines inside the network.

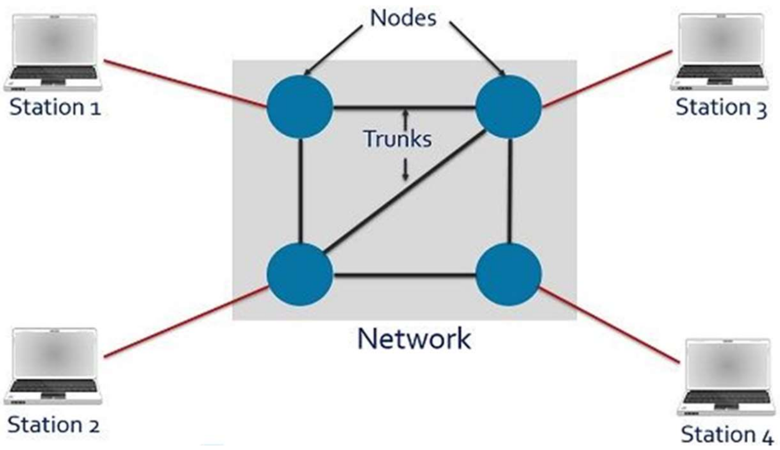


Figure 5: Elements of an optical network

When multiple fiber cables are employed in an optical network, then these are connected through nodes. However, the way in which the multiple nodes are connected together denotes the topology of the network.

The following network topologies can be adopted:

- **Bus Topology** (Figure 6)**:** In a bus topology, the various nodes are connected through a single trunk line with the help of optical couplers. This is a cost-effective method to transmit the signal. However, in case of fault, it is difficult to determine the faulted node.

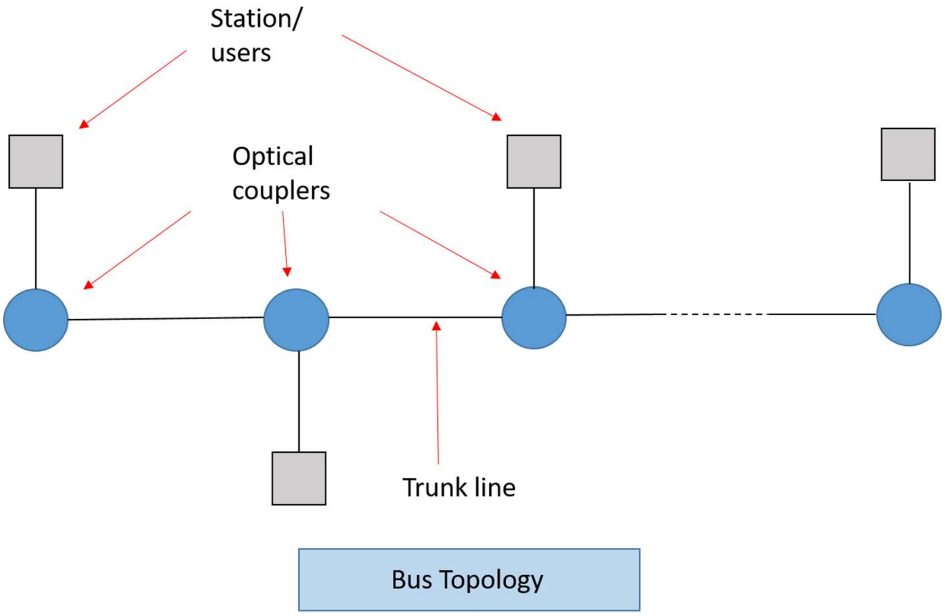
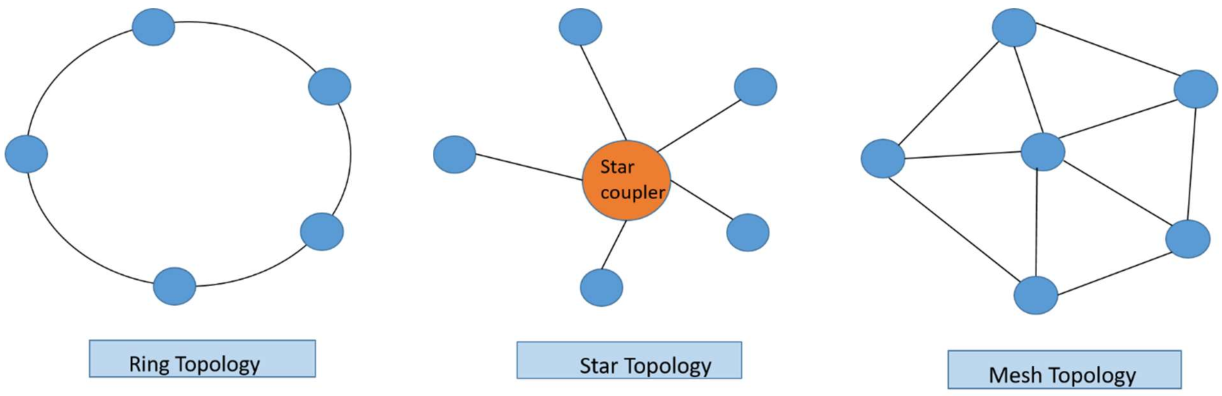


Figure 6: Bus topology network

- **Ring Topology** (Figure 7 (a)): In a ring topology, one single node is joined to its neighbouring nodes forming a closed path. So, the transmitted information is sent from one node to another. To make this topology fault-tolerant it is suggested to use a double or multiple ring topology; if a node fails, the signal travels in reverse over a redundancy ring to reach the desired node.
- **Star Topology** (Figure 7 (b)): In star connection, the various nodes of the network are connected together with a single central hub, called star coupler.
- **Mesh topology** (Figure 7 (c)): in a mesh topology, an arbitrary connection is formed between the nodes in the network. This point to point connection can be changed according to the application. In this topology fault tolerance is achieved by providing multiple routes for data transmission between two nodes.



(a) (b) (C)

Figure 7: Ring. Star, Mesh topology network

5.1.1.1. Anas SMART ROAD: an optic fiber network example

A significant example of an optical fiber network is the infrastructure of the SMART ROAD ecosystem. developed by “Azienda Nazionale Autonoma delle Strade” (ANAS) in Italy [3].

SMART ROAD includes an optic fiber network infrastructure that is designed by dividing, from a logical standpoint, the network into two different and separate types:

- Backbone;
- Segment or “Green Island”

The backbone, with 100 Gigabit Ethernet (GE), connects all Segment Nodes with a Centre Node through fiber optic cables. The backbone is designed for a future upgrade to a multi-ring configuration, which gives a high level of reliability. It is a self-healing network and immunity from possible SR failures is ensured through SR redundancy. Such an architecture enables to avoid malfunctioning caused by SR failures or by the interruption of the means of transmission. The network must meet IEEE 802.3-2015 standard specifications.

The network architecture consists of a Centre Node (CN), connected through a fiber-optic multi-ring backbone with each “Green Island” Segment Node (SN). Each SN consists of a redundant Segment Router

(SR), which enables the connection between the segment and the backbone, and of a number of switches connected to one another with a fiber optic ring (segment ring). This system is divided into two logical blocks, formed by:

- **Passive infrastructure**, that is the physical means of transmission (fiber optic);
- **Active infrastructure**, that is the electronic components that collect relevant data from outside devices and send them to destination according to communication standards. Routers, switches and servers with gateway function make up the active infrastructure.

Each “Green Island” is connected to the backbone through a redundant Segment Router, which must:

- enable base network functionalities planned for connection to the backbone level;
- ensure a redundant 100 Gbps towards the backbone and its redundancy peer device;
- have compact shape factor, low energy consumption, high throughput.

5.1.2. EtherCAT

EtherCAT [4] is a high-performance Ethernet-based industrial communication protocol with support for various network topologies. It appeared in 2003, and since 2007 it has become an international standard. The EtherCAT protocol is based on Ethernet technology and the IEEE 802 specification. It uses the same Ethernet frames and physical layer, but additionally:

- Work in hard real-time mode with a deterministic response time;
- Create many nodes, each of which handles a small number of I / O points;
- Reduce equipment costs when creating a data transmission infrastructure.

While in a conventional Ethernet network the master device uses separate commands to poll the slave devices, the EtherCAT protocol allows you to send only one command to poll and control several slave devices at once. Slave devices read the data they need from the Ethernet frame on the fly or write data for transmission and then forward the frame to the next device. This mechanism allows you to manage up to 65,535 devices in one network at high speed without restrictions in the network topology: line, bus, tree, star, or a combination of them. Moreover, to organize various topologies, hubs or switches are not needed, because the slaves themselves have multiple ports.

As shown in Figure 8, EtherCAT uses regular Ethernet frames for data transmission. The EtherCAT frame has ID 0x88A4 in the EtherType field. Since EtherCAT is optimized for fast cyclic transmission of small chunks of data, it does not use resource-intensive TCP/IP and UDP/IP protocol stacks.

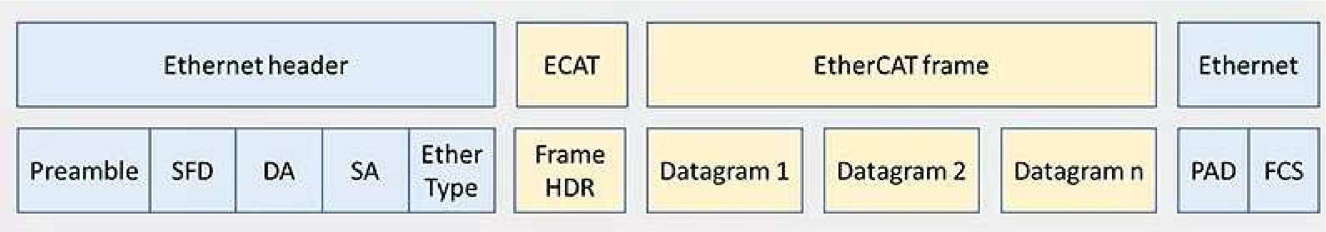


Figure 8 - EtherCAT frame encapsulated in Ethernet frame

During startup phase, the master device configures the slave devices and defines a list of their parameters. The amount of data from one network node can range from one bit to several kilobytes. An EtherCAT frame includes a header and several datagrams. The datagram header indicates the type of data access:

- Read, write, or both;
- Access to a specific device via direct addressing or access to multiple devices via logical (implicit) addressing

In addition to cyclic polling, it is possible to send datagrams event-based (asynchronously). This is a very important functionality in structural health monitoring contests.

The master device sends a command to port 0 of the slave device, where the command is processed on-the-fly by the EtherCAT Processing Unit and then forwarded to the next port. If the port is not connected to another device, then the command is forwarded unchanged to the next port until it returns to port 0 to the master device. This operation is represented in Figure 9.

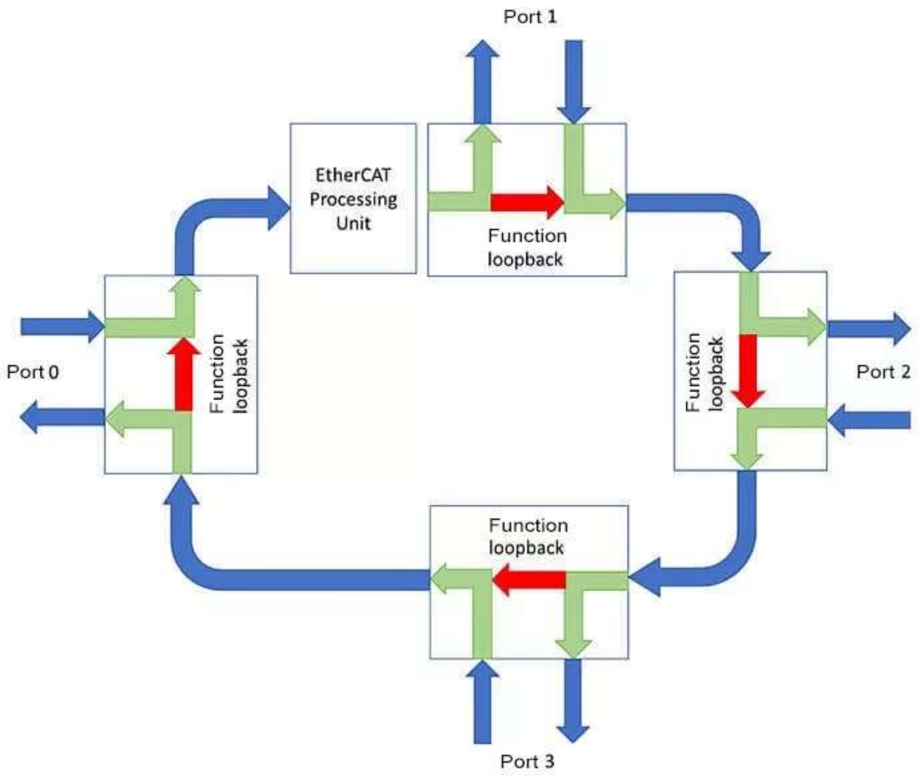


Figure 9 - EtherCAT ports operation

A functionality that makes EtherCAT very attractive for SHM applications is the fact that it use a Distributed Clocks (DC) technology. In an EtherCAT network, the time synchronization mechanism is implemented entirely in hardware. Clocks on slave devices can easily and accurately measure the delay relative to other clocks since the communication uses the logical and full duplex physical Ethernet ring structure, i.e. each EtherCAT packet travels twice through each slave (forward and return paths on different twisted pairs). Based on this delay value, the distributed clock is adjusted to achieve a very accurate time base with a spread well below 1 µs across the entire network (Figure).

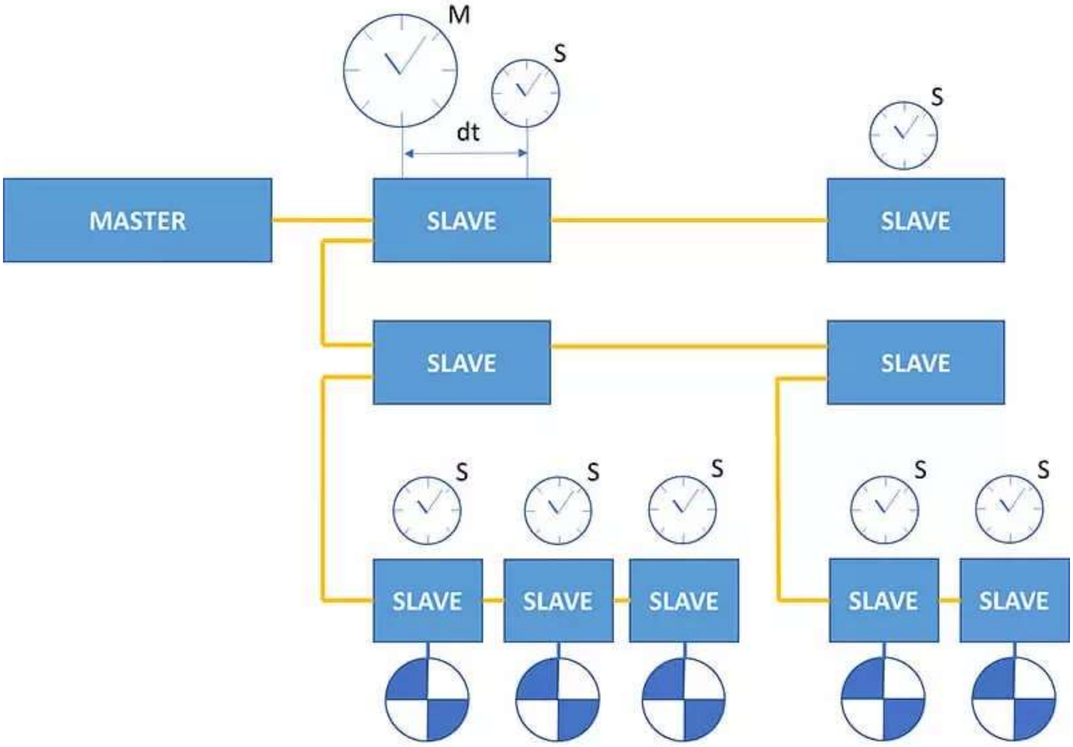


Figure 10 – EtherCAT: full hardware time synchronization with transmission delay compensation

5.2. Wireless networks

In cases when there are no wired networks available along the bridge, it is necessary to use wireless networks. Selecting the appropriate wireless technology is one of the most fundamental decisions to make when building out an IoT system

In today's market, three main types of wireless networks can power an IoT solution:

Local Area Network (LAN)

- **Cellular Network**
- **Low Power Wide Area Network (LPWAN)**

The diagram shown in Figure 11 depicts the relative strengths and weaknesses for each of these wireless networks, in terms of range and bandwidth & battery power.

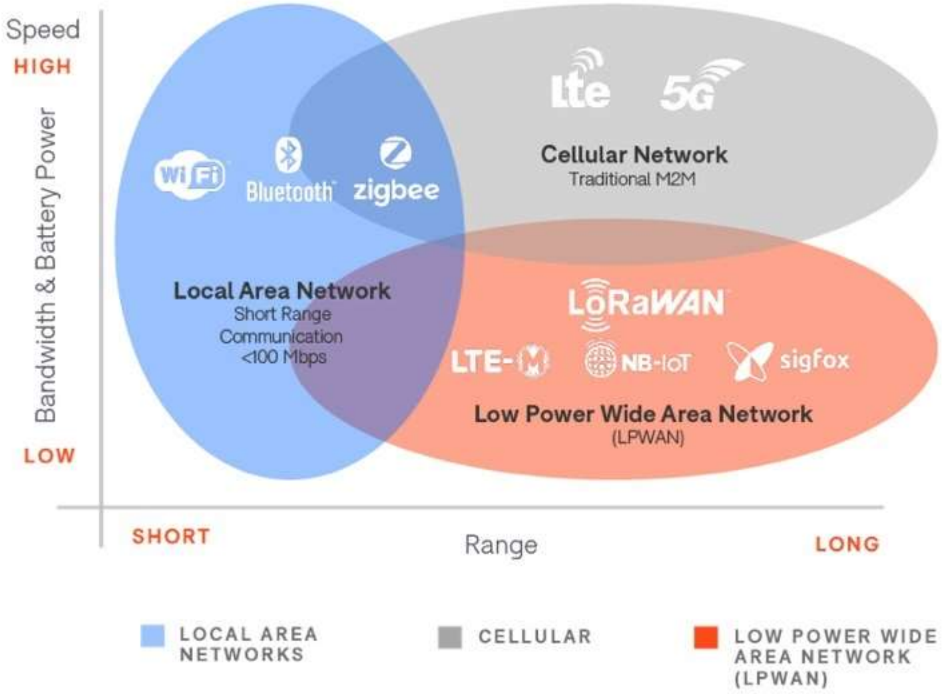
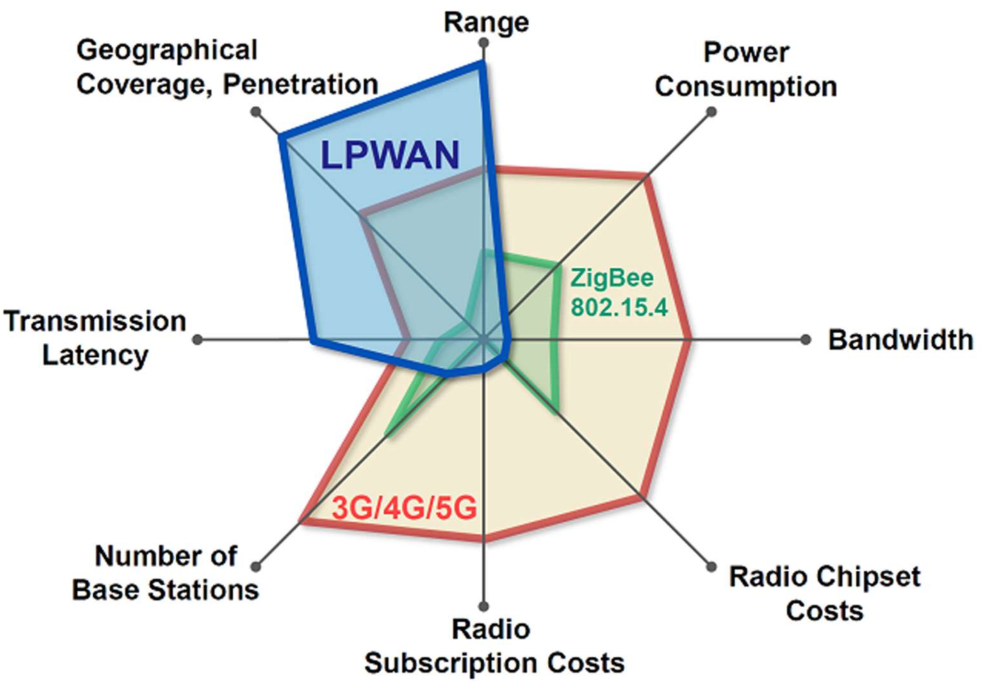


Figure 11 - Wireless network technologies comparison

Even if the "Range vs Bandwidth" graphic gives an immediate idea of the differences between wireless technologies, it is important to consider other parameters, as shown in the Kiviat diagram elaborated by Links Labs [5] and shown in Figure 12.



Source: Links Labs, Peter. R. Egli, 2015

Figure 12 – Kiviat diagram for wireless technologies comparison

LAN wireless technologies, like WiFi, Bluetooth and Zigbee, due to their short range coverage, can be used in contexts of bridges with small dimensions (< 100 meters) and in Line-of-Sight (LOS) conditions between transmitter and receiver/Access Point.

In the next chapter Cellular network 5G and LPWAN are presented.

5.2.1. Cellular 5G

5G is the 5th generation mobile network. It is a new global wireless standard defined after 1G, 2G, 3G, and 4G networks. The global specifications of 5G have been defined by 3GPP (3rd Generation Partnership Project), the industry organization that already has the global specifications for 3G UMTS (including HSPA) and 4G LTE. 5G enables a new kind of network that is designed to connect many units including machines, objects, and devices.

The main technological innovations that 5G brings to wireless communications have been defined by 3GPP as the following:

- **enhanced Mobile Broadband (eMBB**): improved broadband to enable high connection speed and transmission capacity for end users;
- **massive Machine Type Communication (mMTC):** also defined as **Massive IoT**, it is the ability to guarantee extensive coverage to hundreds of thousands of devices per km², generally low-tech devices, often powered by batteries or alternative energy;
- **ultra-Reliable Low-Latency Communication (eRLLC):** also known as critical Machine Type Communication (cMTC), it is ideal for mission critical applications, where security and very low latency (< 10ms) are imperative.

The ITU (International Telecommunication Unit) [5] within the IMT-2020 (International Mobile Telecommunications-2020) initiative aimed at the development of mobile applications beyond 2020, has reported a mapping of the potential scenarios and application cases of 5G in relation to the characteristics more innovative (Figure 13).

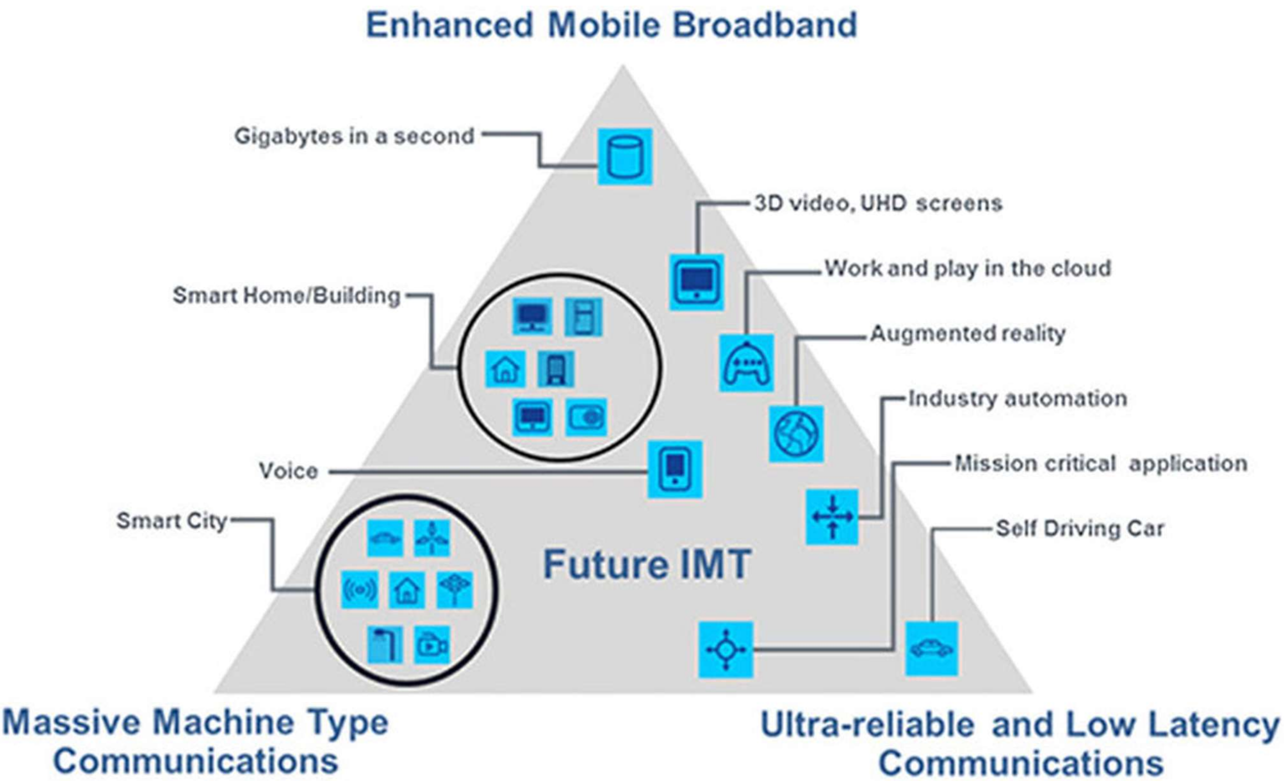


Figure 13 - ITU: use cases and scenarios of 5G

The technological revolution linked to 5G must necessarily give rise to new collaborative models that are able to fuel the value chain in the mobile telecommunications sector, including old and new stakeholders and accelerating development processes in vertical areas such as telemedicine, the Smart City, Industry 4.0, infrastructure monitoring and transports.

In the bridge monitoring framework, 5G technology can be very useful for CCTV cameras streaming and all the traffic monitoring applications connected to it.

5.2.2. LPWAN

LPWAN technologies are telecommunication techniques used for low consumption and extended coverage in IoT applications. LPWAN offers four fundamental characteristics for the world of IoT, which lead to the presumption of the persistence of this technology even in coexistence with 5G, especially in rural areas:

- low costs,
- broad coverage,
- low energy consumption,
- high density of devices manageable from a single cell.

Other interesting characteristics of IoT/LPWA networks are:

- low bitrates,
- nodes with low processing and storage requirements,
- small-sized nodes,
- low latency requirements,
- linear complexity network architecture.

All the key features stated above are summarized in `Figure` 14.

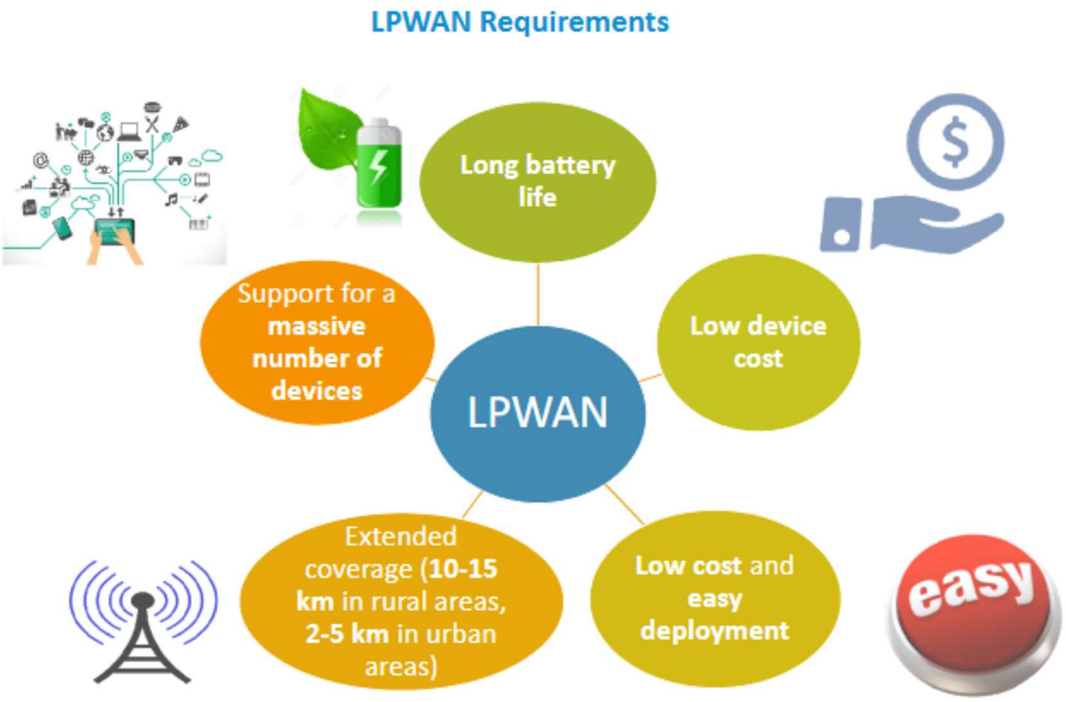
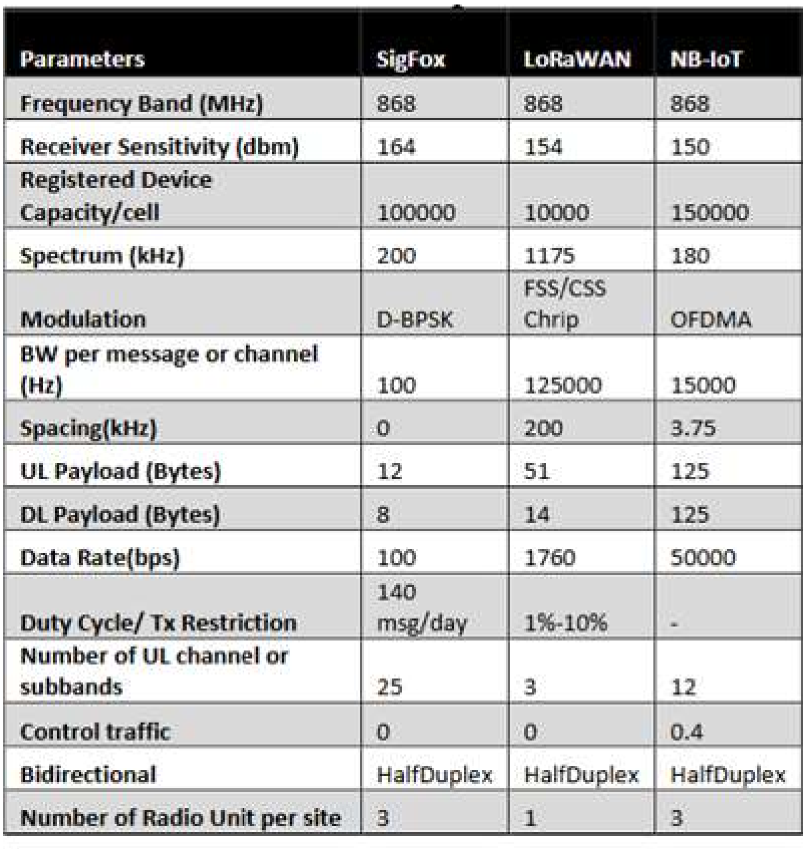


Figure 14 - Key featuers of LPWAN

Some of the most famous LPWAN technologies are:

- **Sigfox**
- **LoRaWAN (Long Range Wireless Area Network)**
- **NB-IoT (Narrow Band Internet of Things)**

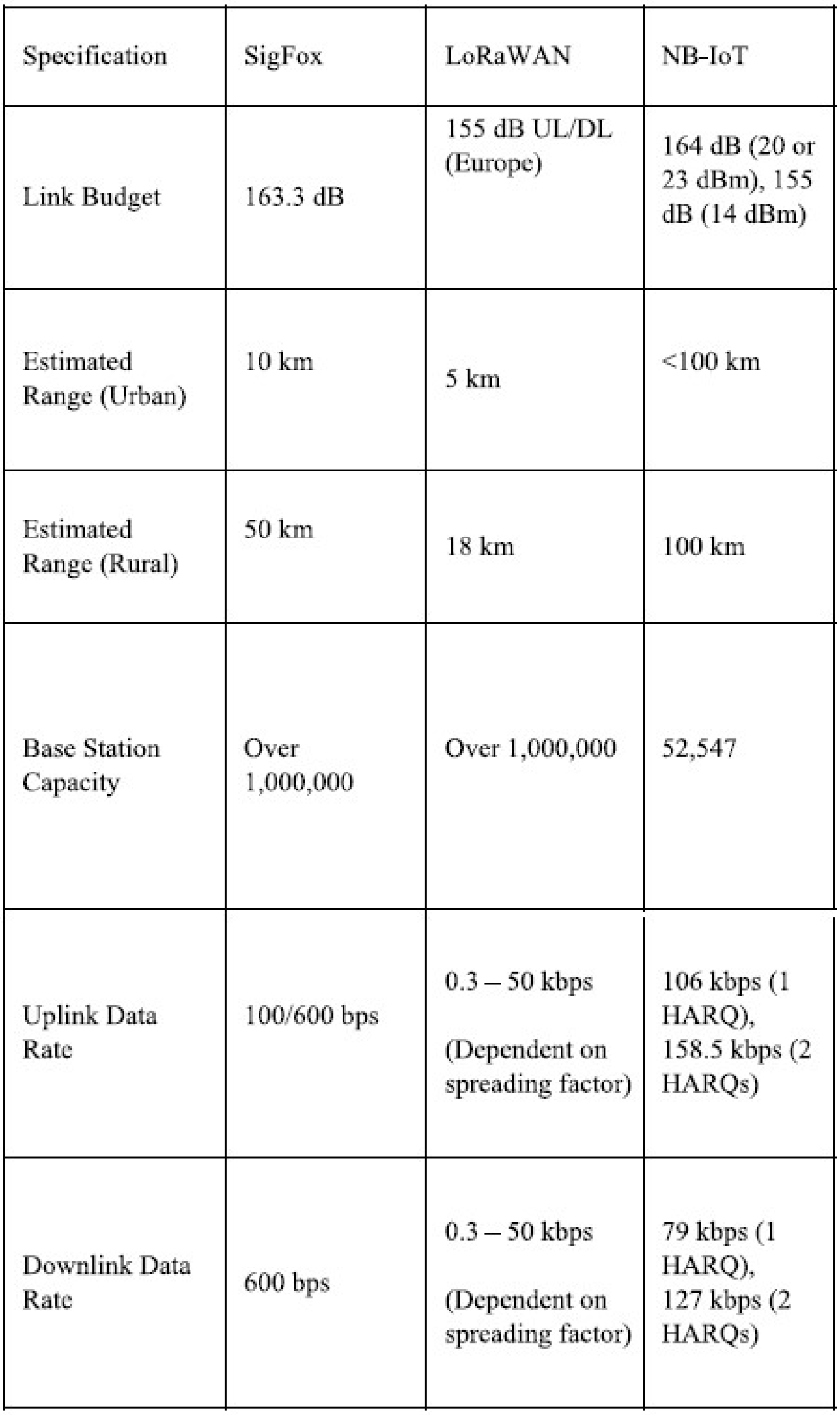
The main transmission parameters of these technologies are presented in the following table:



Parameters	SigFox	LoRaWAN	NB-IoT
Frequency Band (MHz)	868	868	868
Receiver Sensitivity (dbm)	164	154	150
Registered Device Capacity/cell	100000	10000	150000
Spectrum (kHz)	200	1175	180
Modulation	D-BPSK	FSS/CSS Chirp	OFDMA
BW per message or channel (Hz)	100	125000	15000
Spacing(kHz)	0	200	3.75
UL Payload (Bytes)	12	51	125
DL Payload (Bytes)	8	14	125
Data Rate(bps)	100	1760	50000
Duty Cycle/ Tx Restriction	140 msg/day	1%-10%	-
Number of UL channel or subbands	25	3	12
Control traffic	0	0	0.4
Bidirectional	HalfDuplex	HalfDuplex	HalfDuplex
Number of Radio Unit per site	3	1	3

Table 3 - Transmission parameters of LPWAN technologies

Other significant parameters, regarding the network setup and an estimate of the coverage provided by the technological solutions, can be consulted in the following table:



Specification	SigFox	LoRaWAN	NB-IoT
Link Budget	163.3 dB	155 dB UL/DL (Europe)	164 dB (20 or 23 dBm), 155 dB (14 dBm)
Estimated Range (Urban)	10 km	5 km	<100 km
Estimated Range (Rural)	50 km	18 km	100 km
Base Station Capacity	Over 1,000,000	Over 1,000,000	52,547
Uplink Data Rate	100/600 bps	0.3 – 50 kbps (Dependent on spreading factor)	106 kbps (1 HARQ), 158.5 kbps (2 HARQs)
Downlink Data Rate	600 bps	0.3 – 50 kbps (Dependent on spreading factor)	79 kbps (1 HARQ), 127 kbps (2 HARQs)

Table 4 - LPWAN: network and coverage parameters comparison

Below in Figure 15, a more intuitive graphical representation of the different IoT factors of the three main LPWAN technologies is showm.

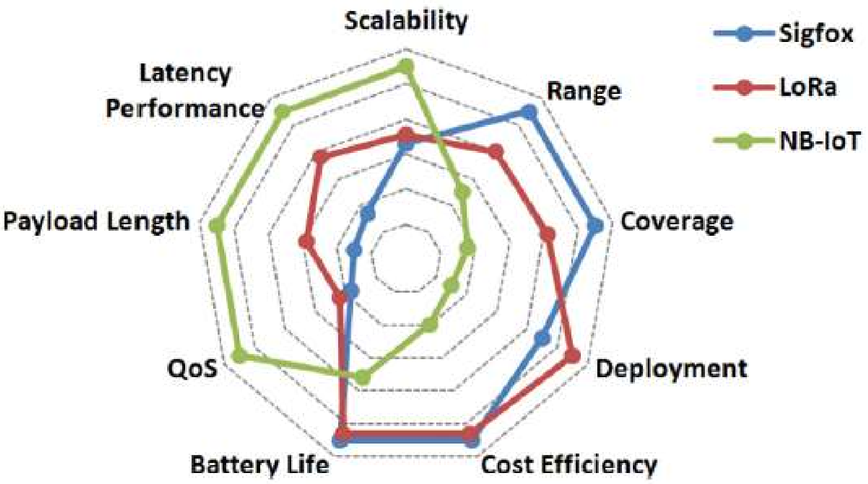


Figure 15 - Kiviat diagram of LPWAN IoT parameters comparison

Analysing the characteristics in detail, it is clear that LoRa/LoraWAN is the most suitable LPWAN technology for use in a digital bridge monitoring system due to its good payload length and latency performance. LoRa is optimal due to its simplicity and installation costs, coverage, and low power consumption.

5.2.2.1. LoRa/LoRaWAN

LoRaWAN [7] is an IoT wireless network that operates in the Industrial, Scientific, and Medical frequency bands (ISM band). This technology uses LoRa modulation, also known as Chirp Spread Spectrum (CSS), where the signal is modulated through chirps—increasing or decreasing signals in frequency. LoRaWAN is well-known in the IoT sector for its low energy consumption, cost-effectiveness, secure data transmission, and wide coverage (up to almost 18 km).

LoRaWAN operates in different classes at MAC layer:

1. Class A (Battery Powered): This mode is the most commonly used in LoRaWAN, involving programmed communication.

2. Class B (Low Latency): Similar to Class A, but with additional time for the final device to receive a message.

3. Class C (No Latency): Allows continuous reception of messages in the final device, increasing power consumption.

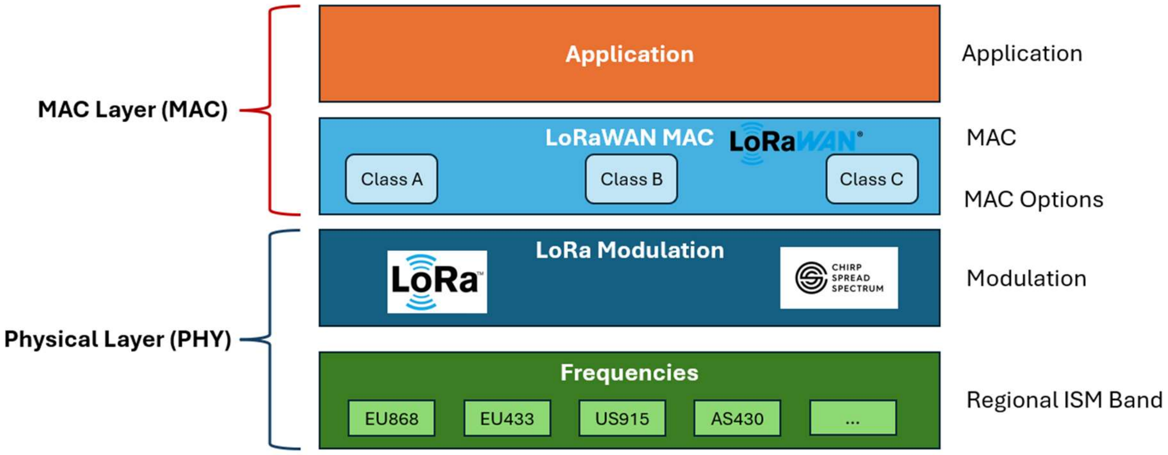


Figure 16 - LoRa/LoRaWAN PHY and MAC Layers

The architecture of LoRaWAN, represented in Figure 16, includes:

- End nodes: Responsible for collecting and processing sensor data.
- Gateway: operates communication between nodes using LoRaWAN technology and connects to a central point through the internet.
- Network server: Registers sensors and gateways on a unique server for data communication and decoding.
- Application: Interpret and store data collected by sensors, making it available for visualization by the client, through dedicated connectors.

Work topologies include star-type, mostly used for high performance and low communication consumption, and mesh-type, employed when all nodes require the same message from the gateway.

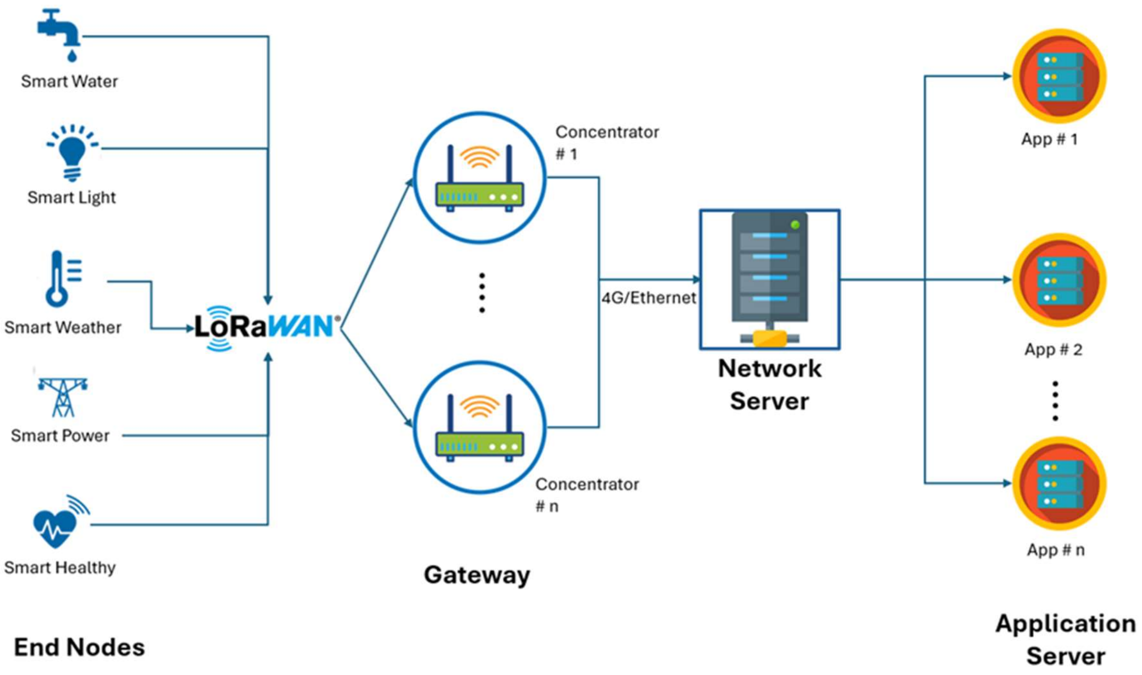


Figure 17 - LoRaWAN archtecture

The minimal sensitivity and SNR (Singl-to-Noise Ratio) supported by LoRaWAN are approximately -140dBm and -20dB, respectively. Specific characteristics for Europe include:

- Frequency band: 867 - 869MHz
- Channels: 10
- Channel Bandwidth Up: 125/250kHz
- Channel Bandwidth Down: 125kHz
- Tx Power Up: +14dBm
- Tx Power Down: +14dBm
- Spreading Factor Up: 7-12
- Data rate: 250bps – 50kbps

Depending on the Spreading Factor (SF) used for communication and the message length, the time on air of the message increases or decreases, affecting channel occupancy. The following figure illustrates this behavior.

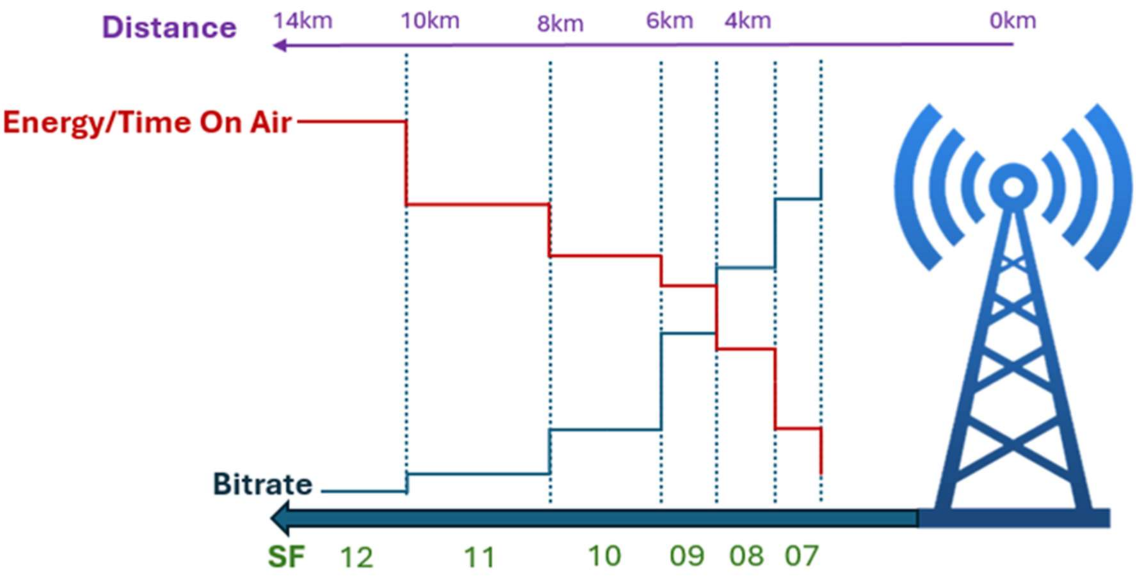


Figure 18- LoRAWAN channel occupancy variation

6. Application layer

The application layer is the responsible of data storage, elaboration and visualization. The table below present the logical blocks and the technological tools related to them.

Function	Technological tools
Data storage	Data lake, database
Data elaboration	Data analytics, Machine Learning, Artificial Intelligence
Data visualization	Dashboards

Table 5- Technology tools of the application layer

1.1. Data storage

A Data Lake is a storage repository that can store large amount of structured, semi-structured, and unstructured data. It is a place to store every type of data in its native format with no fixed limits on account size or file. It offers high data quantity to increase analytic performance and native integration.

Data Lake is like a large container which is very similar to real lake and rivers. Just like in a lake you have multiple tributaries coming in, a data lake has structured data, unstructured data, machine to machine, logs flowing through in real-time (Figure 19).

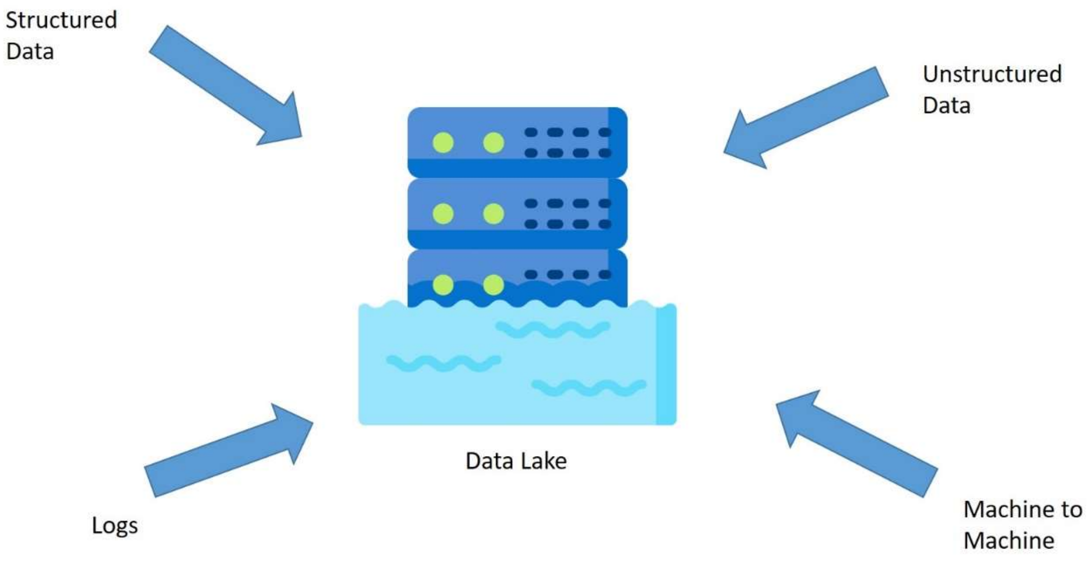


Figure 19- Different types of data flowing through Data Lake

When properly architected, data lakes enable the ability to:

- Power data science and machine learning applications;

- Centralize, consolidate and catalogue the data;

- Quickly and seamlessly integrate diverse data sources and formats;
- Democratize data by offering users self-service tools.
- Include Application Programming Interfaces (APIs) that allow data exchange with the BIM (Building Information Modeling) ecosystem.

The Data Lake can be implemented following the general principles of the architectures called "Lambda", as shown in Figure 20. In an architecture of this type, data is acquired, processed and presented using three different layers:

- **Speed layer**: which allows the acquisition, processing and presentation of data in "streaming"; this means that as a data is acquired from the field it is already sent to the dashboard as well as being archived for subsequent processing;
- **Access layer**: the allows applications to access processed data or views that are the result of batch procedures;
- **Batch layer**: the real Data Lake, containing both all the raw data and the procedures for translating this data into views to be presented to applications using the access layer.

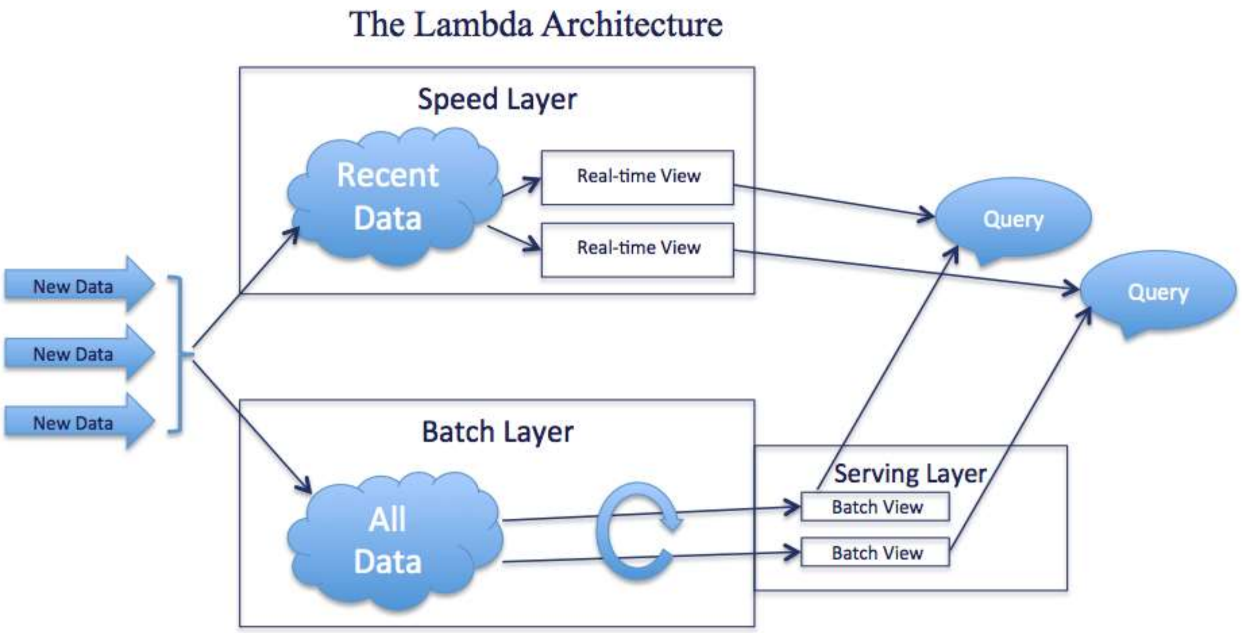


Figure 20 - Generic representation of a Lambda architecture

1.2. Data elaboration

The basic flowchart of Data elaboration for a dynamic BHM (Bridge Health Monitoring) system is shown in Figure 21.

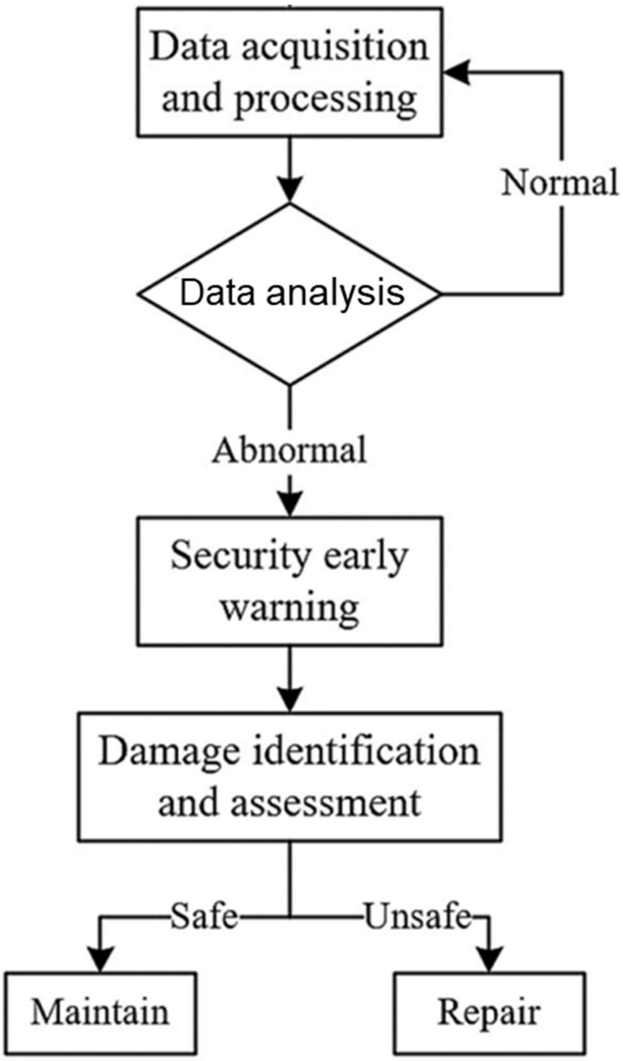


Figure 21 - Basic flowchart of data elaboration in a dynamic BHS

Some ground-breaking categorizations of damage have been introduced in recent years. According to one of the most accepted categorization scheme, damage can be broken down into five groups:

- Level I (Damage detection): This level is identified when a damage event occurs
- Level II (Damage location): This level is detected when damage occurs, and then the location and orientation of the damage are determined.
- Level III (Damage typification): This level is detected when damage occurs, the location and orientation of the damage, and then damage severity is determined, and the kind of damage is estimated.
- Level IV (Damage extent): This level considers the possibilities of limiting or postponing the extent of damage once previous levels have been completed.
- Level V (Damage prediction): After completing the previous four levels, this level assesses the bridge's remaining usable life or its viability status, depending on the situation.

Particularly in the last few years, BHM systems have made a lot of progress thanks to the development of computational intelligence and the use of data-driven approaches based on methods of Artificial Intelligence (AI) and Machine Learning. Controlling uncertainty in SHM systems may be done in a variety of ways. Artificial intelligence and machine learning approaches are effective strategies that have lately gained a lot of traction.

In the modern world, it is crucial to effectively analyze raw data and transform it into information that is insightful and clear. In the field of AI and ML applications, one area of study is the creation of systems that automatically sort data into groups and look for patterns that show what the data means. This mechanism is called Pattern Recognition and can be applied successfully to BHM data elaboration.

Processes involved in BHM data-driven approach can be summarized in seven steps (Figure 22), in many of which AI and ML play a pivotal role:

- **Data acquisition**: there are different requirements for monitoring dynamic vs static characteristics, as described in the 3rd Section of this document;
- **Data Normalization**: process that aims at bringing all data to point to a similar scale;
- **Data Cleaning**: process of identifying and removing errors and duplications, in order to create an affordable dataset;
- **Data Compression**: encoding or rearranging data to minimize their size;
- **Features Extraction**: process of selecting a subset of original features such as the number of useful features (i.e. the ones correlated to damages) is minimized;
- **Data fusion**: information coming from different sources is put together to obtain more accuracy and consistency;
- **Pattern Recognition**: the last step of a ML- based BHM. In this last phase evaluation of the health of the bridge is determined.

Figure 22 - Processes involved in a data-driven BHM

Many Machine Learning approaches are used in pattern recognition, which is an extensively used subject. In an BHM/SHM system, a pattern recognition system is able to analyze a wide variety of data types, including image, video, numbers, and text. Pattern recognition can be examined from several angles. Pattern recognition is based on analytical systems and algorithms. In general, these systems and analytical algorithms are divided into three general categories:

- Regression,
- Classification,
- clustering.

In another way of looking at them, regression and classification algorithms are supervised learning techniques, while clustering algorithms are unsupervised learning techniques. Figure 23Figure provides an overview of the techniques and methods used in pattern recognition.

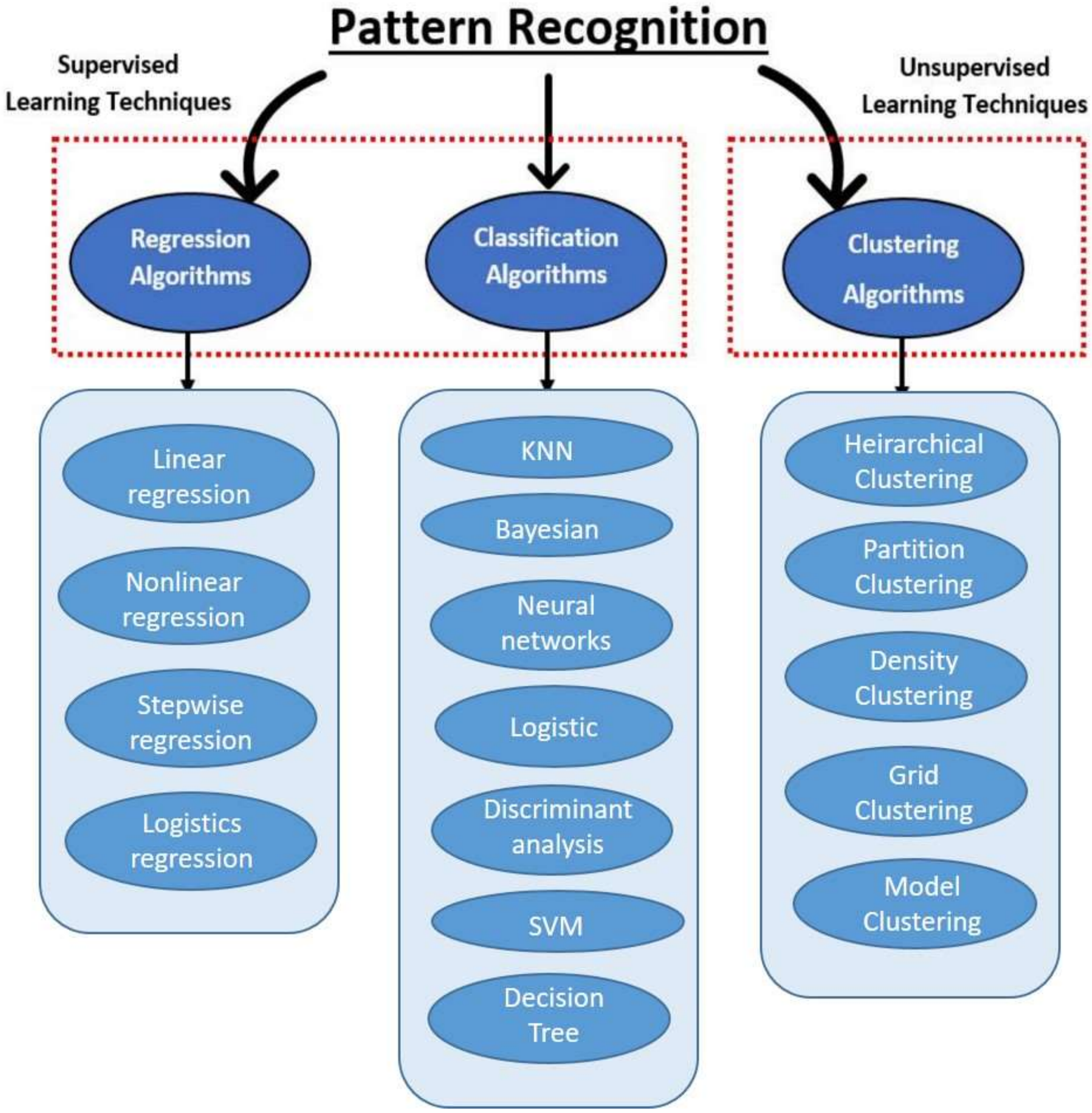


Figure 23 - Pattern recognition techniques and methods

7. Conclusion

This deliverable reports the conceptual framework designed for the application and the usage of the digital monitoring system with respect to the identified target bridge. Initially the fundamental building blocks of the digital monitoring system and their functionalities have been presented. Then we moved on to the elaboration of the Internet of Things based diagram on which the conceptual framework is based, consisting of three main layers: sensing, communication and application. Going into detail about the sensing layer, sensor nodes architecture and acquisition techniques are reported. This document then presents an in-depth analysis of wired and wireless communication technologies, underlining the criteria driving the most suitable choices and at the same time encouraging the integration with infrastructures that are already present in the pilot sites. In the last part some information is provided on data storage and data elaboration techniques, including algorithms pertaining to Machine Learning and Artificial Intelligence to achieve bridge damages estimation.

8. References

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