Capacity for Rail

Towards an affordable, resilient, innovative and high-capacity European Railway System for 2030/2050

Recommendations and guidelines for next generation monitoring and inspection

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Lead contractor for this deliverable:

- UoB

Contributors

- UPorto

Project coordinator

- International Union of Railways, UIC

1 Executive Summary

Condition monitoring systems monitor the immediate state and general degradation of assets. Condition monitoring and condition-based maintenance of railway systems is increasingly important to infrastructure managers as part of the process of operating efficient and cost-effective railways. Faulty or degraded infrastructure elements can lead to inefficient operation, or even failures and thus downtime or even damage to the track and/or trains. In this subproject, technologies are considered for their suitability for application as part of a condition monitoring system, either for current railway elements (i.e. retrofitting) or to be built-in to new elements during production or installation. The technologies and systems being considered need to be low cost and low power, while maintaining high levels of robustness. The successful use of such equipment may lead to the development of prognostic systems which would in turn allow more efficient maintenance scheduling. The work undertaken in this work package has focused primarily on sensing, power, and communications technologies; but it has also considered processing architectures, algorithms, and the required computational frameworks.

In this report, a wide range of sensors are considered, and examples of laboratory and field based evaluations are provided. Technologies are first identified and screened using a technology marketplace / identification framework, before being evaluated for use within the railway industry. Sensing technologies considered include: computer vision systems, accelerometers, gyroscopes, strain gauges, magnetometers, thermometers, weather stations, acoustic sensing, and fibre optics. The sensing technologies are assessed, using the framework developed within the project and described in D4.2.1. This includes evaluation based on power consumption, sensor capabilities, scalability, environmental issues, stability, and installation and maintenance complexity. In addition to the sensing technologies themselves, a number of examples of “support technologies” such as energy harvesting, energy storage, and communications systems are also evaluated. In the former cases these evaluations are generally related to capacity and suitability of use within the environment. In the latter (communications) case the focus is on factors such as speed, bandwidth, reliability, etc. as well as the practicalities of installation.

During the evaluation of specific technologies, the significance of the measurement and processing architecture has become increasingly apparent. It is important to carry out monitoring and inspection using a suitable processing unit and optimised algorithms. The selection of the processing unit can be made based on the requirements of the application which may include elements such as: processing algorithms, performance of the computation system, energy consumption, communication protocols, input/output via digital and analogue channels or communications busses etc.

The identification and evaluation of sensing and measurement technologies, therefore, requires consideration of much more than just the basic candidate technologies in isolation. Recommendations from this work are presented in the form of key considerations and identification of specific parameters and combinations of interacting parameters that must be considered in combination, as well as some general indications of technologies likely to be prevalent in future railway condition monitoring applications.

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5 Abbreviations and acronyms

Abbreviation / Acronym	Description
ADC	Analogue to digital convertor
C4R	Capacity4Rail
CAES	Compressed air energy storage
CAN	Controller area network
CENER	National renewable energy centre
CT	Current transducer
DSP	Digital signal processor
DTU	Technical University of Denmark
FBG	Fibre Bragg Grating
FPGA	Field programmable gate array
FPS	Frame per second
GPIO	General purpose input output
GPRS	General packet radio service
GPS	Global positioning system
GSM	Global system for mobile communication
IEC	International electrotechnical commission
IMU	Inertial measurement unit
ISM	Industrial, Scientific, and Medical
ISO	International Organization for Standardisation
KPI	Key performance indicator
MAC	Media access control
MCU	Microcontroller unit
MVAr	Mega volt amps reactive
MW	Mega watts
NAN	Near-me area network
PSB	Polysulfide bromide battery
PV	Photovoltaic
SMES	Superconducting magnetic energy storage
SNR	Signal to noise ratio
TEG	Thermoelectric generator
UoB	University of Birmingham
VRB	Vanadium redox battery
WLAN	Wide local area network
WSN	Wireless sensor network

6 Background

This report is submitted as D4.2.2 within SP42 of the Capacity4Rail project. This work package focuses on the identification of current of near-future technologies that may be suitable for adoption within the railway industry. The work package is associated with both SP43 and SP44. These consider the application of monitoring technologies to both new-build railway infrastructure, and as retro-fit to existing infrastructure, respectively.

The deliverable D4.2.1 described low-level, mid-level and high-level requirements for sensors, energy harvesting, communication and data integration technologies, as well as an evaluation process. The low-level requirements include sensors, energy harvesting and communication devices. The mid-level requirements are the whole data acquisition and condition monitoring systems. The final level is where the collected information becomes accessible in a layout compatible with existing databases and is available to the infrastructure managers or operators.

This report identifies sensors, energy harvesting technologies and processing units. It also provides examples of how these technologies are evaluated. A range of sensors is introduced including the power consumption, data rate and capabilities.

To supply power for the proposed monitoring systems, energy harvesting applications in both the railway and other industries are explored.

Data communication between the sensors and with a central processing/storage unit is also one of the requirements of this work. Low power, wireless communications are generally focused upon in this report due to their low cost and support for a simple retrofitted installation.

The processing platforms including data processing, storage and communication capabilities are used to reduce large data collection from the sensors by carrying out on site processing and to decrease communication power consumption by only transferring essential information to the user.

7 Objectives

The objectives of WP4.2 are to specify, identify and evaluate sensor, energy harvesting, communications and data integration technologies that can be used as part of integrated solutions for next generation railway monitoring and inspection.

The technologies identified should be: low cost, robust, intelligent and low power.

A wide range of technologies that can be applied to railway infrastructure monitoring are introduced and the pros and cons of them are discussed.

The vast majority of approaches considered here are already used in other domains, or are becoming ready for application in the near future. It is not anticipated that significant entirely new approaches for the railway domain will be developed.

The technologies will also be assessed by the frame work introduced in the 4.2.1 report. The framework is partially designed to consider whole-systems, and as such some elements will be suitable for all technologies while some can be only use in specific circumstances. This will be explained within this report at the appropriate and relevant points.

8 Introduction

This report presents a method that can be used to evaluate condition monitoring technologies, and to identify capability, applicability, barriers and enablers for technologies and systems that could be developed. A condition monitoring system monitors parameters of condition in a system. Changes in the values of the parameters can indicate abnormal behaviours and lead to fault detection. The key elements of a condition monitoring system are: sensors for physically measuring assets, processing algorithms for detecting abnormal behaviour and fault detection, communication systems to transfer data, power supply systems, and user reporting / interfaces. These components are shown in Figure 1.

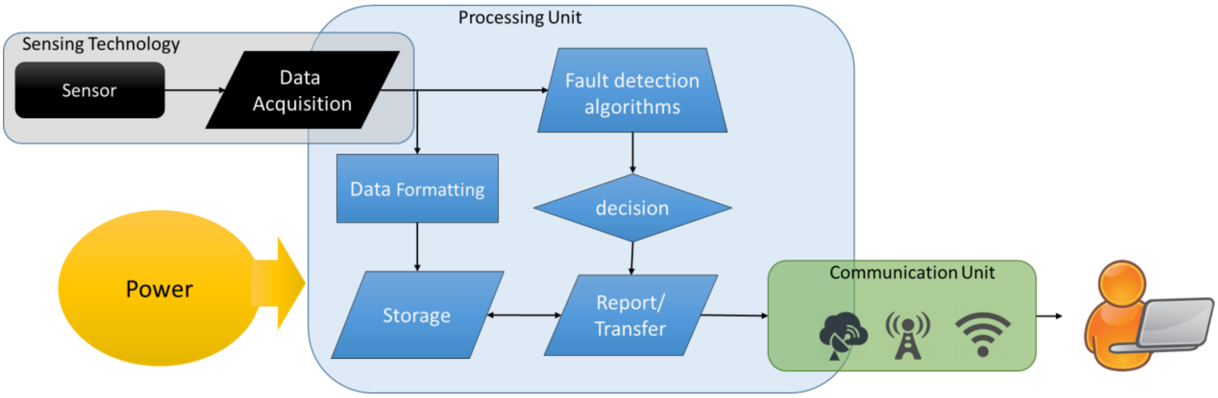

FIGURE 1: AN OVER VIEW OF A CONDITION MONITORING SYSTEM

After identifying the technologies and their ability, an investigation of the sensing techniques is demonstrated. The use of an assessment system to provide a numerical scoring for each of the presented technologies is also demonstrated. This assessment method was developed in the previous report (D4.2.1). The assessments for the sensing technologies rely on scalability, environmental compatibility, long term stability, availability, ease of installation and data transfer methods.

To provide power to condition monitoring systems, energy harvesting technologies are considered. Energy harvesting technologies and the related energy storage systems are also discussed and evaluated in this work. This assessment was based on their stability, condition status reporting, self-diagnostics, environmental compatibility and noise susceptibility.

It is important to design or identify the correct monitoring algorithm. It is also essential to have a processing unit that can function using an appropriate energy harvesting.

The results or the collected the data in a monitoring system must be stored and reported. This needs a method to transfer the data from the equipment to a central unit. Communication technologies are also discussed in this report. Data communication between the sensors or a central processing/storage unit is also one of the requirements of this work. Low power, wireless communications are mainly considered in this report. This is due to them having lower costs and allowing support for simple retrofitted installation. Additionally, wired solutions are also considered for long distance communications.

The vast majority of approaches considered are already used in other domains, or are becoming ready for application in the near future.

9 Technology identification method

To identify the technologies that could be developed based on the current requirement and future railway, a chart-based method was implemented, shown in Figure 2. This chart is to demonstrate the technologies and their capabilities. It also addresses the problems and motivations for each application. The chart is not used to evaluate the applicability of specific implementations of a technology, but to initially brainstorm the potential for the inclusion of a candidate technology in the railway ecosystem.

The terms used in the technology identification method are as follows:

- Drivers: the importance and the motivations behind the technology that should be introduced
- Capability: the requirement for the technology to be realised
- Barriers: the concerns that can negatively affect the technology progression
- Applicability: the application of this technology on the railway

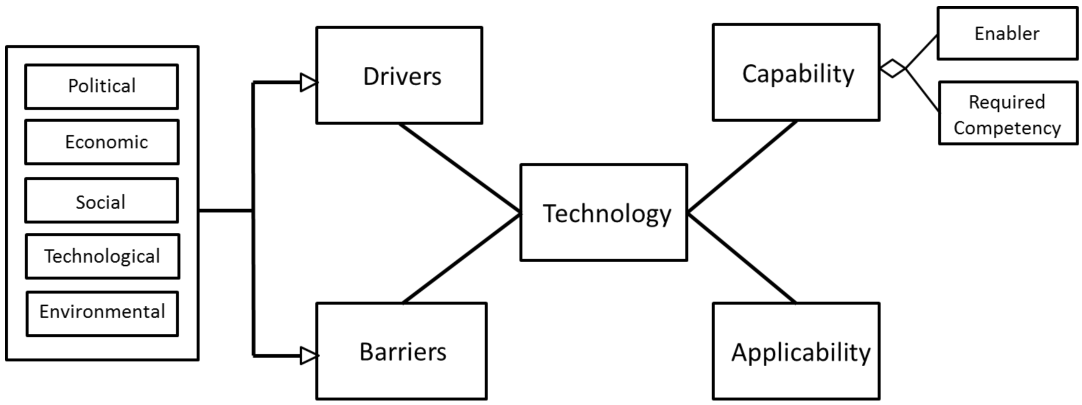

FIGURE 2: OVERVIEW OF THE TECHNOLOGY MARKETPLACE CHART

The chart template, shown in Figure 3, was distributed to experts in workshops as a survey to identify the technologies in different areas.

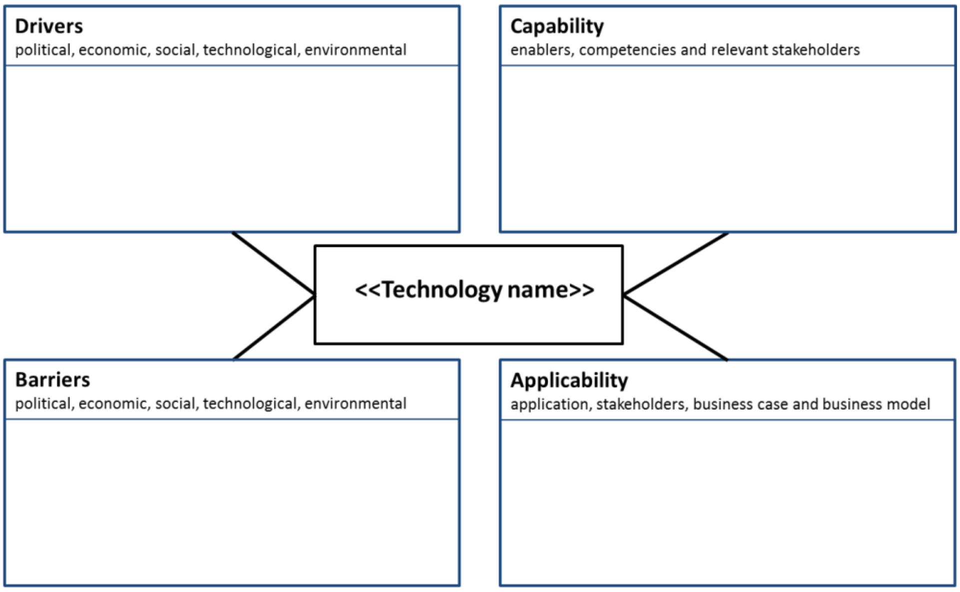

FIGURE 3: TECHNOLOGY MARKETPLACE CHART TEMPLATE

Figure 4 shows an example of the technology marketplace template, competed for the case of an energy harvesting technology to be applied as a power source. This technology could ultimately be used in conjunction with wireless communications technologies to provide a fully independent, isolated system. This would also eliminate issues such as trip hazards and could lead to easier maintenance processes. To enable this technology a combination of engineering skills, science and technologies is required, such as mechanical engineering, material science and a battery storage technology to store the generated power. The application for this would low-power monitoring systems and micro-power equipment. The barriers for applying this technology are the limited number of applications that could be supported and the characteristics of the vibration system for generated power. These analysis techniques can help to identify suitable technologies for application in different circumstances.

This report provides a method to identify sensing, power, processing and communication technologies based on the requirements in railways and infrastructure condition monitoring. There are also examples provided for each technology. However, due to the enhancement in electronics providing specific technologies would not be appropriate for the future railway.

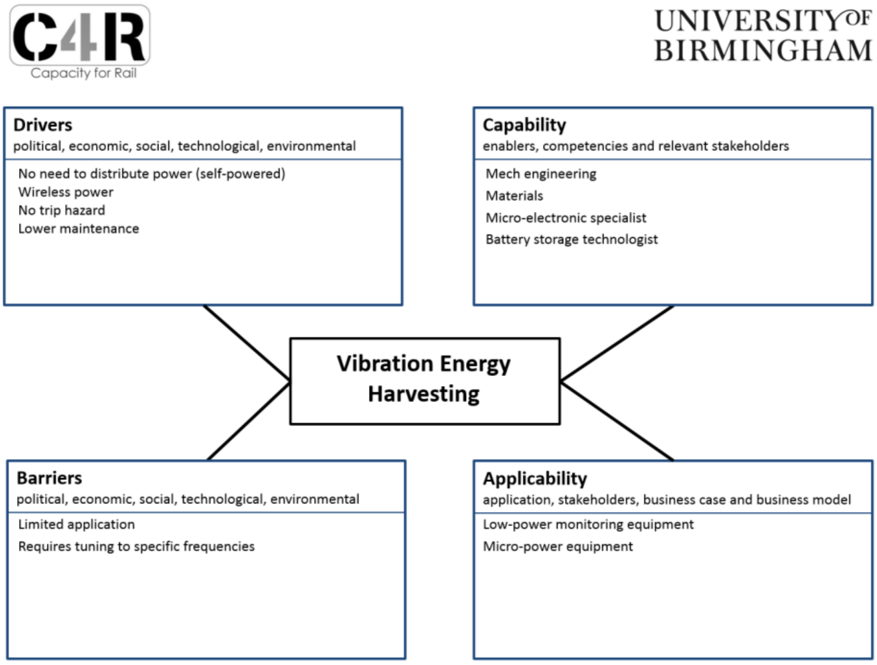

Figure 4: An example of a filled in technology chart

Examples of some of the technologies considered using the chart are presented in Appendix (A).

10 Sensing

A wide range of sensors is described, including details of their use within the rail industry, especially for monitoring the infrastructure or partially related systems. This includes computer visions, accelerometers, gyroscopes, strain gauges, magnetometers, thermometers, weather stations, acoustic and fibre optic. Each sensing technology is also evaluated based on its power consumption, sensor options, scalability, environmental capabilities, stability, installation and maintenance.

10.1 Vision

Computer vision has recently been applied to railroad applications due to its potential to improve the efficiency, objectivity, and accuracy when analysing historical databases of acquired video footage and images. Algorithms can provide a more accurate evaluation of track conditions than human based vision inspection [1]. It is, however, challenging to generate an algorithm that is robust to many unexpected conditions.

There is an opportunity to create methods for inspection without prior knowledge of the components. By detecting differences in components over time, a computer vision system may be able to perform track inspection over thousands of miles of track with minimal human involvement. However, some of these techniques will require a vehicle to operate the monitoring system, and due to the existing technologies, normal line-speed could be too high for the vision processing algorithms to run. In these cases, off-line processing or faster processing systems would be required.

Machine vision combines a wide range of technologies in order to provide useful outputs from the acquisition and analysis of images. This technology is primarily used for inspection and robot guidance. Using adequate machine vision tools, a suitable image is captured and the object of interest is found. The most common method is the template matching technique, where features such as the geometry of the edges are compared with a template image. Differentiation based on brightness and differentiation based on colour are also common [2].

Displacement measurement systems have been recently developed using template matching techniques such as pattern matching, edge detection and digital image correlation. Ribeiro *et al* [3] developed a vision sensor system for the railway that is able to measure displacements in real-time by tracking natural targets on the structural surface, eliminating the need for physical access to the structure to install a physical target panel.

One drawback of vision-based sensors is their minimum resolution, since the minimal unit in a video image is one pixel, which is far from the required resolution in case of small structural vibrations, unless microscopic lens is used.

An example of the vision system for monitoring the track movement is explained in [4] where a digital camera with a resolution of 2048x2048 pixels and 75 frames per seconds (fps) was used.

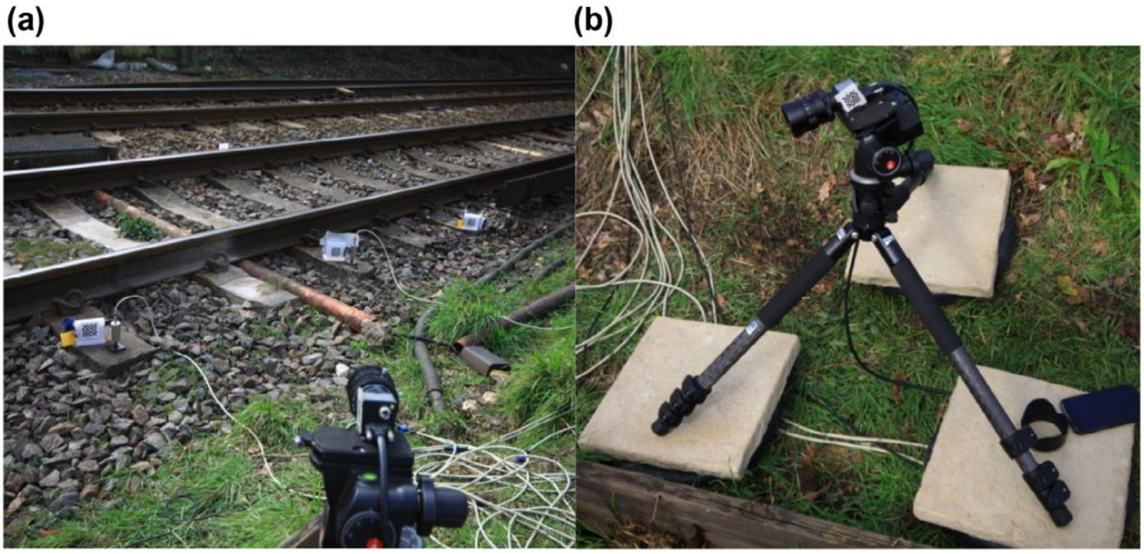

FIGURE 5: (A) CAMERA FACING THE SLEEPERS (B) THE GENERAL SET-UP [4]

The advantage of using cameras for track movements is that they can cover multiple sleepers and can be deployed from the trackside. This will also ease the maintenance for the monitoring system. However, the image processing requires significant complexity, and the cost of the camera would be more than using accelerometers on each sleeper.

Another example of vision processing for monitoring infrastructure is the movement of switches. As a part of the evaluation process, the University of Birmingham has carried out analysis of the movements of a switch using visual techniques. In this work, the movement of the actuator was tracked as shown in Figure 6 and Figure 7.

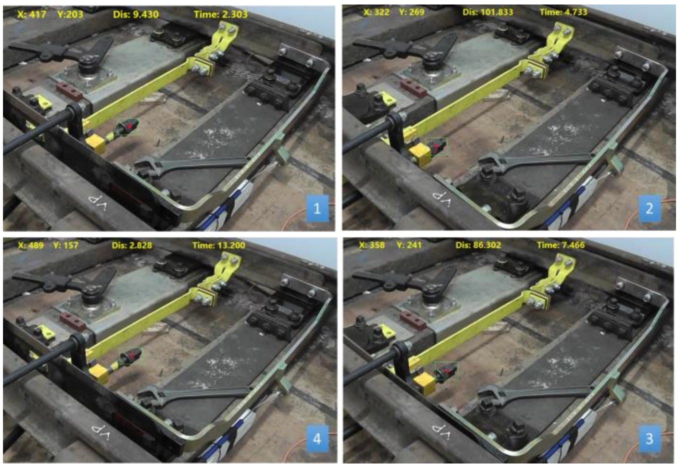

FIGURE 6: FOUR DIFFERENT POSITIONS OF THE TIP OF A SWITCH IDENTIFIED USING IMAGE PROCESSING

The estimated distance trajectory of the actuator is shown in Figure 7.

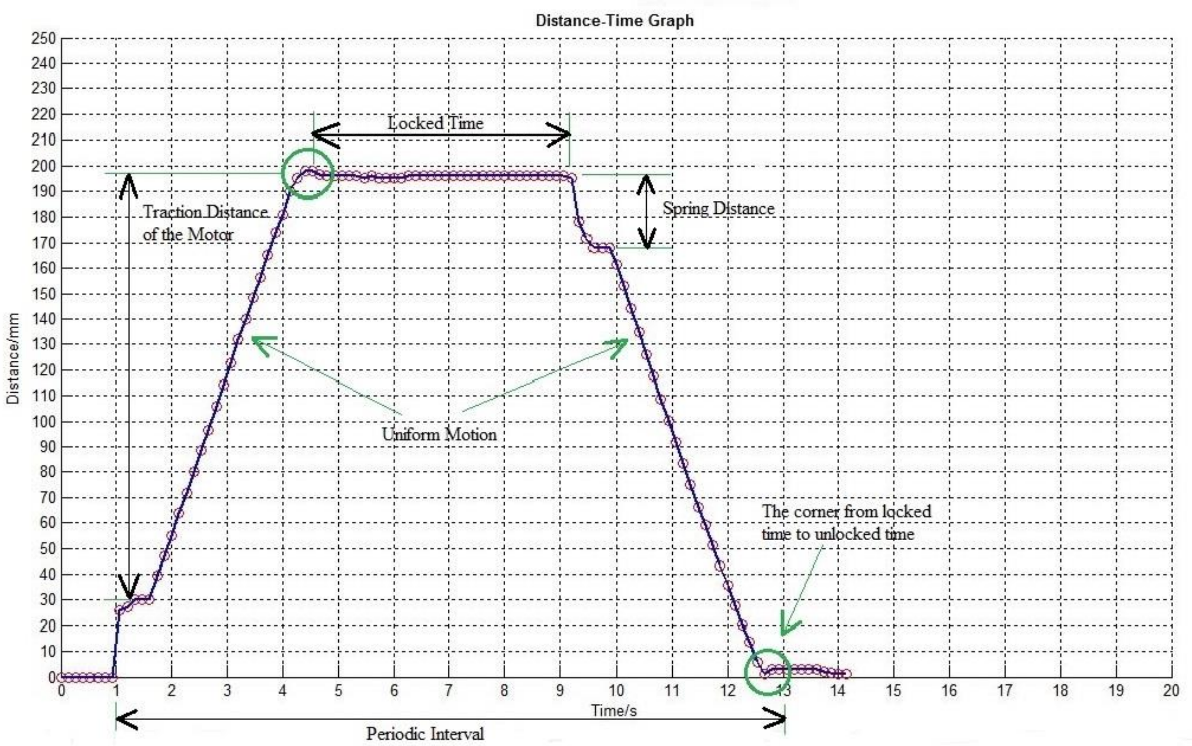

FIGURE 7: TRAJECTORY OF THE SWITCH TIP

A use of a high-speed camera for monitoring the catenary was carried out by the University of Birmingham. A FASTCAM Mini UX100 [5] camera, as shown in Figure 8, was used for the tests.

FIGURE 8: FASTCAM IMAGE CAPTURE DEVICE

Figure 9 demonstrates the results of the image processing algorithms in order to identify the overhead lines and to consider their movements.

FIGURE 9: MONITORING THE OVERHEAD LINES MOVEMENTS USING FASTCAM UX100

One illustration is a camera that is suitable for a railway environment with effective resolution. In this case a 4K Axis camera is proposed [6], shown in Figure 10.

FIGURE 10: AXIS P1428-E 4K ULTRA HD

The evaluation of this camera based on the framework introduced in the D4.2.1 report is shown in Table 1.

TABLE 1: AXIS CAMERA EVALUATION

SENSORS																							
Ref Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibility	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
WEIGHT	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1 Axis P1428	10	10	10	10	5	5	10	0	0	5	5	5	0	5	10	5	10	10	0	5	10	5	**6.1**

The evaluation of the sensor performance shows that this could a suitable sensor. The energy rating for this camera is about 11 W. This can easily be powered up by a solar or wind power system. The evaluation process is shown in Table 2.

TABLE 2: ENERGY SYSTEM EVALUATION FOR THE AXIS CAMERA

ENERGY HARVESTING							
Ref Description	Suitability for installation at different sites	Monitoring and reporting of battery status	Self-diagnostic	Environmental compatibility	Resistance to electromagnetic fields	Mounting simplicity	**ENERGY HARVESTING SCORE**
	17%	17%	17%	17%	17%	17%	
E1 Solare panel BP SX20U	0	10	10	5	5	10	**6.7**

This is system is also suitable for any TCP/IP communication system. However, the cost analysis results are fairly low based on the proposed framework, presented in Table 3.

TABLE 3: COST ANALYSIS OF THE CAMERA SYSTEM

COST PER SENSOR NETWORK (€)							VALUE ANALYSI	
ACQUSITION COST	INSTALLATION COST	MAINTENANCE COST (PER YEAR)	DECOMMISSIONING COST	TOTAL COST (10 YEARS)	COST RANKING	COST INCREASE ON LOWEST	**VALUE RATING (TECHNICAL SCORE / COST)**	**VALUE RANKING**
900.0	100.0	20.0	10.0	1210.0	1	0%	**1.7**	**1**

Another example of vision sensors are laser scanners. Laser scanners can record measurements and evaluate profiles such as rail and wheels. Two and three dimensional models can be produced using these type of sensors. Work has been carried out at the University of Birmingham to assess the capability of using a laser scanner to produce a profile of the railhead. In this work, the Micro-Epsilon ScanControl laser scanner was used, shown in Figure 11.

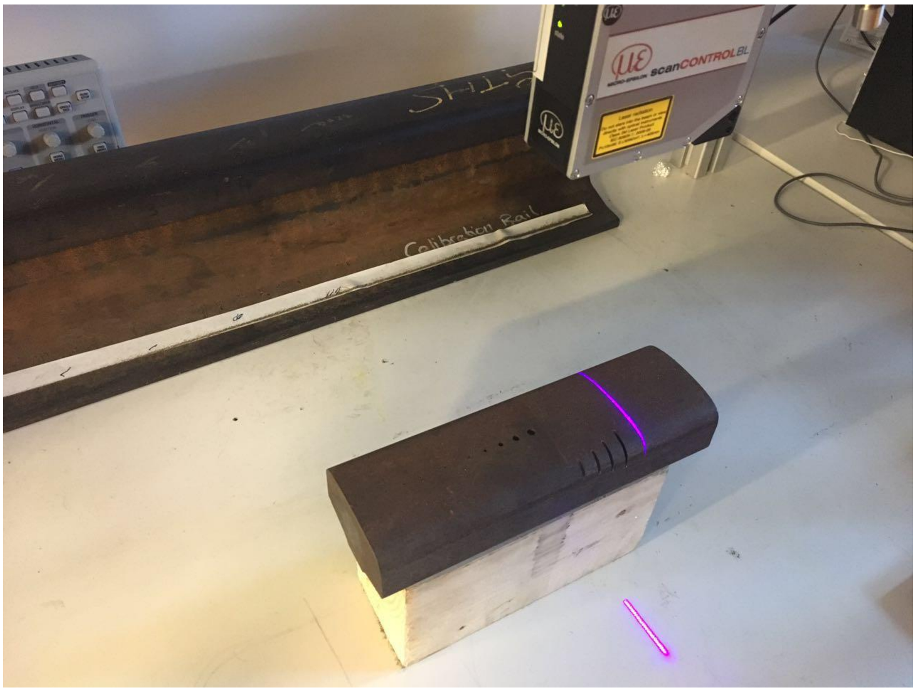

FIGURE 11: MICRO-EPSILON LASER SCANNER AT THE UNIVERSITY OF BIRMINGHAM

Figure 12 is the profile of the rail identified using the laser scanner system and image composition techniques. This can also lead to detection of defects over the railhead. To demonstrate this, a number of processing algorithms were applied and the results for detecting defects of the railhead are shown in Figure 13.

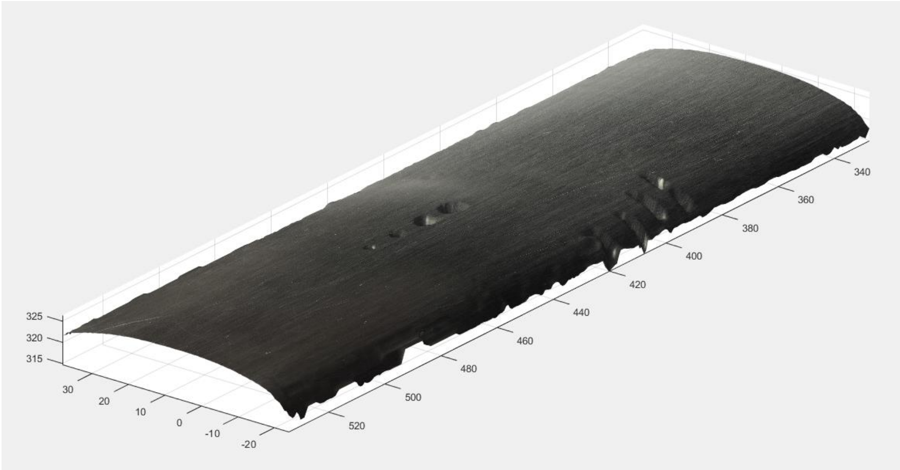

FIGURE 12: RAILHEAD PROFILE PRODUCED BY SCANCONTROL

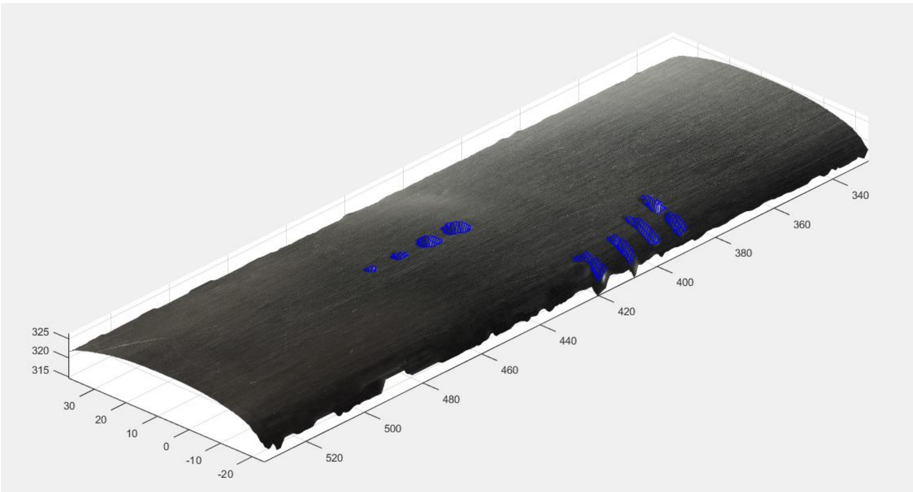

FIGURE 13: IDENTIFYING ABNORMALITIES ON THE RAILHEAD

10.2 GYROSCOPES, GEOPHONES AND ACCELEROMETERS

Gyroscopes are devices that measure rotational motion. Modern gyroscopes can be based on different technologies such as MEMS gyroscopes, ring lasers, fibre optic and quantum gyroscopes.

In terms of functionality, there are two main types of gyroscopes: angular rate gyros and angular position gyros. Angular rate gyroscopes are able to detect the rotation rate and angular position sensors can integrate the angular movement in order get the angular displacement. Until recently, gyroscopes tended to be large and heavy, which limited their application. MEMS technology has recently allowed the development of much smaller and lighter devices, which are mainly used in inertial measurement and navigation systems [7].

Accelerometers are inertial sensors that are able to measure accelerations or vibrations. Either using a single multiple-axis sensor, or a combination of multiple single-axis sensors, it is possible to measure in three orthogonal axes. They can be used for inertial measurement as a sensor of orientation, inclination, tilt and as an impact sensor [8].

Capacitive

Capacitive accelerometers use capacitive sensing to output a voltage that depends on the distance between two planar surfaces charged with an electrical current. When the gap between these surfaces changes, the electrical capacity of the system will also change. The main advantage of this kind of accelerometer is high accuracy and stability.

Piezoelectric

Since acceleration is directly proportional to force, it is possible to detect it using piezoelectric sensing. In a piezoelectric accelerometer, charge accumulates on the crystal and it is then translated into an output of current or voltage. These kind of devices only respond to AC phenomenon such as shock or vibration.

Specifications

Typical accelerometers have a set of basic specifications that must be considered such as: digital/analog output, number of axis, output range, sensitivity (voltage output per g), bandwidth, zero g offset, power consumption and many others [9].

Geophones are motion transducers that are used to measure low-frequency movements. They are small seismic sensors that generate voltage to represent the velocity. In railway applications, they can be mounted on sleepers to measure the movement and vibration produced by passing trains [10].

Inertial measurement units (IMU) include accelerometers and gyroscopes. Using the MEMS technology, the IMUs have become smaller, low power, higher performance, and cheaper. Weston et al [11] clearly explained the use of in-service trains for monitoring the track geometry. The processing techniques can be performed on microcontrollers or computers that have a low power rating. Thus these systems are shown to be highly useful and the use of gyroscopes and accelerometers can determine lateral and vertical irregularities of the track. Additionally, similar sensors have been applied to vehicles to allow automatic identification of other track defects such as hunting and cyclic top; or with different data collection parameters (i.e. faster sampling) it is possible to look for shorter wavelength defects directly at the wheelset interface. These techniques and sensor systems are generally mounted on vehicles to maximise the network coverage, but with higher quality sensors it is also possible to develop localised or trolley mounted systems to perform similar measurements.

As an example, shown in Figure 14, the University of Birmingham has developed a low power (~ 5 W) and inexpensive IMU.

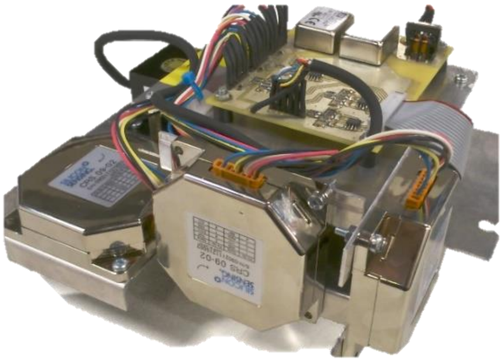

FIGURE 14: UNIVERSITY OF BIRMINGHAM IMU

This IMU was designed to monitor changes in track geometry with fine granularity.
To run this experiment ensuring that there was no interference with any power/signals from the trains and to ease the installation process, the system was designed to be non-intrusive. A battery pack was added to the IMU, which can run the system for up to 24 hours. The IMU was placed in the trailer cab, shown in Figure 15.

FIGURE 15: THE IMU IN THE TRAILER CAB OF A CLASS 395 TRAIN

The evaluation process for the IMU is shown in Table 4.

TABLE 4: IMU EVALUATION

SENSORS																							
Ref Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibility	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
WEIGHT	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1 IMU	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	5	10	10	10	10	10	10	**9.8**

ENERGY HARVESTING							
Ref Description	Suitability for installation at different sites	Monitoring and reporting of battery status	Self-diagnostic	Environmental compatibility	Resistance to electromagnetic fields	Mounting simplicity	**ENERGY HARVESTING SCORE**
	17%	17%	17%	17%	17%	17%	
E1 2000 mA battery	5	10	10	5	5	10	**7.5**

To perform the monitoring from the lineside, the accelerometer can also be mounted on the sleepers to monitor the track movements.

The use of cheap and low power accelerometers, ADXL345 [12], is assessed by designing a low power sleeper node that monitors the track movement, shown in Figure 16.

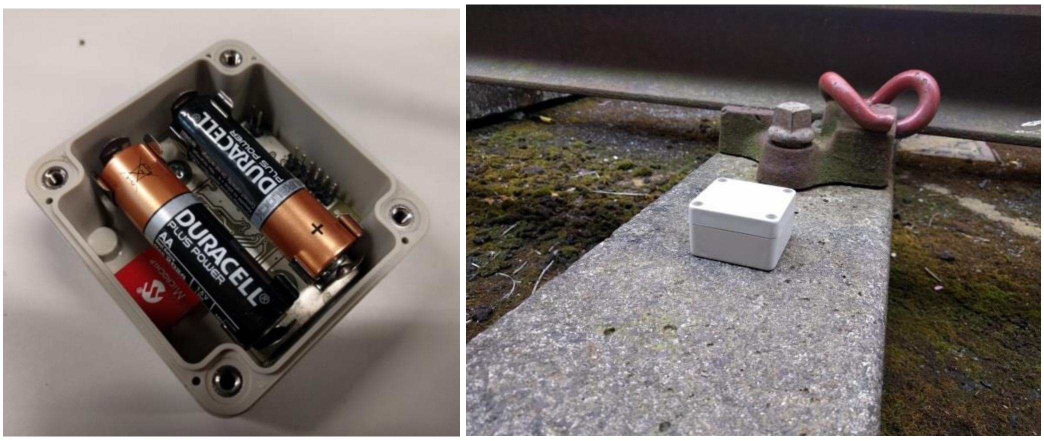

FIGURE 16: UNIVERSITY OF BIRMINGHAM SLEEPER NODE

The nodes can run a battery for up to than 5 years or be powered by a solar panel or wind turbine. The system power consumption is less than 100 mW and it can transfer data wirelessly using an industrial, scientific, and medical radio band (ISM) by Microchip [13], shown in Figure 17.

FIGURE 17: MICROCHIP ISM MODULE

The sensor evaluation for this is presented in Table 5.

TABLE 5: ADXL345 EVALUATION

Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibility	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	SENSOR SCORE
		SENSORS																						
WEIGHT		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1	MEMS Accelerometer ADXL345	10	10	10	10	10	5	10	10	0	0	10	10	0	10	10	5	10	10	10	10	10	5	**8.0**

Table 6 is a comparison of some of the available geophone and vibration sensors.

TABLE 6: GEOPHONES AND VIBRATION SENSORS

Channel	Technology	Model	Description	Range	Sensitivity	
1	Geophone	LF-24	Geo 1 (left)	NA	15	$V/(ms^{-1})$
2	Geophone	LF-24	Geo 2 (co-lo)	NA	15	$V/(ms^{-1})$
3	Geophone	LF-24	Geo 3 (right)	NA	15	$V/(ms^{-1})$
4	Geophone	LF-24	Geo 4 (N/A)	NA	15	$V/(ms^{-1})$
5	Accelerometer	ADXL 103	X	1.7 g	1000	mV/g

6	Accelerometer	ADXL 103	Y	1.7 g	1000	mV/g
7	Accelerometer	ADXL 103	Z	1.7 g	1000	mV/g
8	Accelerometer	CXL04	Z	4 g	500	mV/g
9	Accelerometer	CXL10TG3	X	10 g	166.66	mV/g
10	Accelerometer	CXL10TG3	Y	10 g	166.66	mV/g
11	Accelerometer	KS76(a)	IEPE	120 g	50	mV/g

A set of tests was carried out, by the University of Birmingham, to evaluate the quality of the measurements to assess these sensors. A range of sensors was applied to a single bearer and the outputs recorded simultaneously using a single, common, acquisition system. This allowed a direct comparison of the results obtained from each sensor, and thus a direct comparison of the various sensor technologies. Figure 18 shows the test set-up configuration.

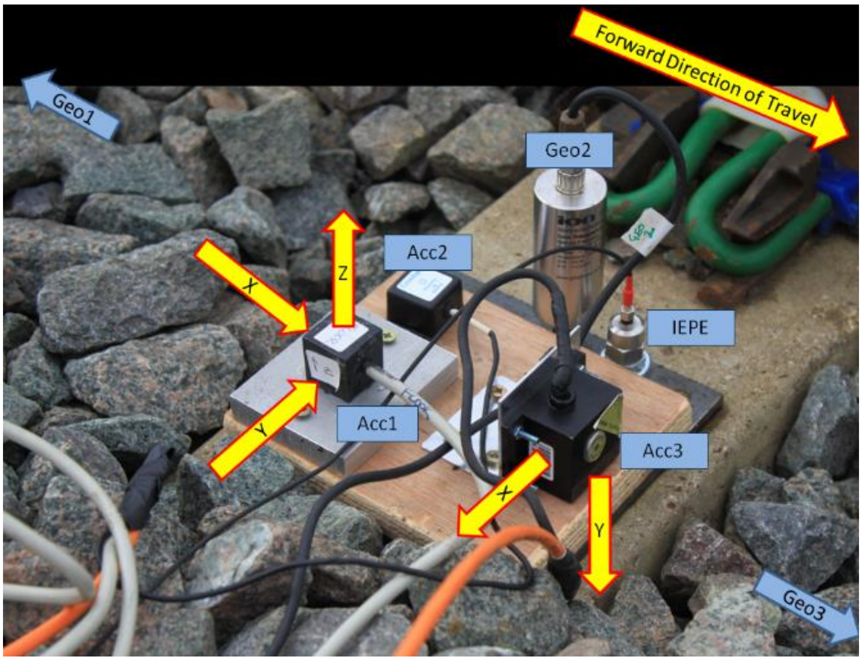

FIGURE 18: SENSORS TESTING ON A SLEEPER

Figure 19 illustrates the results of the vertical speed test. It shows that the accelerometer has a minor drift over time (this can be compensated using post-processing algorithms). Apart from the drift the test demonstrates a good similarity between the two sensors. The accelerometer, CXL04LP1Z, is approximately one tenth the cost of the geophone. This shows that a cheap vibration sensor with suitable post processing algorithms can achieve the same results as an expensive geophone.

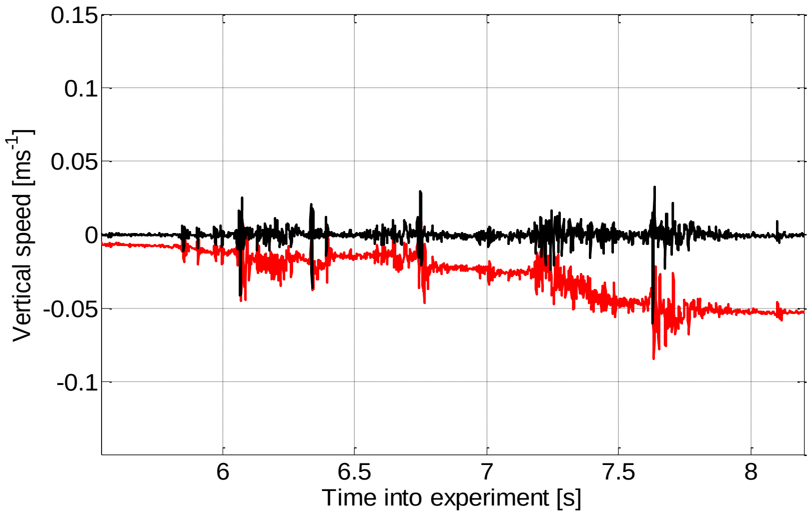

FIGURE 19: GEOPHONE (BLACK) VS ACCELEROMETER (RED)

10.3 STRAIN GAUGE

Strain (ε) is defined as the amount of deformation of a given body due to an applied force. More specifically, ε is the fractional change in length given by $\varepsilon = \Delta L/L$.

Strain can be positive (tensile) or negative (compressive). In practice, the magnitude of measured strain tends to be very small and for that reason it is often expressed as microstrain (με) [14].

One of the most common methods of measuring strain is with a strain gauge, which is a device whose electrical resistance varies in proportion to the amount of strain in it. The most widely used is the bonded metallic strain gauge and it consists of a metallic foil arranged in a grid pattern. This grid is bonded to a thin backing which is attached to the test specimen. Therefore, the strain experienced by the test specimen is also transferred to the strain gauge which responds with a linear change in electrical resistance.

Measurement and signal conditioning

In order to obtain reliable measurements, it is important to properly select the best type of bridge and signal conditioning. In fact, strain gauge measurements produce extremely small changes in resistance and thus it is very important to select the best techniques in order to ensure accurate results [15].

Such small changes in resistance can be measured using strain gauges assembled in a bridge configuration, as shown in Figure 20. This bridge consists of four resistive arms with an excitation voltage V_{EX} applied across the bridge. One to four strain gauges can be used in the same bridge to increase the sensitivity and reduce the disturbance cause by temperature.

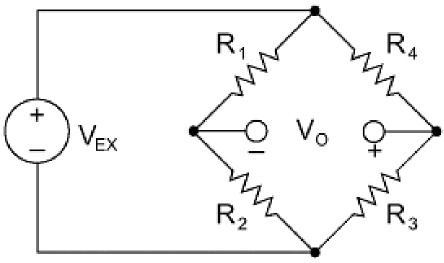

FIGURE 20 - WHEATSTONE BRIDGE

The output of this Wheatstone bridge is given by:

$$V_O = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}\right] \cdot V_{EX}$$

Considering this equation, it can be observed that when $R_1/R_2 = R_4/R_3$, the output voltage is zero and under these conditions the bridge is said to be balanced. When resistors are replaced by an active strain gauge, any change in it will unbalance the bridge and produce a nonzero output voltage.

Ideally, changes in resistance values should only occur when strain is applied, but strain gauges and specimen material to which they are applied also respond to temperature changes [14] [15]. In order to minimize temperature effects, two strain gauges can be used instead of just one. This is called a half-bridge configuration and it is represented in Figure 21.

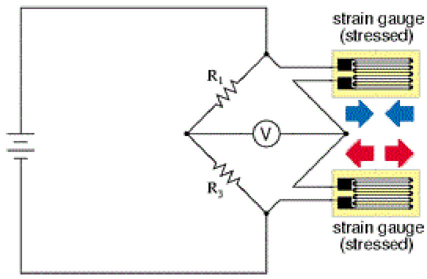

FIGURE 21: HALF BRIDGE CONFIGURATION

Considering both strain gauges are identical, the temperature effects on them will also be identical and the ratio of their resistance does not change. The half bridge configuration also allows double the bridge sensitivity of a single strain gauge.

Besides temperature, other important factors must be considered when using a Wheatstone bridge:

- Resistance values from fixed resistors and strain gauges have tolerances and this will generate some offset voltage. Balancing techniques must be used to rebalance the bridge to zero output, either by adjusting the resistance in the bridge or using software compensation.
- Lead wire resistance is often considered negligible, which can be a source of measurement errors. When lead wires are a few meters long, their resistance will have a considerable effect on the overall resistance of each arm of the bridge. This can be compensated by measuring

the wire resistance and taking it into account when calculating the strain. However, temperature will also have an effect on these resistances. If just one strain gauge is used, a 3-wire configuration will solve this issue.

As for the signal conditioning, it is important to consider the following [15]:

Excitation: A constant voltage source is used to power the bridge; the excitation values are typically between 3 and 10V. A higher excitation voltage generates a higher output voltage, but this can also cause self-heating and therefore larger measurement errors.

Filtering: Hazardous and noisy electrical environments can considerably affect a measurement. Low-pass filters are generally used to remove high-frequency noise.

Fixed resistors: Unless a full bridge configuration is used, the bridge must be completed with fixed resistors. High precision fixed reference resistors with tolerances of 0.1% or 0.01% are easily available in the market.

Remote sensing: When the strain gauges, if the excitation voltage source and the signal conditioner are far away from each other, a voltage drop might exist in the wires connecting the voltage source to the bridge. Some signal conditioners include a remote sensing function in order to compensate these voltage drops.

One of the drawbacks of these sensors is that the signal to noise ratio is low and can be easily affected by the electromagnetic fields.

A generic sensor evaluation for strain gauges is as follows:

TABLE 7: STRAIN GAUGES EVALUATION

SENSORS																								
Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibiliity	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
WEIGHT		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1	Strain gauge	10	10	10	10	10	0	0	10	0	0	10	10	0	10	10	5	0	0	10	10	0	5	**5.9**

10.4 MAGNETOMETER

The magnetometer is an instrument for measuring the strength and direction of magnetic fields. It includes a sensor that is able to measure the magnetic flux density (Tesla), and since this flux density in air is proportional to the magnetic field strength, the magnetometers are capable of detecting fluctuations in the Earth's field. Modern magnetometers can be divided into two classes:

- vector type, that measures both the direction and the magnitude of the magnetic-field
- scalar type, that measures only the magnitude of the magnetic field. Table 8 lists the main characteristics of the most common types of magnetometer.

TABLE 8: MAGNETOMETER TYPES

Type	Field range	Frequency range	Characteristics
Fluxgate	100 pT – 200 µT	DC – 2kHz	Low power, small size and wide-operating temperature range
Induction Coil	1 fT – 1 T	0.01Hz – 1MHz	Low Power, large frequency and field range
SQUID(1)	1 pT – 100 µT	DC – 10kHz	Highest sensitivity but requires cryogenic refrigeration
AMR(2)	5 nT – 200 µT	DC – 10KHz	Medium power, small size and low cost
Hall effect	10 µT – 50 T	DC – 1MHz	Very small size and low cost
NMR(3)	20 µT – 100 µT	DC – 5 Hz	Highest absolute accuracy (10pT resolution). Used as a calibration standard.

(1) Superconducting Quantum Interference Device
(2) Anisotropic Magnetoresistance
(3) Nuclear Magnetic Resonance

They can be used for axle-counting systems and collaborate with the interlocking technologies. A vehicle detection system is proposed based on the use of a magnetometer in [16]. The evaluation of a generic MEMS magnetometer is shown in Table 9.

TABLE 9: MAGNETOMETER EVALUATION

SENSORS

Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibility	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules
	WEIGHT	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
S1	Magnetometer	10	10	10	10	10	0	10	10	0	10	10

Ref	Description	Custom submission rate of	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	SENSOR SCORE
	WEIGHT	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1	Magnetometer	10	10	10	10	0	0	0	10	10	0	0	**6.8**

10.5 TEMPERATURE

Temperature sensors measure the amount of heat energy that is generated by any object or system. Using a temperature sensor, it is possible to detect any change in temperature and produce either an analogue or digital output.

In the railway, rails are made of steel and changes in temperature cause expansion or contraction in the rails. Tracks can buckle because of expansion of the rails, which can cause significant disruption on the network, hence the monitoring of rail temperatures may be an indicator of potential incidents.

There are currently different types of temperature sensors available which have different characteristics. It is possible to divide them into two major types: non-contact temperature sensors, which monitor changes in temperature by using convection and radiation; and contact temperature sensors, which, as the name suggests, need to be in physical contact with the object being sensed and use conduction to monitor changes in temperature.

Thermistors

A thermistor is a type of resistor which changes its physical resistance when exposed to temperature variations. They are generally made from ceramic materials like cobalt, manganese or oxides of nickel. One of the key advantages is the fact that they are accurate and rapidly respond to temperature changes [17].

There are two types of thermistors: NTC – negative temperature coefficient and PTC – positive temperature coefficient. With a temperature increase, NTC thermistors decrease their resistance, while PTC increases.

Thermistors are rated by their resistive value at room temperature (usually 25°C), the time to react to the temperature change (their time constant) and their power rating. For sensing purposes, these sensors' values are generally in the kilo-ohms range.

RTD – Resistance temperature detector

RTD's are precision sensors made from conducting metals with high-purity such as nickel, platinum or copper wound into a coil. The electrical resistance of an RTD changes as a function of temperature, but unlike thermistors, the output is extremely linear, producing much more accurate measurements. However, they tend to have poor thermal sensitivity, meaning that a change in temperature only produces a small resistance change [18].

Like the thermistor, RTD's are passive resistive devices. When a given current flows through the sensor, an output voltage that increases linearly with temperature is obtained. A typical PT100 has a base resistance of 100 Ω at 0°C, increasing to about 140 Ω at 100°C, with a temperature range between -200 to +600°C.

Since RTD is a resistance detector and a current needs to flow through it, variations in the resistance values might occur due to the Joule effect, causing reading errors. To minimize these errors, a small current should be used.

Thermocouple

Thermocouples are electrical devices that consist of two distinct conductors forming electrical junctions placed at different temperatures. As a result of the thermoelectric effect, they produce a temperature-dependent voltage that can be interpreted to measure temperature. Due to their simplicity, they are the most commonly used type of temperature sensor [18].

In contrast to thermistors and RTD's, thermocouples do not require any external form of excitation. Their disadvantage is that, they tend to have very low accuracy (>1°C), and produce a very low output of hundreds of μV.

Silicon bandgap temperature sensors

Silicon bandgap temperature sensors are commonly used in electronic equipment since they can be easily included in a silicon integrated circuit. They have good stability in extreme environmental conditions due to the integral stability of crystalline silicon. Being a reliable and low cost type of sensor with decent accuracy and consistent measurements, they are mainly used in overheating protection systems, power supplies or air-conditioning.

Table 10 presents the evaluation for these sensors:

TABLE 10: TEMPERATURE SENSORS EVALUATION

Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibliity	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
WEIGHT		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1	Non contact IR	10	10	5	10	5	0	5	5	5	10	10	10	10	0	0	5	0	0	10	10	10	10	**6.4**
S2	Thermistors	10	10	10	10	10	0	0	10	0	10	10	10	0	5	5	5	5	0	10	10	10	5	**6.6**
S3	Silicon bandgap	10	10	10	10	10	5	0	10	5	10	10	10	10	10	10	10	10	10	10	10	10	5	**8.9**
S4	RTDs	10	10	10	10	10	10	10	10	0	10	10	10	0	10	10	5	10	10	10	10	10	5	**8.6**
S5	Thermocouples	10	10	10	10	10	0	10	10	0	10	10	10	0	10	10	5	10	10	10	10	10	5	**8.2**

Despite the fact that S3, the silicon bandgap solution, has the highest score, depending on the application, it might be appropriate to apply a different weighting system. In circumstances where a non-intrusive approach is required a non-contact IR sensor might be considered to be more suitable than the low-cost silicon bandgap approach. This is captured in the cost evaluation part of the technology evaluation framework.

10.6 ENVIRONMENTAL SENSING

Climate changes can widely affect the railway systems.

Higher temperatures, precipitation and more common severe and extreme weather conditions can cause substantial damage or disruption to the railway. High temperatures can cause rail bulking, expansion of swing bridges, overheating of the electrical equipment and overhead line sag [19].

Excessive rain can cause flooding. It can also cause scour of bridges, affect the signalling systems and result in track circuit failure. Drought and flood could cause earthworks problems and shrinking of the soil. This can lead to void appearances and movements of the foundations [19].

Heavy snow causes traction issues and with high winds fallen trees and objects on the track can occur.

Icy conditions and other situations with frozen and unfrozen precipitation on the rails of the track can affect the traction systems, as well as causing other problems with track switches. Monitoring systems for detecting snow or ice around a track switch can lead to the prevention of obstruction of the switch and its moving parts, or any other possible faults of the switch and point machines [20].

10.6.1 Precipitation Sensor

Precipitation sensors can usually detect the amount of rain or snow and have selectable sensitivity levels. They are generally low power and robust. Laser, optical, micro rain radar and precipitation collectors are the main systems which are used for precipitation measurements.

The Hydreon RG-11 Rainfall Sensor is an example of an optical rain sensor [21] and its evaluation is shown in Table 11.

Table 11: RG-11 Precipitation Sensor Evaluation

		SENSORS																						
Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibility	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
WEIGHT		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1	Precipitatoin sensor (RG-11)	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**10.0**

Using this evaluation, it can be concluded that the RG-11 sensor is well suited for railway applications in which precipitation monitoring is required. This sensor also has low-power requirements and is comparably inexpensive; it could likely be powered using energy harvesting systems such as solar or wind.

10.6.2 HUMIDITY

A humidity sensor measures both moisture and air temperature. It outputs the relative humidity, which is the ratio of the measured moisture in the air to the highest amount of moisture that can be held at that air temperature.

Typical humidity sensors use capacitive measurement, which relies on electrical capacitance. The sensors are composed of two metal plates containing a non-conductive dielectric between them. Moisture from the air is collected in the dielectric film causing the electric potential between the two metal plates to change. These voltage changes represent the level of moisture in the air [22].

There are other, yet less common, types of humidity sensors like resistive and thermal conductivity sensors. Like many other sensors, humidity sensors can be defined by their size and packaging, accuracy, repeatability, long-term stability, etc.

Humidity is important in the rail industry as it has a direct relationship to adhesion and thus the performance of the wheel / rail interface. Humidity sensors can be used for weather forecast solutions. An example of this that describes work carried out at the University of Birmingham to consider the operation of Rail Head Treatment Trains and their deployment optimisation is presented in [23].

10.6.3 WIND SPEED

Wind data is important for the safety of transport systems. Railway weather stations measure wind speed and direction [24]. For instance, the measurement of wind data in railway tunnels is essential as the restricted space potentially increases the risk of an incident. In larger tunnels or underground/ covered railway stations extraction fans are used to control air flow. If a fire occurs inside the tunnel wind measurements made by anemometers are used to create zero wind conditions in the area of the incident to prevent the spread of fire [25, 26]. Additionally, studies have been carried out at the University of Birmingham to consider the potential benefits of the use of wind measurement data in the wider railway context. Of note, these included consideration of the impact of wind speed on catenary stability and overhead line reliability [27].

A wind speed sensor, also called anemometer, is one of the most commonly used weather sensors. It consists of three or four hemispherical cups mounted on horizontal arms on a vertical shaft in such a way that the air flowing past the cups in a horizontal direction makes the shaft turn at a rate proportional to the wind speed. Vane anemometers are similar, but they can also measure wind direction using a dedicated vane.

Ultrasonic anemometers are also commonly used not only in weather stations but also in aviation systems, wind turbines, ship navigation, etc. They can measure wind speed with very high time resolution when compared to mechanical anemometers (30Hz or more), which makes them suitable for wind turbulence measurements.

Recently, acoustic resonance anemometers have also been developed and used in many applications. They are smaller in size, physically robust and can be easily heated making them resistant to icing. One drawback of this technology is its inferior accuracy when compared to classic ultrasonic anemometers [28].

Wind speed can be measured using anemometers, which can vary. Cup and vane anemometers are the most common type of system to measure wind speed and they are generally low power.

More robust and low maintenance types are ultrasonic anemometers, an example is shown in Figure 22 . They use the time of flight of an ultrasound signal between pairs of transducers. They can also measure very low wind down to 0.01 ms^{-1} and work in a wide temperature range.

FIGURE 22: HIGH RESOLUTION SONIC ANEMOMETER BY GILL INSTRUMENTS [29]

TABLE 12: R3-100 ANEMOMETER EVALUATION

SENSORS																							
Ref Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibility	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
WEIGHT	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1 Anemometer R3-100	10	0	10	5	10	5	10	10	10	10	0	10	5	10	10	5	10	10	10	10	10	10	**8.2**

10.7 FIBRE OPTIC

Fibre-optic sensors are fibre-base devices that can be used to measure temperature, strain, vibrations and acceleration, displacements and many other physical parameters.

Light from a laser or a similar source is sent through an optical fibre which experiences very subtle changes of its most important parameters that are measured when the same light reaches a detector [30].

This kind of technology has many advantages:

- no electric cables are used. They can be used in explosive and high-voltage environments;
- no electromagnetic interference issues. Light is immune to EMI and does not disturb other electrical devices;
- wide temperature range operation;
- multiplexing: a single fibre optic line can be used to interrogate an optical source.

The most common types of fibre optic sensors are called Bragg Grating Sensors. The basic principle is that the wavelength of the maximum reflectivity of a fibre Bragg grating depends not only on its period but also on temperature and mechanical strain. The effects of temperature and strain can be isolated by using reference gratings which are not subject to strain or temperature. The evaluation is shown in Table 13.

TABLE 13: FIBRE OPTIC SENSOR EVALUATION

SENSORS																								
Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatiblility	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
WEIGHT		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1	Bragg Grating	10	0	0	0	10	10	10	10	10	10	0	10	5	10	10	10	10	10	10	10	10	10	**8.0**

Fibre optic cables can also be used in communication systems, which is an additional advantage.

Optical Fibre Bragg Grating (FBG) is a sensing technology that measures changes in the wavelength of light transmitted using a fibre optic cable. Strain on the cable changes the wavelength, as shown in Figure 23.

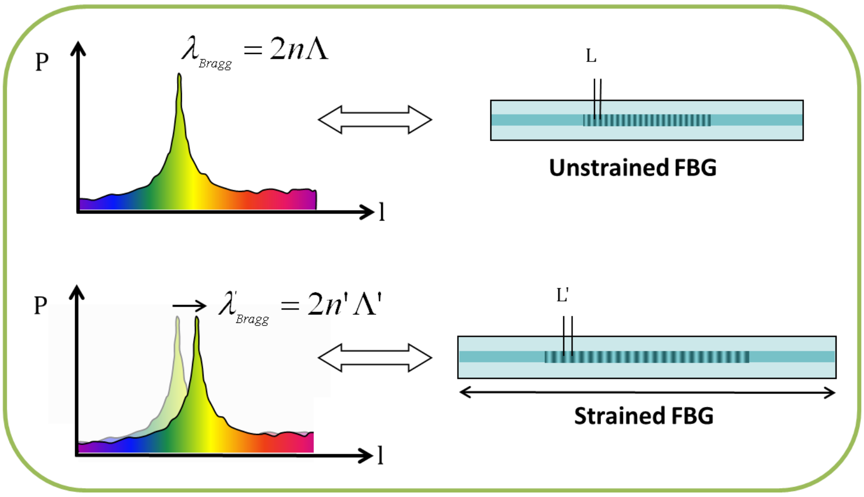

FIGURE 23: USE OF FBG TO IDENTIFY STRAIN [31]

The use of FBGs for railway applications is considered to be of interest due to the natural synergy between long, linear, track sections and the fibre optic form factor. Work within the Capacity4Rail project considering FBG technologies has tended to centre on the slabtrack / new infrastructure model. A review of trackside monitoring solutions using strain gauges and FBGs is presented in [32]. The use of this technology to determine movements and slippage of geotechnical structures such as dikes, dams, embankments and slopes has also been demonstrated in [33].

10.8 ACOUSTIC

An acoustic sensor is a device that measures the sound pressure level (microphones), usually from a couple of Hz to 20 kHz. There are also ultrasound sensors that are capable of detecting sound waves above that range.

Acoustic sensors (microphones) are air coupled and sensitive to noise. Therefore the signal to noise ratio (SNR) depends on the environment, and it can be low.

In the railway, they can be used to monitor the environmental noise, wheel/rail interface effects, axle bearings, wheelsets and gearboxes [34]. Currently, track based noise qualification systems and maintenance schemes are well placed to provide an improved calculation of rolling noise with continuous monitoring. This is to provide track noise management tools, for use in noise mapping and hot spot action plans. Microphones can be used for monitoring systems to measure the real roughness values and track decay rate values [35].

Microphones are usually low power but in most applications they require pre-amplifiers for a better SNR while being transmitted over the wire, as they are highly sensitive to electromagnetic noise. Figure 24 is an example of a free-field microphone that can be installed on the trackside due to its weatherproofing capabilities [36].

FIGURE 24: FREE-FIELD IP55 MICROPHONE

The evaluation for this microphone is shown in Table 14.

TABLE 14: EVALUATION OF A FREE-FIELD MICROPHONE

Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibiliity	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
WEIGHT		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1	130A24 Microphone	0	0	0	0	10	10	10	10	0	0	0	10	5	10	10	10	10	10	10	10	10	10	**6.6**

10.9 CURRENT

Current measurements of electric motors such as point machines and ventilation fans can be used for monitoring purposes. Electrical or mechanical faults affect the magnetic field within the induction machines. The effect can be extracted from the current measurements within the stator. This method, by analysing the measured current signals, can detect faults within the motor and any existing failures in power electronic or invertor systems. Motor current signature analysis is a non-intrusive online monitoring method often used for fault detection and diagnosis of induction machinery [37].

One of the advantages of this method is that access to the machinery is not needed. Split-core clamp current transducers (CT) can be used to avoid any inference in electrical wiring, shown in Figure 25.

FIGURE 25: SPLIT-CORE CURRENT SENSOR [38]

Table 15 is a general evaluation for the split-core current transducer.

TABLE 15: EVALUATION FOR A CT

SENSORS																							
Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Wake up under event	Different time for sensing/sending	Scalability	Environmental compatibiliy	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	SENSOR SCORE
WEIGHT		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
S1	Split-core CT	0	0	0	0	10	10	10	10	10	0	10	10	5	10	10	10	10	10	10	10	10	10	7.5

Monitoring point machines and track circuit systems are the main uses of current transducers and current monitoring systems in the railway domain [39].

10.10 CONCLUSIONS – SENSING TECHNOLOGIES

In this section, a variety of sensing technologies and their importance in the rail industry have been presented. A framework based assessment of each sensor has also been carried out. A number of laboratory sensor evaluation examinations were carried out and the results have been discussed.

The next section focuses on the energy harvesting technologies that can be used to provide suitable power to support these sensing technologies.

11 Energy Harvesting and Storage Systems

In this section, a number of energy harvesting techniques and technologies are described. The section also considers the power capability and system reliability for each technology.

Energy harvesting is an attractive technique for a wide variety of self-powered micro-systems. Wireless sensor networks are a good example of such systems particularly when minimal maintenance or user interaction is a requirement.

The use of energy harvesting in railways will reduce the need for running cable around the infrastructure; thus reducing some of the cable related maintenance regimes. It will also simplify the installation of new monitoring systems, especially at locations where the access to the grid is difficult, for example around railway bridges.

Small amounts of energy harvested from sources such as solar, magnetic, thermal or vibration can be used to power sensing devices in remote locations. Studies have shown that the power density of energy harvesting devices can be hundreds of µW; however the literature also reveals that power requirements of many electronic devices are in the mW range. Therefore, a key challenge for the successful deployment of energy harvesting technology remains, in many cases, the minimisation and management of the energy used [40].

11.1 Solar

Modern solar power systems have a variety of uses in off-grid applications to provide electrical power at sites where the grid is inaccessible or too costly.

Photovoltaic (PV) cells are one of the most mature energy harvesting technologies. They are widely used to provide power to homes and businesses, as well as electronic devices, including sensors. PV cells are made from different semiconducting materials, including various forms of silicon such as monocrystalline, polycrystalline and amorphous, as well as other different compounds. Each of these have different kinds of energy conversion efficiency, defined as the ratio of the incident solar power to the electrical power generated. Cell efficiencies can vary from 6% for amorphous silicon to a little over 40% for multiple-junction research cells [41] [42]. Typical single-junction silicon cells produce approximately 0.5-0.6V and they are usually connected in series to provide usable voltages for easy integration with electronic circuitry.

Since sensors will be placed at an outdoor location, a small solar panel can be a good alternative to provide the necessary power. Sun light is in fact an abundant energy source and PV cells are inexpensive and well established. Also, the voltage and current levels can be easily matched with microelectronics and they have a relatively consistent efficiency over a broad range of wavelengths.

However, using this technology in hazardous environments can be a challenge. Even though there are no moving parts the cells can last for decades, and special considerations must be taken into account when installing them. They must be placed in a correct orientation in order to maximise the output power, and they must also be kept clean and free from obstructions. When placed next to the rail, they might end up covered with dust at each train passage thus seriously reducing the system's efficiency.

Also, the energy is delivered for only part of the day and it highly depends on latitude and atmospheric conditions. Power outputs for different conditions are shown in Figure 26, where the power output from a 10x5 cm solar panel with 13% efficiency is represented as a monthly average.

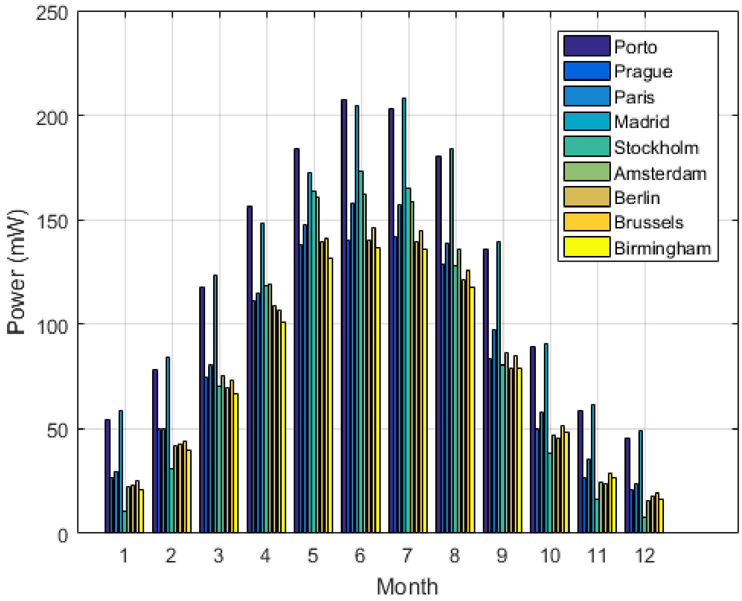

FIGURE 26: SOLAR POWER (MONTHLY AVERAGE)

Less favourable latitude and atmospheric conditions can limit the sensor nodes to discrete measurements because of the considerably lower power output from the solar panels.

BP Solar panels, shown in Figure 27, are photovoltaic modules that can be used in conjunction with batteries and wind turbines. These can produce up to 5W and are available in a range of sizes. The maximum size is approximately 500x600x50 mm [43].

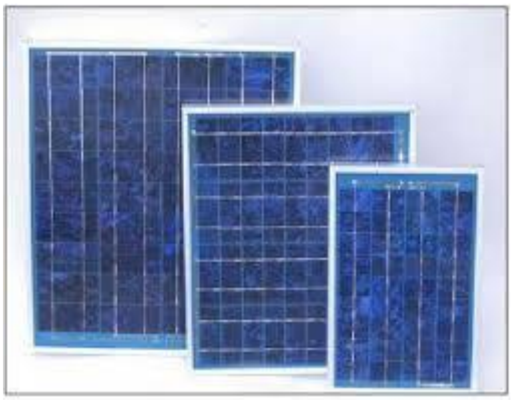

FIGURE 27: BP SOLAR PANELS

TABLE 16: EVALUATION FOR SOLAR GENERIC PANELS

ENERGY HARVESTING								
Ref	Description	Suitability for installation at different sites	Monitoring and reporting of battery status	Self-diagnostic	Environmental compatiblity	Resistance to electromagnetic fields	Mounting simplicity	**ENERGY HARVESTING SCORE**
	Weight	17%	17%	17%	17%	17%	17%	
E1	Solare panel BP SX20U	5	5	0	5	10	10	**5.8**

Solar and similar energy harvesting technologies are usually used in combination with battery storage systems. However, the outputs of these technologies need specific power electronic circuits to make the outputs suitable for charging batteries. Figure 28 shows an example of the type of power electronics that regulates the voltage outputs for appropriate charging systems [44].

FIGURE 28: STECA VOLTAGE REGULATOR FOR SOLAR PANELS

11.2 THERMAL

Energy can be harvested wherever a difference in temperature exists. Human or animal skins, vehicle exhaust systems or domestic radiators are some of the typical applications for this kind of energy harvesting technique [45], although the greater the thermal gradient, the greater the potential for energy harvesting generally is.

Small scale thermoelectric generators generally consist of hundreds of thermocouples that are connected together electrically in series and thermally in parallel. These thermocouples operate using the well-known Seebeck effect to generate electrical energy.

The energy generated by thermoelectric conversion is extracted from the TEG (thermoelectric generator) using an interface circuitry which consists mainly of a step-up voltage converter carefully tuned to match the TEG's internal resistance to ensure an efficient operation.

There are currently small solid state TEG's available in the market that can be a good alternative to install on the rail and generate energy from temperature differences. However the installation technique must guarantee a low thermal resistance between the rail and the TEG. Also, a heat sink is normally installed in order to maximise the temperature difference between hot and cold sides, making the whole EH system bulkier.

Finally, these thermal generators tend to have a relatively high cost and low power generation when compared to solar, wind and piezoelectric generators.

Micropelt MPG-D655 is an example of thermogenerator device [46], shown in Figure 29 .

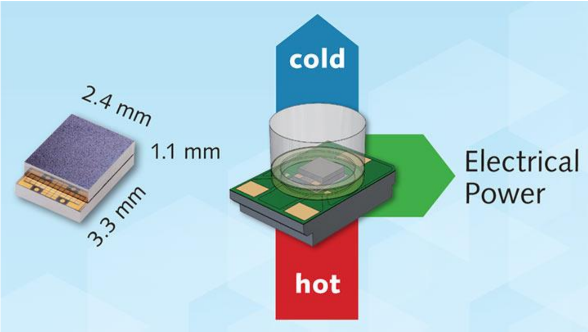

FIGURE 29: MICROPELT THERMOGENERATOER [46]

Table 17 shows the evaluation of this technology.

TABLE 17: MICROPELT THERMOGENERATOR EVALUATION

ENERGY HARVESTING								
Ref	Description	Suitability for installation at different sites	Monitoring and reporting of battery status	Self-diagnostic	Environmental compatiblity	Resistance to electromagnetic fields	Mounting simplicity	ENERGY HARVESTING SCORE
	Weight	17%	17%	17%	17%	17%	17%	
E1	Micropelt thermogenerator	5	0	0	5	10	0	**3.3**

11.3 WIND

Wind turbines are used in order to convert the air flow to mechanical power. The mechanical power is then converted to electricity using generators. However, using wind turbine can be limited to the geographic location of interest. They usually operate from 3 to 25 m/s and beyond that they have to stop [47]. In order to have an optimised use of a wind turbine, especially where the wind gusts can go over the normal operation limit, the output of the turbine should also be compatible with the electronics and energy storage system. Thus a low voltage DC output 12-48V is desirable.

An example of a wind turbine to address this is shown in Figure 30.

FIGURE 30: LE-V50 VERTICAL AXIS WIND TURBINE [48]

This turbine can operate in locations where wind gusts reach 27 m/s or temperatures go down to -40°C. It features enhancements that reduce the stress and fatigue on the blades during prolonged periods of storm force winds. Features include polycarbonate cowlings, blade load spreader plates, an upper baffle plate to prevent damage to the upper cowling and the turbine is painted black to reduce the build-up of rime ice.

The LE vertical axis wind turbines are compact, silent and lightweight turbines designed to trickle charge batteries or for low power electronic devices such as data-loggers, radio and telemetry equipment [48]. The evaluation information for this wind turbine is shown in Table 18.

TABLE 18: LE-v50 EVALUATION

ENERGY HARVESTING								
Ref	Description	Suitability for installation at different sites	Monitoring and reporting of battery status	Self-diagnostic	Environmental compatiblity	Resistance to electromagnetic fields	Mounting simplicity	**ENERGY HARVESTING SCORE**
	Weight	17%	17%	17%	17%	17%	17%	
E1	LE-v50 wind turbine	5	5	5	5	10	10	**6.7**

11.4 ELECTROMAGNETIC

Radio frequency radiation belongs to part of the electromagnetic spectrum between 10 kHz and 300 GHz. RF energy harvesting allows the wireless devices to harvest energy from RF signals and it is a wireless energy transfer technique [41], demonstrated in Figure 31.

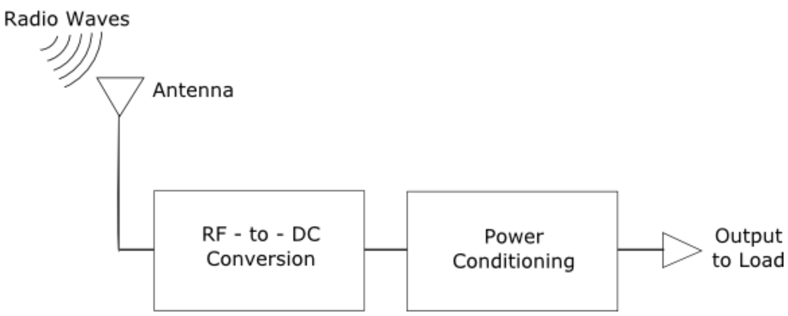

FIGURE 31: RF-BASED POWER SUPPLY

The power source can either be ambient RF energy harvested from DTV, GSM and 3G or a dedicated power RF power transmitter for the wireless sensor node. In both cases, there is a need for a RF receiver that should be easily installed near the sensor. One of the main advantages of this method is that the harvested energy is controllable and predictable. On the other hand, there is a limit on how much power can be transmitted by an RF source when using microwaves. In the IEEE 802.11 standard, the maximum transmission power is 1 W in the USA, 100 mW in Europe and 10 mW/Mhz in Japan [41, 45].

A DC power bus can be installed along the rail to power a set of RF transmitters. This kind of solution would eliminate the installation of wires from the power source to the sensor node, thus reducing the overall installation costs and complexity.

Other known techniques are inductive coupling and magnetic resonance coupling. The first one is based on magnetic coupling that is able to deliver electrical energy between two coils tuned to resonate at the same frequency, while the latter utilises evanescent-wave coupling to transfer the electrical energy between two resonators. These techniques are known as near-field wireless transmission. Although it is possible to obtain high conversion efficiencies, the receiver and transmitter must be very close to each other. This drawback makes it hard to take advantage of this kind of wireless energy transmission for railway applications [42].

Currently, there are commercial products available which are capable of transferring power wirelessly with up to 30% efficiency. Some are already being used in the gas and oil industries. Powercast products are good examples of this type of energy harvesting technology [49]. The evaluation for such a system is shown in Table 19.

TABLE 19: POWERCAST EVALUATION

ENERGY HARVESTING								
Ref	Description	Suitability for installation at different sites	Monitoring and reporting of battery status	Self-diagnostic	Environmental compatibility	Resistance to electromagnetic fields	Mounting simplicity	**ENERGY HARVESTING SCORE**
	Weight	17%	17%	17%	17%	17%	17%	
E1	Powercast	5	10	10	10	5	0	**6.7**

11.5 KINETIC/VIBRATION

Mechanical vibration is a source of ambient energy commonly converted into usable electrical energy. Generally, the electrical energy is generated by using vibrations present in the environment to apply strain energy to a piezoelectric material which becomes electrically polarized when subjected to strain.

Piezoelectric materials can be used as transducers that couple electrical energy and mechanical force. That way, when the piezoelectric is subjected to a mechanical stress an electrical charge is produced.

Although there are other methods of converting energy using mechanical vibration such as electromagnetic, electrostatic and a few others, piezoelectric transducers are best suited for railway applications. These transducers are self-contained elements with no additional requirements which makes them easy to install. They can be miniaturized as needed. As a disadvantage, these transducers tend to have high output impedance which requires special considerations while designing the energy harvesting circuitry.

Figure 32 represents the displacement of the rail when the train *Alfa Pendular* passes by. A dynamic strain stress machine was used to evaluate in lab the energy generated using a piezoelectric transducer from *PI Ceramic.* These experiments were performed using an energy storage module recommended for this transducer and the voltage generated was measured at the storage capacitor. The main results are shown in Figure 33.

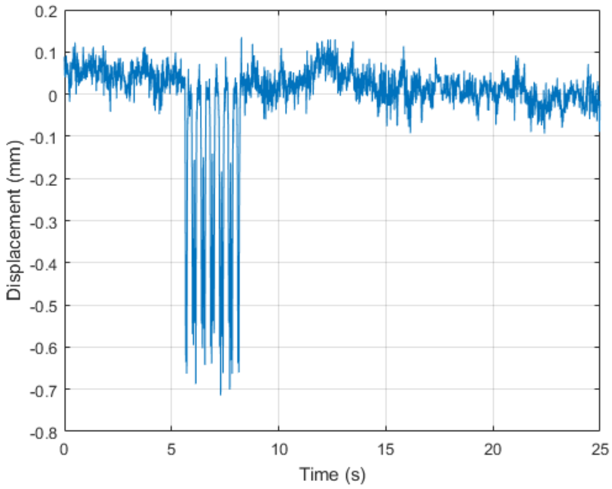

Figure 32: Rail displacement for an Alfa Pendular train

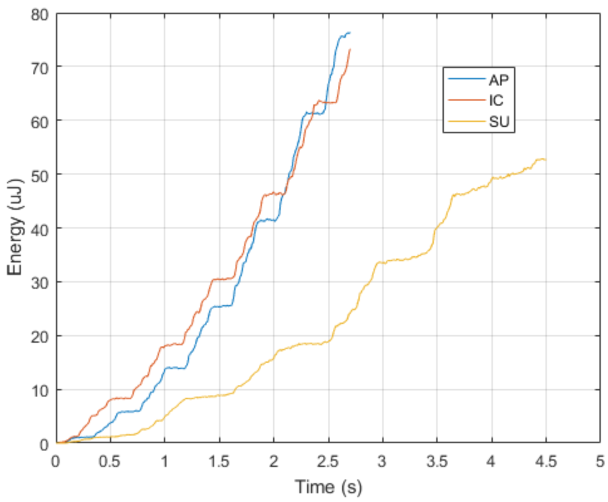

Figure 33: Energy generated by AP - Alfa Pendular; IC - Intercity; SU - Suburban

Figure 33 shows that the amount of generated energy varies from 52 µJ for a suburban train, up to 76 µJ for a high speed *Alfa Pendular* train. These results can be easily enhanced by simply using a stack of several transducers connected in series or/and by changing the frequency of vibration to match the resonance.

Figure 34 shows some flexible, compact and cheap piezoceramic actuators.

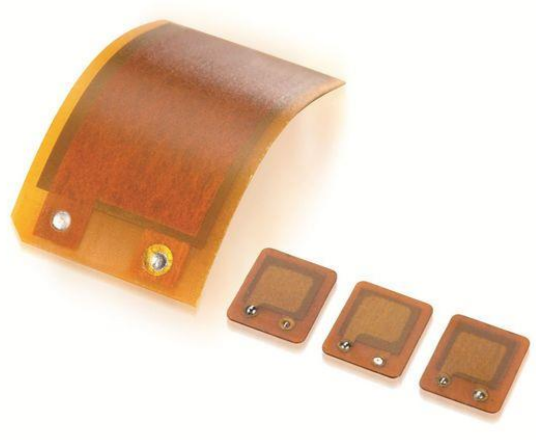

Figure 34: P-876 DuraAct patch transducers [50]

To generate electricity, this module connects to an OEM electronic device, shown in Figure 35.

Figure 35: Electronic module for P-876 module [51]

The evaluation for this system is shown in Table 20.

Table 20: PI system evaluation

ENERGY HARVESTING								
Ref	Description	Suitability for installation at different sites	Monitoring and reporting of battery status	Self-diagnostic	Environmental compatiblity	Resistance to electromagnetic fields	Mounting simplicity	ENERGY HARVESTING SCORE
	Weight	17%	17%	17%	17%	17%	17%	
E1	PI system	5	10	10	10	5	5	**7.5**

11.6 Energy storage systems

In order to obtain standalone systems, energy storage is the key component for creating sustainable energy systems. Current technologies, such as solar photovoltaic and wind turbines, can generate energy in a sustainable and environmentally friendly manner; yet their intermittent nature still prevents them from becoming a primary energy carrier. Energy storage technologies have the potential to offset the intermittency problem of renewable energy sources by storing the generated intermittent energy and then making it accessible upon demand.

11.6.1 Technologies

11.6.1.1 Chemical batteries

A rechargeable battery comprises three major components: the positive electrode (cathode), the negative electrode (anode) and the electrolyte, solid or liquid, which together form an electro-chemical cell. The electrodes are immersed in the electrolyte and the cell produces a voltage. Usually this voltage is less than 2V, but several electrochemical cells connected in series provide the output voltage. During discharge, redox (reduction oxidation) reactions take place and the electric current flows in the external circuit from the cathode to the anode. As the reactions are reversible, the battery can be recharged by applying an external voltage across the electrodes. Depending on the electrodes and the electrolyte, there are many different batteries that can operate in different conditions for different applications. As the durability of the batteries depends on the depth of discharge, it is important to bear this in mind in evaluating these technologies.

11.6.1.1.1 Lead-acid

This is a mature technology, especially with the experience gathered from decades of use in the automotive and rail industries.

One of the more modern types of lead-acid batteries is AGM (absorbed glass mat). AGM is a special glass mat design that aims to wick the battery electrolyte between the battery plates. AGM batteries contain enough liquid to keep the mat moist with the electrolyte and if the battery is broken no free liquid is available to leak out.

Another type is the Gel Cell which contains a silica gel that the battery electrolyte is held in; this thick paste shape material allows electrons to flow between plates and will not leak from the battery if the case is broken.

Both batteries have similar characteristics; such as deep cycle, low self-discharge, safe for use in areas with limited ventilation systems, and they can be transported safely without requiring any special handling or being spilled. These batteries are maintenance free.

AGM is preferred when a high burst of amps may be required. Gel Cell batteries are usually more expensive and do not offer the same power capacity as the same physical size AGM batteries. The Gel Cell batteries have slow discharge rates and slightly higher ambient operating temperatures. One of the drawbacks of the Gel Cell is that they must be recharged correctly or the battery will fail. The battery charger being used to recharge the battery(s) must be designed or adjustable for Gel Cell Batteries with special regulators. Gell cell batteries also have a greater life expectancy [52].

Gel batteries are suitable for repeated cycling and heavy discharge circumstances. They are also resistant to freezing. These types of batteries are currently used in conjunction with wind, solar and other energy harvesting systems [53].

11.6.1.1.2 Nickel cadmium (NiCd)

A mature technology, initially deployed at appliance level, it offers advantages such as robustness to deep discharges, a long lifecycle, temperature tolerance, and a higher energy density than lead-acid. Drawbacks are the use of cadmium, a highly toxic material, the costs, the need for advanced monitoring during charge and discharge, due to the memory effect, and the periodic need to perform a complete cycle. In Europe, however, its use for consumer appliances has been banned by Directive 2006/66/EC. The technology has been deployed at the Golden Valley Electric Association, Alaska, providing 27 MW for 15 min or 46 MW for 5 min for VAR support, spinning reserve, frequency regulation, power system stabilisation, load following, load levelling and black start applications.

11.6.1.1.3 Nickel-metal hydride (NiMH)

A variant of NiCd, this technology has a higher energy density and is more environmentally friendly due to the use of non-toxic materials. The drawbacks include the high self-discharge of the basic version and the dependency on the limited supply of rare earth materials. It is used in consumer electronics. In rating terms, it is available up to the kW scale, being used in electric vehicles.

11.6.1.1.4 Lithium ion (Li-ion)

Highly deployed in the market for small appliances, these batteries have a very high efficiency and reliability, a good energy density and a slow self-discharge rate. However, they are still expensive for medium and large-scale power, even though they are being deployed more widely, which will probably lower the cost. Their energy capacity may reach 30 MWh.

11.6.1.1.5 Sodium sulphur (NaS)

This is a high-temperature battery, with a working temperature in the region of 300˚C. Its advantages include quick reversibility between charging and discharging, efficient operation, the ability to provide pulse power over six times its continuous power rating, low maintenance, long life, and good scale production potential. One drawback is that it needs to maintain a high operating temperature, which discharges it indirectly. It is an economic option for both power quality and peak saving. Some authors state that this technology has corrosion problems that may impair its reliability.

In Europe, some systems have been installed in Germany. At present, the world's largest sodium sulphur battery is installed in Japan with a rating of 220 MWh.

11.6.1.1.6 Sodium nickelechloride (Na-Ni-Cl or zebra)

Small and light, this technology possesses a fast response, robustness to full discharge and a very high energy density. Its drawbacks include its high cost and self-discharge. Some authors foresee a great potential for these devices in conjunction with intermittent renewable energy. Until now, the technology has mostly been used in electric vehicles and submarines

11.6.1.2 Flow batteries

Flow batteries are electrochemical devices which store energy in solutions (electrolytes) containing dissolved electroactive species. To release energy, a reversible electrochemical reaction between the two electrolytes takes place as the electrodes form the electrochemical cells. Unlike conventional batteries, which contain the reactive compounds, redox flow batteries use electrolyte solutions stored in external tanks, so the capacity of the system is determined by the size of the electrolyte tanks, while the system power is determined by the size of the cell stacks, allowing independent scaling of power and energy capacities. Flow batteries are highly flexible in terms of energy, as the energy is proportional to the amount of electrolyte utilised. They have a high efficiency, short response times when compared to other batteries, symmetrical charge and discharge, and quick cycle inversion. Also, they can be optimised for either real power (MW) or reactive power (MVAR). The drawbacks are the low power density, the toxicity of some materials used and insufficient deployment at commercial level. Nevertheless, vanadium redox (VRB) and zinc bromide (Zn-Br) batteries are available on the market. Other subtypes exist, such as the vanadium bromide battery, the zinc cerium battery, or the polysulphide bromide (PSB) battery, but are at an earlier stage of development. A PSB plant was to be built at Innogy’s Little Barford PowerStation, UK, with 15 MW/120 MWh. VRB systems are installed at several locations worldwide, including a 15 kW x 8 h power system in the SYS Lab in Risø (DTU), Denmark, a 250 kW x 8 h system installed by PacifiCorp in Moab, Utah, for load levelling (peak shaving) and a 50 kW x 4 h system operated by the National Renewable Energy Centre (CENER), Spain.

11.6.1.3 Metal-air batteries

Metal-air batteries use metal as a fuel to supply electricity. This technology is said to have a high potential in the future. However, it still needs development, particularly with regard to the charging stage. Some devices are unable to recharge and need material replacement. Their low efficiency and low power output are barriers still to be overcome. The most developed system is zinc-air, although some references are also found to lithium-air. Its biggest advantage is the environmental impact, as it uses non-toxic and recyclable materials. The technology is still at an early stage of development, with some characteristics still to be evaluated.

11.6.1.4 Flywheels

Flywheels take advantage of the possibility to store electricity as kinetic energy. When it charges, the flywheel accelerates. When it discharges, the kinetic energy is withdrawn. There are two main types: low- and high-speed, also termed high-power and high energy, respectively. The first type is cheaper but has a short discharge time (some seconds to a few minutes).

The second type can supply energy for more time (up to an hour) but is about 100 times more expensive. The advantages of this technology are its apparent immunity to the number of cycles, the speed of charging and discharging, power rating and modularity. The drawbacks are the limited energy storage for the low-speed type and the cost of the high-speed type. This technology has been successfully deployed in remote electric systems, allowing further penetration of renewable energy sources at such locations. This is the case with the Flores and Graciosa islands in Portugal.

11.6.1.5 Superconducting magnetic energy storage (SMES)

In SMES, the energy is stored in a magnetic field created by the flow of direct current in a superconducting coil. These coils do not degrade with usage or time, so durability and reliability depend only on the auxiliary equipment, such as power converters. The advantages of SMES are high efficiency, durability and reliability, short response times, no self-discharge and low maintenance. The disadvantages are the very high cost and the impact of the magnetic field. It may be used for short-duration energy storage, particularly in PQ (power quality) and small-sized applications. This technology is suitable for connection at distribution level or at an end-user site for high-quality power. Several installations have been deployed worldwide, particularly in the US. Europe also possesses some devices, for example at the Technical University of Munich. Some authors envisage, as a goal for this technology, the production of 100 MW devices by 2050 with an efficiency of 99%.

11.6.1.6 Supercapacitors

Energy is stored in the electric field produced between the two electrodes of the capacitor. Compared with normal capacitors, supercapacitors make use of their particular structure to provide an outstanding capacitance. The main features are their exceptional efficiency, the performance at low temperatures, no need for maintenance, immunity to deep discharges, speed of response, and extreme durability. Drawbacks are the high cost, high self-discharge, and low energy density. The technology is comparatively young, but has been evolving at a remarkable pace and is regarded as an excellent solution for voltage regulation. These systems are being increasingly used in Japan in voltage regulators.

11.6.1.7 Hydrogen storage systems (with fuel cells)

Hydrogen can be used as storage medium for electricity. Hydrogen can be produced by extracting it from fossil fuels, by reacting steam with methane or by electrolysis. This last method is the one that allows electricity to be stored in a direct way. Moreover, it is the most promising as it is the most cost efficient and does not produce pollutants. In terms of storage of the hydrogen itself, it can be stored using one of the following three techniques: pressured vaporous hydrogen, cold liquid hydrogen, or hydrogen compound in chemical or physical structures. The first technique is suitable for big installations, the second one for the transportation of large quantities or mobile applications and the third one for applications where portability and space are relevant [9]. Finally, the hydrogen is supplied to a fuel cell which then uses it to produce electricity.

Several types of fuel cells exist, with different levels of efficiency and cost. Some types are quite sensitive to non-continuous cycles.

11.6.1.8 Thermal energy storage (TES)

Thermal energy storage involves storing electricity as heat, either at low or high temperatures. When needed, the stored heat is converted into electricity by heat engines. In broad terms, two thermal storage processes can be used [21]. One is based on the heat capacity of the storage medium and the other on the phase change of the storage medium. Several materials may be used as the storage medium, including water, molten salt and lithium fluoride. Some thermal storage systems use either ice or chilled water, accumulating during the night all or part of the freezing capacity needed for the day. The technology can be found in fossil or biomass thermal power plants, where it is seen as a way of increasing efficiency by storing thermal energy at lower demand moments and using it at peak demand. Similar systems are used in some concentrating solar power plants, as a way of storing the energy for times when it is more needed and/or keeping production constant by minimising the impact of events such as passing clouds. A third possibility is using this technology to convert electricity into heat, storing it and then inverting the process when that energy is needed.

11.6.2 Classification and status

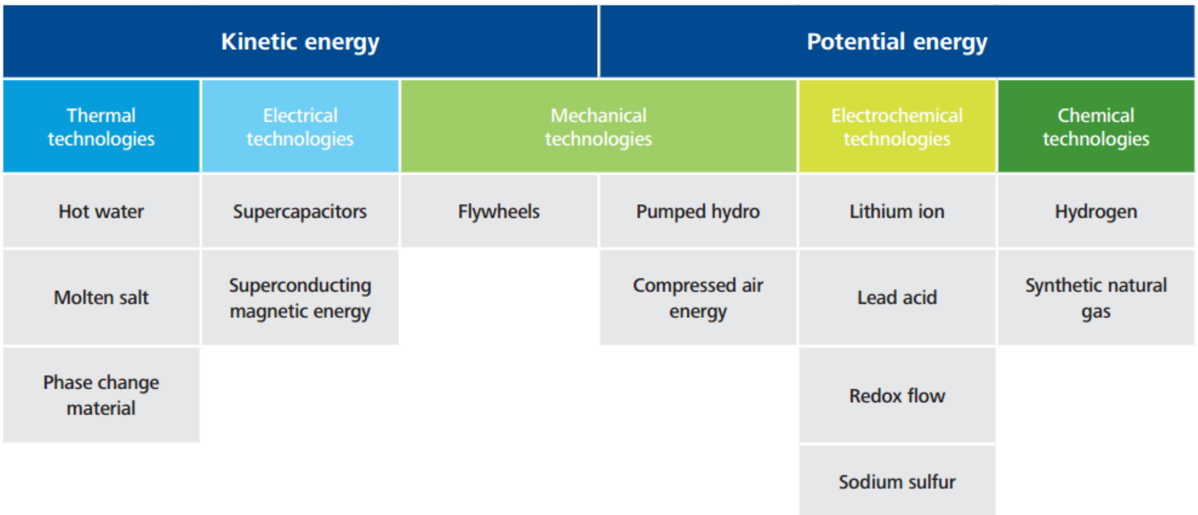

Figure 36: Energy Storage Technologies

The combination of the information on availability with assessments of maturity is shown in Figure 37. These are qualitative assessments from 1 (lower) to 5 (higher) based on the available literature.

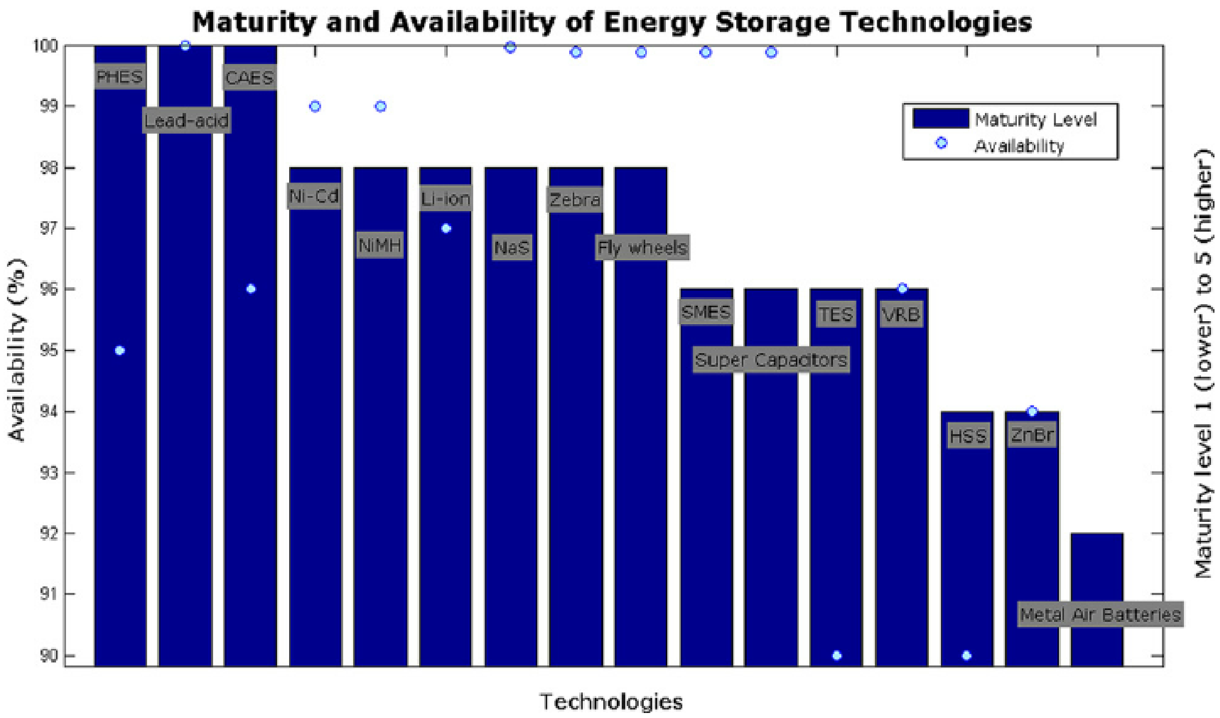

Figure 37: Maturity and Availability of Energy Storage Technologies

Several aspects need to be examined to evaluate and differentiate the storage technologies available in order to select the most suitable device for a desired application. There is no perfect technology for storage, which means that any solution has to take the best advantage of a given technology or find a good compromise in a synergy of technologies. Like any appliance using energy, storage devices exhibit losses. To evaluate the efficiency of a storage device, the full cycle has to be taken into account: charging, keeping that charge and discharging. The different technologies used are important for evaluating efficiency. Some devices use chemical transformations, others are based on physical processes, and a few are able to store electricity directly. In some cases, energy is needed for the device to keep the charge, while in others some energy is lost through time. Both situations are considered to involve a loss of efficiency. Durability, or expected remaining life time, is an important factor for energy storage technologies. In some cases, it depends on the number of cycles, cycle depth or the no-return level of discharge. For instance, the use of Gel batteries to store electricity generated by solar panels is considered to be standard practice. This combination has evolved due to the Gel batteries size availability, value, weather proofing aspects and charging cycles [54].

11.7 Conclusions – Energy Harvesting and Storage Systems

In this section, functional, practical and available energy harvesting technologies were discussed. One key observation is that each energy harvesting technology needs a matched and appropriate storage system. It has also been shown that choosing the best or most appropriate technology requires the complete details of the application.

Some examples for each technology have been presented and evaluated using the technology evaluation framework defined in WP42.2.

The next section will consider processing technologies, in particular data collection, communication, storage, and numerical processing.

12 Processing

Having a suitable processing unit is important to carry out monitoring and inspection routines. The selection can be made based on the application requirements: processing algorithms, performance of the system, energy consumption, communication protocols, input/output digital and analogue channels.

This section explains the use of different processing hardware and software. This also includes case studies on monitoring systems that have been carried out.

The processing platforms including data processing, storage and communication capabilities which are used to reduce large data collection from the sensors by carrying out online processing and to decrease communication power consumption by only transferring essential information to the user.

Advances in embedded microprocessor designs have enabled the creation of low-power sensing nodes. These sensing nodes usually consist of sensing modalities such as temperature and vibration, etc. The nodes are typically of small physical dimensions and are operated by battery power and/or energy harvesting. These nodes can sometimes link together to become of part of a bigger networked system, i.e. a sensor network, and transmit data via each other or share the data processing to save power and time. This means that the energy consumption is an important issue. For example, failure of a node in a sensor network due to energy consumption can lead to a loss of some information. There are methods to save energy, such as conserving energy in a sensor node by aggregating packets along the sensor paths to reduce overhead in data transmission [55].

12.1 Hardware platform

A wireless sensor network includes sensor nodes and at least one base station. Both sensor nodes and base station include a processing unit with different processing power and computational requirements.

Usually, sensor nodes have limited processing speeds and storage capacity with low power requirements. Since the major part of the power needs to come from the wireless data transmission between the nodes and the base station, a proper balance between data processing and wireless communication must be found. Depending on the application, data from the sensors can be processed at the node level, thus considerably reducing the amount of information to be transmitted and the overall power consumption. On the other hand, at the base station level, power and computational processing needs tend to be higher. Processing units for both sensor nodes and base stations will be discussed in the following subsections.

12.1.1 Microcontrollers

Microcontrollers are widely used for many applications. They are small computers usually programmed in C language that integrate a processor core, memory and also inputs and outputs. Nowadays, microcontrollers are designed with high computing capabilities able to run at hundreds of Megahertz which allows complex mathematical calculations to be performed.

They are normally developed specifically for a determined embedded system. In fact, most manufacturers already offer microcontroller-based solutions designed for low power wireless sensors networks (WSNs). This kind of solution facilitates the implementation of a system, when compared to other processing units like FPGAs, where most of the system code has to be written from scratch.

The low cost and low power consumption make this kind of solution well suited for local sensor nodes. A solid example of this kind of processing unit is the *SAM R21* series from *Atmel,* since it integrates an ultra-low power 32 bit microcontroller and a wireless transceiver on a single chip.

Selecting the correct low-power MCU for system design can be a challenging task, which is done by comparing current consumption of specific MCUs by different manufacturers. To address this issue, the basic information about an MCU, including peripherals, speed, package information, number of general purpose input outputs (GPIOs) and power characteristics should be considered [56].

To calculate the true MCU power consumption, the general current consumption, sleep time current, wake-up time, wake-up sources and peripherals operating while in low-power mode or full performance need to be considered.

12.1.2 MICROPROCESSORS

A microprocessor such as those used in personal computers as opposed to a microcontroller, uses external memory to provide program and data storage. Programs are usually stored in non-volatile memories such as serial Flash or NAND and when powering up they are loaded into external DRAM memory.

Because of these characteristics, the amount of DRAM that can be connected to a microprocessor is in the range of gigabytes, but the drawback is that the processor will not be up and running as quickly as a microcontroller. Another major difference is the power supply requirements. While microcontrollers only need a single power supply, a microprocessor might require several different voltage rails for its core, DDR and other elements.

For a sensor node with small computational needs, an MCU (Microcontroller) is a more appropriate option. Using an MCU the power consumption can be decreased and the boards can be smaller. On the other hand, a CPU based commercial computer can be a good solution for the base station. CPU has the ability to handle large amounts of data coming from the sensors and can be easily connected to physical or 3G/4G networks for remote access.

12.1.3 DSP

DSPs (Digital Signal Processors) are processing units specially developed for signal processing applications like discrete Fourier transforms, signal convolutions, finite impulse filters and many others. They are designed to be small and with low power consumption.

DSPs are usually programmed in C language and use floating and fixed-point processing. Their utilization is rapidly growing and replacing regular microcontrollers in applications that demand high speeds and processing power. They also combine peripheral circuits, memory and a microprocessor on a single chip.

A particular and crucial drawback of DSP based systems is their difficulty in responding to functional and timing specifications. This problem is related to the sequential processing approach of DSP architecture. This architecture decreases the overall bandwidth when the solution needs to incorporate complex and time critical operations, making DSP based systems non-deterministic and thus compromising timing specifications. In order to deal with this problem, complex high level scheduling algorithms to handle time-critical aspects must be implemented. As an alternative, multi-core DSPs can be used, but this comes with higher costs and integration complexity efforts [57].

12.1.4 FPGAs

An FPGA (Field Programmable Gate Array) is a general-purpose silicon device consisting of configurable modules that can be configured to perform hardware implementations of software applications. FPGAs contain an array of programmable logic blocks, and a hierarchy of reconfigurable interconnects that allow the blocks to be wired together. Logic blocks can be configured to perform complex combinational functions, or to act as simple logic gates like AND or XOR. Figure 38 shows how the programmable gates interconnect with each other [58].

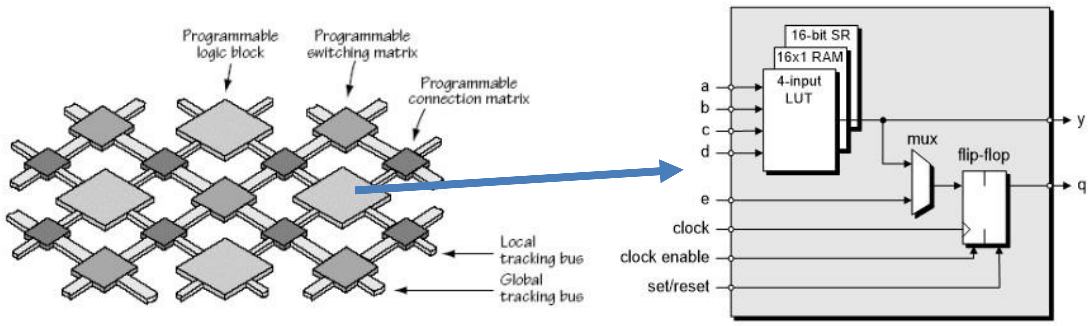

FIGURE 38: FPGA ARCHITECTURE [58]

It is possible to program the interaction between the cells and configure the FPGA using a hardware description language like VHDL or Verilog.

There are two basic types of FPGAs: OTP (One Time Programmable) and SRAM-based reprogrammable. The latter is the most common one and can be reprogramed as many times as needed. This kind of FPGA needs a system memory to store all the data, so it can be reprogrammed each time it powers up. OTP FPGAs use anti-fuses to make permanent connections in the chip and do not require any system memory to download it, however if a change to the program is needed after programming it, the chip has to be replaced [59].

In an FPGA, not just the software is programmed but also the hardware, making it much more complex when compared with microcontrollers or DSPs. This is a drawback, since it takes more time to implement, but it comes with advantages like performance scaling, design integration and flexibility. In fact, it is possible to design blocks or processors running in parallel and to integrate them in a single chip.

12.1.5 Embedded Systems

Embedded systems are a collection of programmable components (microcontroller, microprocessors, DSP or FPGAs), internal memory, communication buses and other additional peripherals. The integration of these components provides a dedicated real-time computer system. They are dedicated to specific tasks and can be easily connected to sensors and usually have low power [60].

An embedded system can be assumed as a computer system having software embedded. An embedded system is usually an independent system or it can be connected to a larger system with a unique task.

Figure 39 is an example of a microcontroller based embedded system. The system runs on a battery and has a range of communication buses to include: GPS, external storage, remote monitoring, indicators and sensors. These systems can mainly provide small processing power, storage and remote connections.

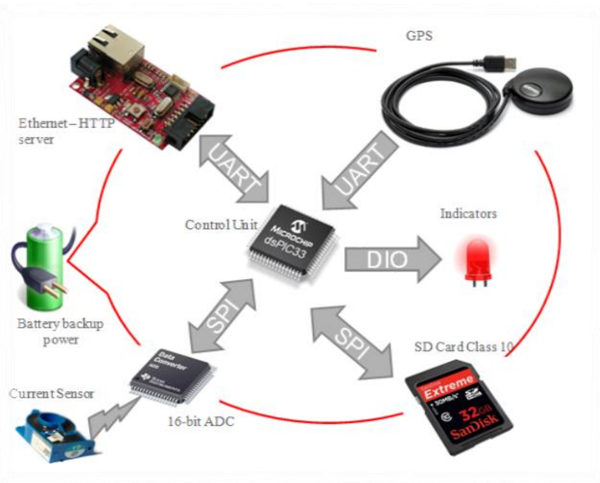

FIGURE 39: EXAMPLE OF AN EMBEDDED SYSTEM ARCHITECTURE

Figure 40 shows examples of some industrial computer systems that are based on microprocessors and which can support a wider range of temperature and higher humidity conditions compared to normal personal computers.

To evaluate hardware technologies for a specific application, data rate, data size, processing complexity, environmental aspects, communication technologies and power consumption are the main key points to be considered. For example, the industrial computer systems shown in Figure 40 are fanless units that can be used in harsh environments where oil and dust can cause damage to the ventilation systems in typical computing units. They are also capable of working in a wider temperature range and have a specific IP rating where they need to be exposed to other industrial systems.

FIGURE 40: INDUSTRIAL STANDMOUNT EMBEDDED COMPUTERS [61]

As an alternative to PC based solutions, commercialised low cost computers or embedded systems such as Raspberry PI, Arduino and development tools provided by electronic manufactures can be used for small scale monitoring and processing systems where form factor or power consumption are more important system parameters.

12.2 MONITORING ALGORITHMS

In order to obtain a benefit from a monitoring system, decision support processing is often applied. The complexity of such processing, and other system parameters, can determine where best to install the processing. This then has a direct impact on the hardware required, and on the architecture of the monitoring system. The aims of including monitoring algorithms in the system are to:

- reduce the cost of maintenance;
- achieve early fault detection and prediction applications;
- provide performance optimisation and improvements in reliability.

Condition monitoring algorithms generally fall into two categories: model-free and model-based. Model-free solutions are data-driven and do not necessarily require any prior knowledge of the physical system being monitored. These systems are generally appropriate for detection, but require substantial statistical datasets to provide accurate diagnosis. Model-based systems use a representation of the physical system, and its parameters, to refine the processing. This can lead to improved diagnosis capabilities, but these systems are generally more complex to implement.

12.2.1 MODEL-FREE

12.2.1.1 PHYSICAL REDUNDANCY

Having multiple sensors installed for measuring the same physical quantity can be used to improve the accuracy of detection. Additionally, the differences between measurements can also be indicative of sensor faults. Detection of sensor faults is a benefit of this approach, however one of the disadvantages of this method is that it leads to additional hardware, power requirements, cost and weight.

12.2.1.2 Checking limits

Measurements are compared automatically. If the measurement exceeds the threshold a fault is believed to have happened. Two significant disadvantages of this method are:

- Since the plant variables may vary widely due to normal input variations, the test thresholds need to be set quite conservatively;
- A fault in a single component could affect the other variables, resulting in difficulties in diagnosis of the faulty component.

12.2.2 Model-based

The mathematical performance of the system is realised in the form of equations. This can be used as a facility to develop designs or improve control algorithms. It also provides a better way of understanding particular system behaviours [62].

In order to achieve a mathematical model of a dynamic system, the following tasks should be considered: finding subsystems, representing the equations, analysis and interpretations, and tests and examinations [63].

The model-based approaches can be categorised into three main types: quantitative, qualitative and process history [64].

12.2.2.1 Quantitative models

Quantitative models can be categorised into two forms: process models and signal models.

12.2.2.1.1 Process models

In a quantitative method, a mathematic model, which represents the performance of the system, is essential. This is used to provide analytical redundancy, which is relied upon for most of the process of model-based monitoring methods.

Measurements from sensors and calculated results from models are used for the assessment of generated quantities. The differences between the modelled and measured quantities are ‘residuals’. If the residuals exceed a pre-defined threshold then it indicates an abnormality within the system [65]. This method, illustrated in Figure 41, can be explained in three phases: mathematical model, residual generation and assessment, and decision making.

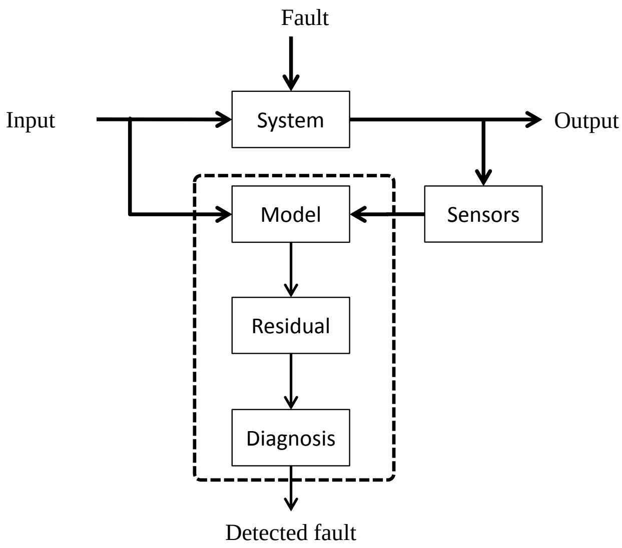

FIGURE 41: QUANTITATIVE MODEL METHOD

Common residual based techniques are:

- *Parameter estimation*: In this tactic the system parameters are used in the set values. The values are compared with inputs and outputs and any difference that surpasses certain thresholds indicates a fault [66].
- *Observer based*: Approximation of the outputs from measurements by use of algorithms such as Kalman filters [65]. A model is used to estimate the performance of the system in advance by considering the past, present and expected computed results from the model. For example, Kalman filters have often been used for noise reduction and to generate a more acceptable signal from the sensor measurements.
- *Parity relations*: Multiple sensors for measurement of the system increases the reliability of the information. A fault within any of the sensors can be then detected based on its abnormal behaviour compared to others [64, 67].

12.2.2.1.2 SIGNAL MODELS

In this method the output of the system is examined. Deviations within the output signal can be related to a particular fault. Thus, analysis of the deviations can result in fault detection. This method is used in rotating machines, especially vibration and current analysis, such as point machines [66]. The approaches which are mainly used in fault detection and diagnosis systems using signal models are [68]:

- Spectrogram analysis: This is a frequency and time domain analysis by using procedures such as Fourier and Wavelet transformations to describe the behaviour of the system in order to extract abnormalities;
- Envelope analysis: This is time and/or frequency domain analysis, where the signal is characterised within appropriate domains. For example, in time domain analysis, norms, peaks and total duration demonstrate behaviours of the system.

In these methods, the use of filters such as low-pass, band-pass or high-pass filters helps to limit a certain bandwidth of the signal to pass for further amplitude and frequency analysis.

12.2.3 QUALITATIVE MODELS

Qualitative models are knowledge-based expert systems. These are used to generate residuals. The residuals allow detection of changes in the system performance and can lead to fault detection. This can consist of simple *if* and *then* statements implemented in a computer program [69]. Consequently, an alarm can be generated after indication of a fault. However, unidentified behaviours cannot be handled in this method.

For this form of fault detection, fault trees and abstraction by quantisation are commonly used:

- Expert systems: A simple *if* and *then* statement in a computer program is an example of an expert system based on the designer and operator knowledge:

  if condition 1 *and* 2 *then*
  State A is occurred.
  end if

  if State A *and* B
  Fault class *x* has happened.
  Alarm activation.
  end if

- Fault trees: In this method, a set of possible indications that lead to a failure is shown by a sequence of block diagrams. It has levels of nodes, where each represents a threshold of a possible fault and connects to the previous levels by logic operators such as 'AND' or 'OR'. Figure 42 demonstrates an occurrence of a fault within a system using a combination of seven other faults which are measurements and thresholds within system components and characteristics.

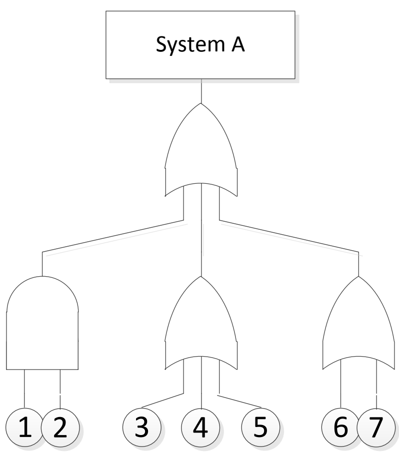

FIGURE 42: AN EXAMPLE OF A FAULT TREE DIAGRAM

- Generalisation by quantisation: Inputs and outputs are measured by an analogue to digital convertor (ADC) within a processing unit with a suitable level of quantisation. Therefore, the data are considerably reduced and this helps to reduce data communication within the condition monitoring system.

12.2.4 Process history methods

In this method a large quantity of historical data is used to implement *a priori* knowledge using qualitative or quantitative approaches. Qualitative analysis, artificial intelligence techniques (e.g. neural network and fuzzy logic) and statistical feature extraction are common methods in this approach [64].

In a system where the parameters are unknown, analysis of the historical behaviour can help to track changes over time and to observe system performance. This leads to finding abnormalities in the system behaviour, which will lead to further fault detection examination [64].

12.3 Data Storage

Data storage is a vital and simple requirement of condition monitoring system. Every monitoring system requires the storage of data. Data storage and retrieval methods are an important aspect of monitoring systems. Current approaches for this matter follow either a local storage model, where sensor data is stored locally on each sensor node, or remote storage on base stations. Since sensor nodes have a small storage capacity, low computing power and limited energy available, the traditional network and data storage and retrieval solutions cannot be used. In fact, in a typical wireless sensor application, the radio consumption of the sensors dominates the total energy consumption. Raw data can be processed at the node level in order to reduce the amount of data to be transmitted, whilst maintaining all the important information KPIs (key performance indicator).

Data can be stored locally or transferred to a central database. SD cards, FlashROMs and other semiconductor memories are low power and inexpensive solutions for temporary data storage. The temporary stored data can then be transferred to a big data storage centre for a permanent solution.

12.4 Conclusions – Processing

Hardware platforms, monitoring algorithms and data storage systems have been explained in this section. Where the hardware is to be supported by energy harvesting technologies, this may require optimised algorithms to consume less energy or a network that can distribute the work and save time in processing in each node.

A number of embedded computing solutions have been introduced and consideration given to the appropriateness of different solutions for different applications.

The processing algorithms are also essential, as different solutions have different energy requirements. However, the correct performance of the algorithms in detecting problems must be the first priority.

The storage systems can be local or network based. Thus the communication technologies and their data rate, reliability and power consumption are important. This is discussed in the next section.

13 Communications

A range of technologies is presented in this section, which considers the choice of the appropriate wireless and wired communication technologies that could fit with the requirements defined earlier in the work package. Wireless communications are generally used for external access where the embedded system or the sensing node is required to transfer information to the central system or other wireless systems. Wired communication technologies are mainly used for internal electronic systems, such as processors to wireless modules or local storage systems.

In this section, a number of different communications mechanisms will be considered and their operating principles discussed before the technology evaluation framework is used to consider their potential suitability in different monitoring systems.

13.1 Wireless

Wireless communication is used to transfer data, or in some cases power, between two or more points/nodes. Low power wireless technologies are described in this section. Their related standards and the use of frequency channels and performance are also explained.

13.1.1 RFID

RFID is a short range, identification / tagging system which can be used to link electronic records with physical assets. In the railway, RFID systems can be used to facilitate infrastructure asset catalogues and automated tracking of trains. This can lead to the following advantages:

• Traffic and Passenger Information: which provides accurate and reliable information about the location of a train. This real-time information is forwarded to a central system and usually used to provide data to the passenger information displays at stations and network operators.

• Operation and Maintenance: Information about the configuration of wagons within a train can be determined by using RFID systems. This information can be integrated with other systems such as track inspection systems, so that the recorded information can be automatically matched to the specific wagon to reduce errors.

• Controlling and Positioning of Trains: Some on-board systems require a precise position of the train, for example to control stopping positions. The reader accurately reports the position when the train passes over an ID-tag. An alternative configuration would be positioning readers at the trackside and reading the tagged wagons as they pass. If tags are consistently positioned, at the mid-point of the train, the identification of the tag would be correlated with the length of the wagon and the exact speed could be determined in the software application.

In addition to the standard configuration, some customised applications can be developed to integrate with RFID such as [70]:

• Track inspection system;

• Signal asset tracking system;

• Safety audit;

• Inventory and maintenance;

• Equipment distribution and management;

• Car accounting systems;

• Rail yard information management.

The first commercial RFID application was developed by several companies such as Kongo, Sensormatic and Checkpoint late 60s. Marketing took place during the 80s and 90s with different rates of acceptance in different parts of the world.

The increasing use of commercial RFID systems creates the need for a standard. Most of these tasks were carried out by the International Standards Organization (ISO) and International Electrotechnical Commission (IEC). The first standards were written for tracking and animal identification (ISO-11784 and ISO-11785) and for applications with contactless cards (ISO-14443).

The frequency bands are described in Table 21.

Table 21: RFID frequencies

Band	Regulations	Range	Data speed	Remarks
120–150 kHz (LF)	Unregulated	10 cm	Low	Animal identification, factory data collection
13.56 MHz (HF)	ISM band worldwide	10 cm - 1 m	Low to moderate	Smart cards (MIFARE, ISO/IEC 14443)
433 MHz (UHF)	Short Range Devices	1–100 m	Moderate	Defence applications, with active tags
865-868 MHz (Europe) 902-928 MHz (North America) UHF	ISM band	1–12 m	Moderate to high	EAN, various standards
2450-5800 MHz (microwave)	ISM band	1–2 m	High	802.11 WLAN, Bluetooth standards
3.1–10 GHz (microwave)	Ultra wide band	Up to 200 m	High	Requires semi-active or active tags

In relation to radio spectrum, the distribution of bands used for RFID is as follows:

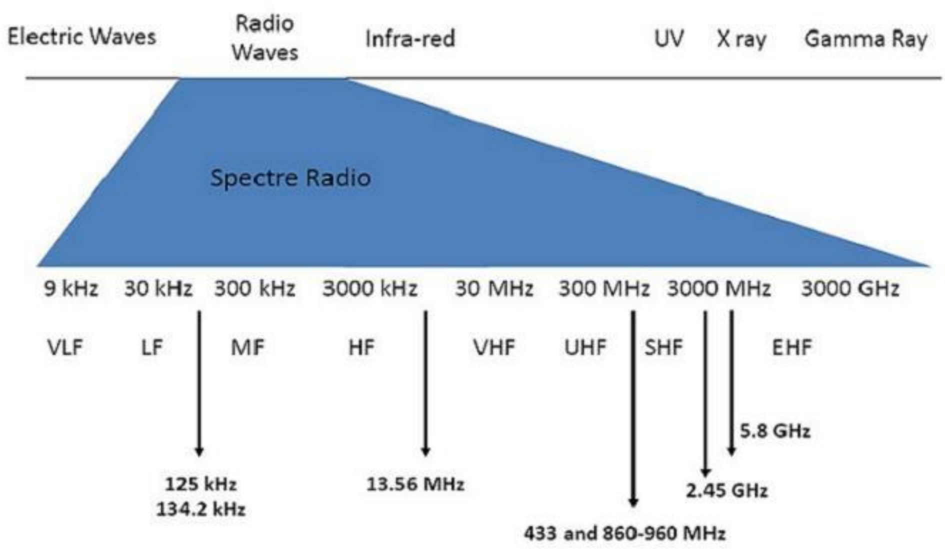

FIGURE 43: RFID FREQUENCIES SPECTRUM

In RFID systems, there are both passive and active systems.

The labels or tags in passive RFID systems do not have their own power supply, so that the range of such systems depends directly on the field radiated by the reader. The energy received on the label is rectified and amplified to power the internal circuit of the tag.

For near-field applications it is necessary to use low carrier frequencies, see Table 22. The most common frequencies are 128 kHz (LF) and 13.56 MHz (HF). It should be noted that the fact of using a low carrier frequency produces a narrow bandwidth and a very low data rate (about 1 Kbps).

TABLE 22: RFID NEAR FIELD FREQUENCIES

Frequency	Magnetic Field
119 – 135 kHz	66 dBuA/m a 10 m
13.553 – 13.567 MHz	42 dBuA/m a 10 m

Far-field applications have the advantage over near field applications, because when operating at higher frequencies the antenna size is significantly smaller (decreasing the cost of manufacture). Typically, working frequencies are UHF (860-960 MHz) bands and Microwave (2.45 GHz).

RFID band 3 (865-868 MHz) is regulated by the note A - 135 CNAF. The CNAF facilities authorized RFID devices with the following characteristics:

TABLE 23: RFID FAR FIELD FREQUENCIES

Frequency bands	Channel spacing	Max Power
865 – 865,6 MHz	200 kHz	100 mW (ERP)
865,6 – 867,6 MHz	200 kHz	2 W (ERP)
867,6 – 868 MHz	200 kHz	500 mW (ERP)

The band RFID 4 (2446 - 2454 MHz) is regulated by Note A - 129 of CNAF. Radiofrequency identifier devices can use the ISM frequency band 2446-2454 MHz channelization unrestricted or duty cycle, with a maximum authorized equivalent isotropic radiated power of 500 mW.

In 2004 the standard UHF Generation 2 Air Interface Protocol (EPC 18000-6C), was created in order to improve the former standards. Working frequency was changed to 860-960 MHz so the tags can transmit at 4 different speeds 80 Kbps, 160 Kbps; 320 Kbps o 640 Kbps.

The industrial, scientific and medical band is a part of the radio spectrum that can be used for any purpose without a license in most countries.

13.1.2 Short Range - ISM band – 868/915 MHz

The industrial, scientific and medical (ISM) radio bands are radio bands reserved internationally for the use of radio frequency (RF) communication for industrial, scientific and medical applications. This band is also used for RF energy, such as microwave ovens.

ISM bands have also been shared with (non-ISM) license-free error-tolerant communications applications, such as wireless sensor networks in the 868/915 MHz (a.k.a short range devices) and 2.450 GHz bands, as well as wireless LANs and cordless phones in the 915 MHz, 2.450 GHz, and 5.800 GHz bands. Because unlicensed devices are required to be tolerant of ISM emissions in these bands, unlicensed low power users are generally able to operate in these bands without causing problems for ISM users.

The short range ISM band (~900 MHz) is usually designed for low power low baud-rate systems to be covered in a short area. The range can vary from a few metres to a couple of hundred metres and the power consumption is directly affected by the distance.

For low power, stand-alone trackside monitoring systems this technology could be useful as it can easily be driven by energy harvesting systems and it is cost efficient compared to other wireless technologies.

An example of a low power short range wireless module is shown in Figure 44.

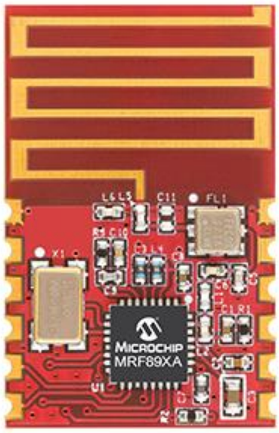

FIGURE 44: MICROCHIP 868 MHZ LOW POWER RADIO TRANSCEIVER MODULE [71]

13.1.3 LR-WPANS

The Low-Rate Wireless Personal Area Network (LR-WPANs), IEEE 802.15.4, standard was ratified in early 2003 and it was mainly intended to define the physical layer and media access control for low-rate, low-power and low-cost wireless personal area networks.

The main features of IEEE 802.15.4 are easy installation, reliable data exchange, medium range, low cost, long battery life and:

- Data rates from 20 Kbps to 250 Kbps;
- Operating frequencies 868 MHz (1 channel), 915 MHz (10 channels) and 16 channels in 2.45 GHz;
- Different topologies: star and mesh topology;
- Addressing (short) 16 bits or extended (64 bits);
- Collision avoidance through CSMA-CA;
- Use of acknowledgments to ensure reliable transmissions;
- Guarantee time slots assignation (GTS);
- Low energy consumption;
- Power emission control;
- Link quality indication (LQI).

Table 24 summarises the main features for this standard.

TABLE 24: MAIN FEATURES OF THE IEEE 802.15.4 STANDARD

Frequency Band - Range Data Transmission	868 MHz – 20 kbps 915 MHz – 40 kbps 2.4 GHz – 250 kbps
Range	10-1000 m
Latency	< 15 ms
Channels	868/915 MHz: 1+10 channels 2.4 GHz: 16 channels
Addressing Mode	64 bits IEEE (extended addressing)
Access Channel	CSMA-CA
Security	128 AES
Network	Up to 2^{16} devices
Temperature Range	-40° a +85° C

As any other IEEE 802 standard, it is based on the OSI model with certain modifications, shown in Figure 45.

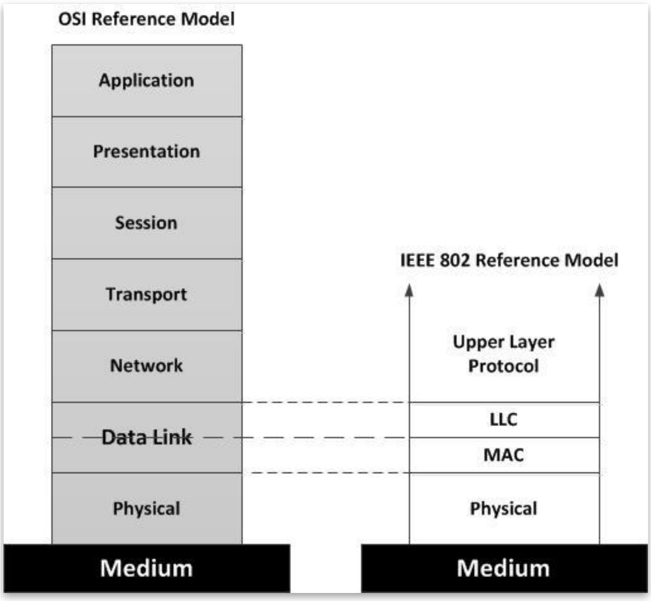

FIGURE 45: OSI MODEL VERSUS IEEE 802

The IEEE 802.15.4 offers two physic level (PHY) options: PHY 2.4 GHz and PHY 868 MHz in Europe and 915 MHz in the ISM band for the US. Both are based in extended direct sequence spread spectrum methods (DSSS) and they share the same basic architecture of low rate and low power transmissions.

The 2.4 GHz band suffers from higher interference problems due to the number of operations in this band. Consequently, 868 and 915 MHz bands are a good alternative and perform less propagation loss.

The 2.4 GHz PHY band allows 250 Kbps transmission speed while 868/915 MHz PHY offers 20 Kbps and 40 Kbps, respectively. The higher transmission rate in the 2.4 GHz PHY band comes from the use of a higher modulation order.

According to transmission channels, 27 frequency channels are available in the three bands. 868/915 PHY supports only a channel between 868 and 868.6 MHz and ten channels between 902.0 and 928.0MHz. Nevertheless, both bands are considered close enough in frequency that the same hardware can be used for both, thus diminishing manufacturing costs. The 2.4GHz PHY band supports 16 channels between 2.4 and 2.4835 GHz with a wide space of 5 MHz between channels, relaxing the requirement for the filter in the transmitter and in the receiver.

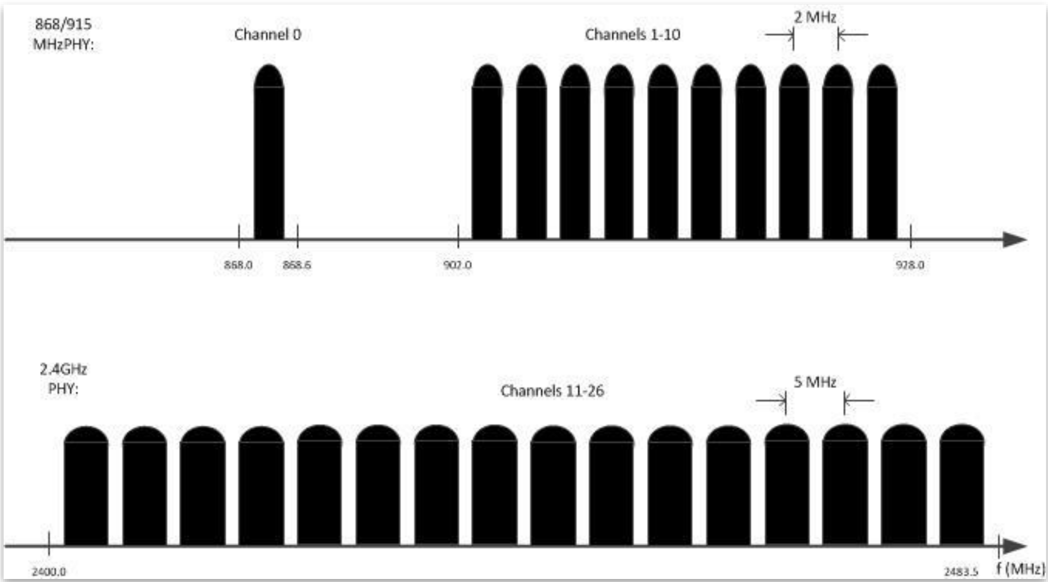

FIGURE 46: 802.15.4 CHANNELS

In a LR-WPAN network, based on the IEEE 802.15.4 standard, two types of device are defined [72].

- **FFD (Full-Function Device)** that can operate as coordinator or as an end-device.
- **RFD (Reduced-Function Device)** that is designed for very simple applications with less resources and memory.

A FFD can communicate with both FFD and RFD devices, while a RFD can only communicate with a FFD and as a result, two kinds of network configurations can be deployed: star and peer-to-peer.

- **STAR TOPOLOGY**. Various devices are connected to a single central controller, called the PAN coordinator. This coordinator can start, stop or reroute traffic around the established network.

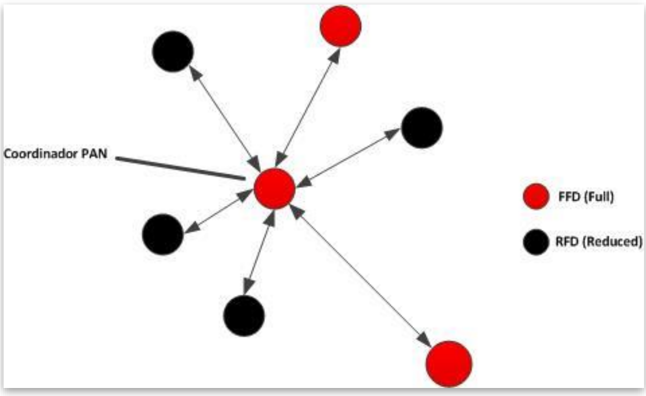

FIGURE 47: STAR TOPOLOGY IN 802.15.4

The network coordinator is the FFD type and each device provides bidirectional communication with the coordinator. Additionally, all devices operate with extended addresses and unique network. They can be used to communicate directly with the coordinator or can be mapped to a short address.

Typical applications include home automation, and infrastructure or health monitoring systems.

- **PEER-TO-PEER TOPOLOGY**. This topology has a PAN coordinator network, shown in Figure 48; however, any device can connect to another (in the range of coverage). In this case, the establishment of connections is more complex.

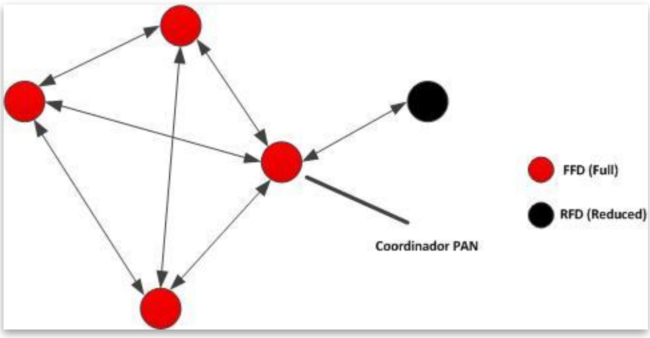

FIGURE 48: PEER-TO-PEER TOPOLOGY OF 802.15.4

Each node establishes a connection with every other device that can be reached. As there are more links, the data transmission increases but the network is also more reliable. Additionally, it is possible to send data from one point to another through intermediate nodes, so that large distances can be covered.

The 802.15.4 networks using this topology can be ad-hoc so that their own routes can be defined and they can recover from errors. This kind of topology is very useful for monitoring and control applications.

A special case of peer-to-peer topology is the cluster tree or tree network where most nodes are FFD type. Multiple blocks of this type can be added to grow longer-range networks, demonstrated in Figure 49. The main issue in having a network with a broad coverage radius is that the message latency significantly increases.

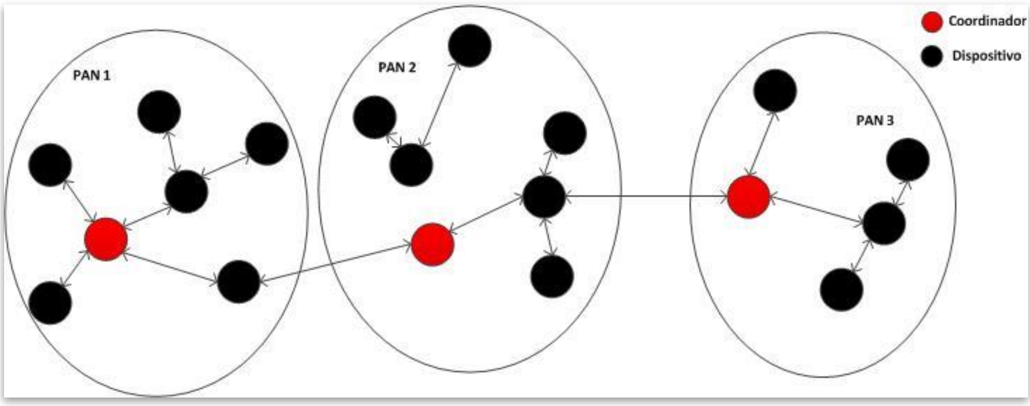

FIGURE 49: CLUSTER TREE TOPOLOGY OF 802.15.4

13.1.4 PHY AMENDMENT FOR SMART UTILITY NETWORK (4G)

The IEEE 802.15.4g, Smart Utility Network (SUN), task group within the IEEE 802.15 working group was created to shape a standard for the physical layer radio communications for utility Neighbourhood Area Networks (NAN). With this standardisation effort, 802.15 has extended its portfolio of standards to cover long range applications.

Some of the more important features of the 802.15.4g are:

- Operation in available license, i.e. 700 MHz to 1 GHz bands and the 2.4 GHz band;
- Data rates from 40 Kbps to 1000 Kbps;
- PHY frames length up to a minimum of 1500 octets;
- Ensure coexistence with the other systems operating in the same band including 802.11, 802.15 and 802.16 systems;

The 802.15.4g standard has specified three possible physical layers:

- MR (multi-rate and multi-regional) - FSK PHY. Specified for the following frequency bands:
    - 169.4-169.475 MHz, 863-870 MHz (Europe)
    - 450-470, 896-901, 901-902, 928-960, 1427-1518 (US bands)
    - 902-928 (US unlicensed band)
    - 470-510, 779-787 (China)
    - 917-923.5 MHz (Korea)
    - 920-928, 950-958 (Japan)
    - 2400-2483.5 (Worldwide)

The PER used to measure the receiver sensitivity is increased to 10% (with respect to the 1% in the IEEE 802.15.4). The single-side clock frequency tolerance requirements at the transmitter are between

30 ppm and 50 ppm; the transmitter symbol rate tolerance is required to be less than or equal to ±300 ppm; and the peak transmitter symbol rate jitter is required to be less than or equal to ±40 ppm.

- MR-OFDM PHY. Specified for the following frequency bands:
    - 470-510, 779-787 (China)
    - 863-870 MHz (Europe)
    - 902-928 (US unlicensed band)
    - 917-923.5 MHz (Korea)
    - 920-928, 950-958 (Japan)
    - 2400-2483.5 (Worldwide)

The subcarrier spacing for MR-OFDM is constant and equal to 31250/3 Hz. The data rate for MR-OFDM ranges from 50 kbps to 800 kbps and used DFT sizes of 128, 64, 32 and 16 are defined by the standard. The modulation schemes are BPSK, QPSK, and QAM.

- MR-OQPSK PHY. Specified for the following frequency bands:
    - 470-510, 779-787 (China)
    - 868-870 MHz (Europe)
    - 902-928 (US unlicensed band)
    - 917-923.5 MHz (Korea)
    - 920-928, 950-958 (Japan)
    - 2400-2483.5 (Worldwide)

The 802.15.4e amendment provides some “hooks” or tools that can be used to facilitate frequency hopping but there is still substantial standardization work that needs to be done before the 802.15.4g PHY and 802.15.4e MAC amendments to 802.15.4 can be utilized as the foundation for interoperable communications between FSK devices that require frequency [73].

13.1.5 Bluetooth

Bluetooth technology is a wireless communications technology that is simple, secure and it can be found in billions of devices ranging from mobile phones and computers to medical devices and home entertainment products.

The key features of Bluetooth technology are low power and low cost. The Bluetooth Specification defines a uniform structure for a wide range of devices to connect and communicate with each other.

When two Bluetooth enabled devices connect to each other, this is called pairing. The structure and the global acceptance of Bluetooth technology means any Bluetooth enabled device, almost anywhere in the world, can connect to other Bluetooth enabled devices located in proximity to one another.

Connections between Bluetooth enabled electronic devices allow these devices to communicate wirelessly through short-range, ad hoc networks known as *piconets*. Piconets are established dynamically and automatically as Bluetooth enabled devices enter and leave radio proximity, meaning that it can easily be connected whenever and wherever it is required.

The range of Bluetooth technology is application specific. The core specification mandates a minimum range of 10 m, but there is no set limit and manufacturers can tune their implementations to provide the range needed to support the use cases for their solutions.

An overview of the main Bluetooth specifications is given below:

- Spectrum

Bluetooth technology operates in the unlicensed industrial, scientific and medical (ISM) band at 2.4 to 2.485 GHz, using a spread spectrum, frequency hopping, full-duplex signal at a nominal rate of 1600 hops/sec. The 2.4 GHz ISM band is available and unlicensed in most countries and the frequency bands are illustrated in Figure 50.

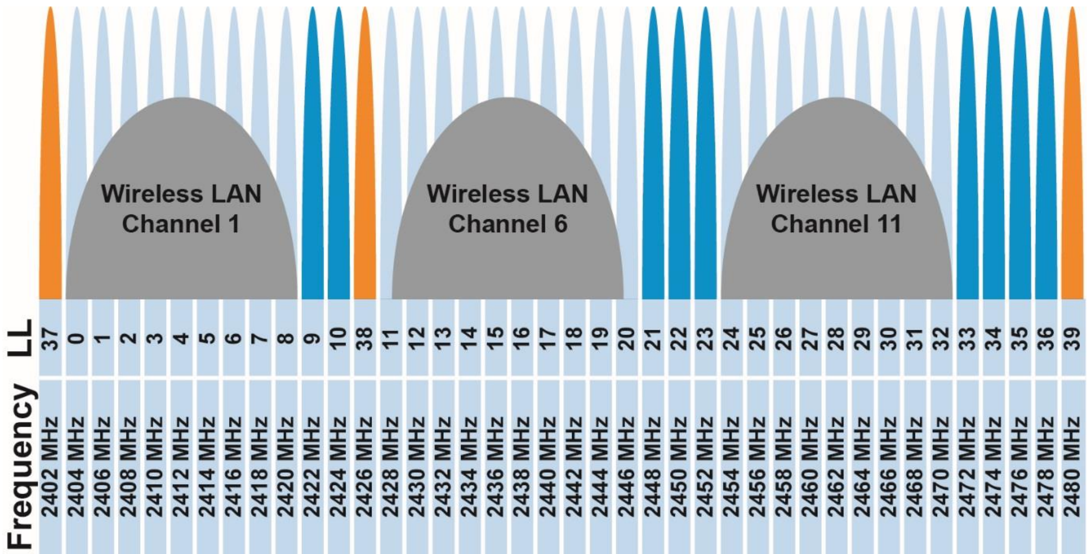

FIGURE 50: FREQUENCY BANDS IN BLUETOOTH

The three advertising channels (37, 38 and 39), and nine of the data channels (9, 10, 21, 22, 23, 33, 34, 35 and 36) are located between the three most commonly used Wireless LAN channels in the 2.4 GHz band.

- Interference

The adaptive frequency hopping (AFH) capability of the Bluetooth technology was designed to reduce interference between wireless technologies sharing the 2.4 GHz spectrum.

AFH works within the spectrum to take advantage of the available frequency. This is done by the technology detecting other devices in the spectrum and avoiding the frequencies they are using. This adaptive hopping among 79 frequencies at 1 MHz intervals gives a high degree of interference immunity and also allows for more efficient transmission within the spectrum. For users of Bluetooth technology this hopping provides greater performance even when other technologies are being used along with Bluetooth technology.

- Range

The range depends on the application and a minimum range is mandated by the core specification. There is not a limit and manufacturers can tune their implementation to support the use case they are enabling.

Range may vary depending on class of radio used in an implementation:

- Class 3 radios – have a range of up to 1 metre
- Class 2 radios – most commonly found in mobile devices – have a range of 10 meters.
- Class 1 radios – used primarily in industrial use cases – have a range of 100 meters.

- Power

The most commonly used radio is Class 2 and the power consumption is 2.5 mW.

Bluetooth technology is designed to have very low power consumption. This is reinforced in the specification by allowing radios to be powered down when inactive.

The Generic Alternate MAC/PHY in Version 3.0 HS enables the discovery of remote AMPs for high speed devices and turns on the radio only when needed for data transfer, giving a power optimisation benefit as well as aiding in the security of the radios.

Bluetooth low energy technology, optimised for devices requiring maximum battery life instead of a high data transfer rate, consumes between 1/2 and 1/100 the power of classic Bluetooth technology.

13.1.5.1 Bluetooth Low Energy (BLE) / Bluetooth Smart

Bluetooth Smart is the intelligent, low power version of Bluetooth wireless technology. While the power-efficiency of Bluetooth Smart makes it appropriate for devices running off a small battery for long periods, Bluetooth Smart has the ability to work with an application on smartphones or tablets [74].

Bluetooth Smart technology consumes only a fraction of the power of Classic Bluetooth radios. Bluetooth Smart extends the use of Bluetooth wireless technology to devices that are powered by small, coin-cell batteries such as watches and toys. Other devices such as sports & fitness, health care, keyboards and mice, beacons, wearable and entertainment devices are enhanced by this version of the technology. In many cases, it makes it possible to operate these devices for more than a year without recharging.

As with previous versions of the specification, the range of the radio may be optimized according to the application. The majority of Bluetooth devices on the market today include the basic 10 meter, the range of the Classic Bluetooth radio, but there is no limit imposed by the specification. With Bluetooth

Smart, manufacturers may choose to optimize range up to 150 meters, particularly for in-home sensor applications where longer range is a necessity.

Bluetooth Smart features provide:

- Ultra-low peak, average and idle mode power consumption;
- Ability to run for years on standard coin-cell batteries;
- Low implementation costs;
- Multi-vendor interoperability;
- Enhanced range;
- Data Transfers:

  Bluetooth Smart (low energy) supports very short data packets (8 bytes minimum up to 27 bytes maximum) that are transferred at 1 Mbps. All connections use advanced sniff-sub rating to achieve ultra-low duty cycles
- Frequency Hopping:

  Bluetooth Smart (low energy) uses the adaptive frequency hopping common to all versions of Bluetooth technology to minimize interference from other technologies in the 2.4 GHz ISM Band. Efficient multi-path benefits increase the link budgets and range
- Host Control

  Bluetooth Smart (low energy) places a significant amount of intelligence in the controller, which allows the host to sleep for longer periods of time and be woken up by the controller only when the host needs to perform some action. This allows for the greatest current savings since the host is assumed to consume more power than the controller
- Latency

  Bluetooth Smart (low energy) can support connection setup and data transfer as low as 3 ms, allowing an application to form a connection and then transfer authenticated data in few milliseconds for a short communication burst before quickly closing the connection
- Range

  Increased modulation index provides a possible range for Bluetooth Smart (low energy) of over 100 meters
- Robustness

  Bluetooth Smart (low energy) uses a strong 24 bit CRC on all packets ensuring the maximum robustness against interference
- Security

  Full AES-128 encryption using CCM to provide strong encryption and authentication of data packets
- Topology

Bluetooth Smart (low energy) uses a 32 bit access address on every packet for each slave, allowing billions of devices to be connected. The technology is optimised for one-to-one connections while allowing one-to-many connections using a star topology.

13.1.6 Wi-Fi

IEEE 802.11 [75] is a set of media access control (MAC) and physical layer (PHY) specifications for implementing wireless local area network (WLAN). They are created and maintained by the IEEE LAN/MAN Standards Committee (IEEE 802). The base version of the standard was released in 1997 and has had subsequent amendments. The standard and amendments provide the basis for wireless network products using the Wi-Fi brand.

The 802.11 family consists of a series of half-duplex over-the-air modulation techniques that use the same basic protocol. The 802.11 workgroup currently documents use in four distinct frequency ranges: 2.4 GHz, 3.6 GHz, 4.9 GHz, 5 GHz, and 5.9 GHz bands. Each range is divided into a multitude of channels. Countries apply their own regulations to both the allowable channels, allowed users and maximum power levels within these frequency ranges.

- 802.11-1997 was the first wireless networking standard, but 802.11b was the first widely accepted standard, followed by 802.11a, 802.11g, 802.11n and 802.11ac.
- 802.11b and 802.11g use the 2.4 GHz ISM band and direct-sequence spread spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM) signalling methods, respectively.
- 802.11a uses the 5 GHz U-NII band, which, for much of the world, offers at least 23 non-overlapping channels rather than the 2.4 GHz ISM frequency band, where adjacent channels overlap. Better or worse performance with higher or lower frequencies (channels) may be realized, depending on the environment.

802.11b, 802.11g, and 802.11n-2.4 utilize the 2.400 – 2.500 GHz spectrum, one of the ISM bands. 802.11a and 802.11n use the more heavily regulated 4.915 – 5.825 GHz band. These are commonly referred to as the "2.4 GHz and 5 GHz bands" in most sales literature. Each spectrum is sub-divided into channels with a centre frequency and bandwidth, analogous to the way radio and TV broadcast bands are sub-divided.

The 2.4 GHz band is divided into 14 channels, shown in Figure 51. These channels are spaced at 5 MHz apart, beginning with channel 1 which is centred on 2.412 GHz. The latter channels have additional restrictions or are unavailable for use in some regulatory domains.

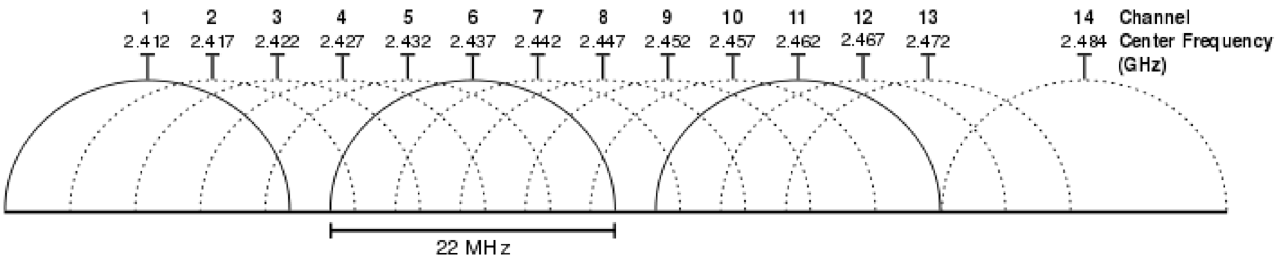

FIGURE 51: GRAPHICAL REPRESENTATION OF WI-FI CHANNELS IN 2.4 GHZ BAND

The channel numbering of the 5.725 – 5.875 GHz spectrum is less intuitive due to the differences in regulations between countries.

Many newer consumer devices support the latest 802.11ac standard, which uses the 5 GHz band and is capable of multi-station WLAN throughput of at least 1 gigabit per second.

Since the spectral mask only defines power output restrictions up to ±11 MHz from the centre frequency to be attenuated by −50 dB, it is often assumed that the energy of the channel extends no further than these limits. It is more correct to say that, given the separation between channels, the overlapping signal on any channel should be sufficiently attenuated to minimally interfere with a transmitter on any other channel. Due to the near-far problem, the transmitter can impact a receiver on a "non-overlapping" channel, but only if it is close to the victim receiver (within a meter) or operating above allowed power levels.

The current 'fastest' norm, 802.11n, uses double the radio spectrum/bandwidth (40 MHz) compared to 802.11a or 802.11g (20 MHz). This means there can be only one 802.11n network on the 2.4 GHz band at a given location, without interference to/from other WLAN traffic. 802.11n can also be set to use 20 MHz bandwidth only to prevent interference in a dense community.

Wi-Fi networks have limited range. A typical wireless access point using 802.11b or 802.11g with a stock antenna might have a range of 35 m indoors and 100 m for outdoor applications. IEEE 802.11n, however, can more than double the range.

Range also varies with frequency band. Wi-Fi in the 2.4 GHz frequency block has a slightly better range than Wi-Fi in the 5 GHz frequency, which is used by 802.11a and optionally by 802.11n.

On wireless routers with detachable antennas, it is possible to improve the range by fitting upgraded antennas which have higher gain in particular directions. In general, the maximum amount of power that a Wi-Fi device can transmit is limited by local regulations in every country.

Due to reach requirements for wireless LAN applications, Wi-Fi has fairly high power consumption compared to some other standards. Technologies such as Bluetooth (designed to support wireless PAN applications) provides a much shorter propagation range between 1 and 100 m; however, in general it has lower power consumption. Other low-power technologies such as IEEE802.15.4 standard have fairly long range, but a much lower data rate. The high power consumption of Wi-Fi makes battery life in mobile devices a concern.

13.1.7 WIRELESS SENSOR NETWORK

A wireless sensor network (WSN) is a wireless network that includes spatially distributed nodes using sensors to monitor system conditions. A WSN system also has a gateway that provides a wired or another wireless method that links the WSN to the bigger networks, e.g. internet. Wireless communication protocol can vary based on the application. Some use standards such as 2.4 GHz on either IEEE 802.15.4 or IEEE 802.11 standards and some may use 900 MHz ISM bands.

The position of sensor nodes does not need to be engineered or pre-defined. This allows random deployment based on the location availability within an asset that is going to be monitored. The sensor network protocols and algorithms possess self-organising capabilities. Another advantage of sensor networks is that instead of sending the raw data to the other nodes or the main unit, sensor nodes use their processing systems to locally perform simple computations and transmit only the required and partly processed data [76].

The sensor nodes are usually scattered in a field and WSN systems have three types of network topologies:

- Star topology: each node connects directly to a gateway;
- Cluster tree topology: each node connects to a node higher in the tree and then to the gateway, and data is routed from the lowest node on the tree to the gateway;
- Mesh networks topology: in this topology nodes can connect to any other nodes in the system and pass data through the most reliable path available.

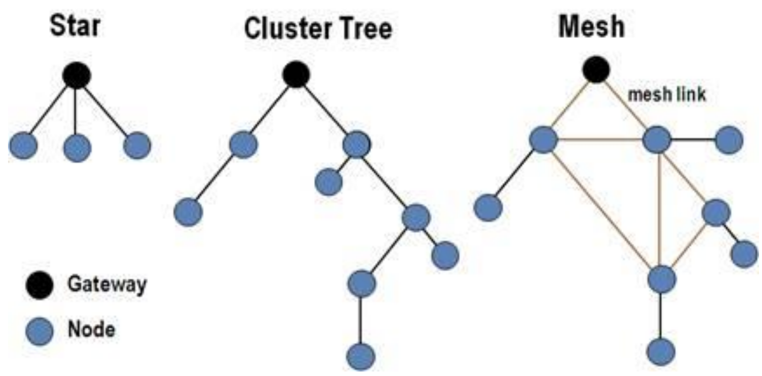

FIGURE 52: WSN NETWORK TOPOLOGIES [77]

Examples of the use of sensor networks in the rail industry were demonstrated in the EU FP7 project WiRailCom [78].

13.1.8 CELLULAR

Cellular communications may be used as a long range alternative to local wireless communications systems. Generally, cellular systems have a lower bandwidth than local wireless networks, but they may be appropriate where the installation of local infrastructure is difficult. While wired or wireless networks are used for localised data collation or exchange, cellular systems can also be used to communicate with remote systems or data repositories.

13.1.8.1 GSM/GPRS

GSM (Global System for Mobile Communications, originally Groupe Spécial Mobile), is a standard developed by the European Telecommunications Standards Institute (ETSI) to describe protocols for second generation (2G) digital cellular networks used by mobile phones. It is the default global standard for mobile communications with over 90% market share, and is available in over 219 countries and territories [79].

GSM is an open, digital cellular technology used for transmitting mobile voice and data services. It supports voice calls and data transfer speeds of up to 9.6 Kbps, together with the transmission of SMS (Short Message Service).

GSM was expanded over time to include data communications: first by circuit-switched transport and then packet data transport via GPRS (General Packet Radio Services).

GPRS is a packet oriented mobile data service on the 2G and 3G cellular communication global system for mobile communications. European Telecommunications Standards Institute (ETSI) originally standardised GPRS and it is now maintained by the 3rd Generation Partnership Project (3GPP).

GPRS usage is typically charged based on volume of data transferred, contrasting with circuit switched data, which is usually billed per minute of connection time. Usage above the bundle cap is either charged per megabyte or disallowed.

The GPRS service implies variable throughput and latency that depend on the number of other users sharing the service concurrently, as opposed to circuit switching, where a certain quality of service (QoS) is guaranteed during the connection. In 2G systems, GPRS provides data rates of 56–114 Kbit/second. 2G cellular technology combined with GPRS is sometimes described as 2.5G, that is, a technology between the second (2G) and third (3G) generations of mobile telephony. It provides moderate-speed data transfer, by using unused time division multiple access (TDMA) channels in, for example, the GSM system.

GPRS builds on the GSM network platform, so operators can leverage their existing infrastructure, such as base stations and Mobile Switching Centres (MSCs). The GPRS core network is based on Internet Protocol (IP) standards, which make it ideal for providing wireless access to other IP-based networks, such as Internet Service Providers (ISPs) and corporate Local Area Networks (LANs). GPRS enables people to enjoy advanced, feature-rich data services, such as e-mail on the move, multimedia messages, social networking and location-based services.

There are fourteen bands defined in 3GPP TS 45.005, which succeeded 3GPP TS 05.05, shown in Table 25.

TABLE 25: GSM FREQUENCY BANDS

System	Band	Uplink (MHz)	Downlink (MHz)	Channel number
T-GSM-380	380	380.2–389.8	390.2–399.8	dynamic
T-GSM-410	410	410.2–419.8	420.2–429.8	dynamic
GSM-450	450	450.6–457.6	460.6–467.6	259–293
GSM-480	480	479.0–486.0	489.0–496.0	306–340
GSM-710	710	698.2–716.2	728.2–746.2	dynamic
GSM-750	750	747.2–762.2	777.2–792.2	438–511
T-GSM-810	810	806.2–821.2	851.2–866.2	dynamic
GSM-850	850	824.2–849.2	869.2–894.2	128–251
P-GSM-900	900	890.0–915.0	935.0–960.0	1–124
E-GSM-900	900	880.0–915.0	925.0–960.0	975–1023, 0-124
R-GSM-900	900	876.0–915.0	921.0–960.0	955–1023, 0-124
T-GSM-900	900	870.4–876.0	915.4–921.0	dynamic
DCS-1800	1800	1,710.2–1,784.8	1,805.2–1,879.8	512–885
PCS-1900	1900	1,850.2–1,909.8	1,930.2–1,989.8	512–810

GSM networks operate in a number of different carrier frequency ranges with most 2G GSM networks operating in the 900 MHz or 1800 MHz bands.

The transmission power in the handset is limited to a maximum of 2 Watt in GSM 850/900 and 1 Watt in GSM 1800/1900.

- GSM-900 and GSM-1800 are used in most parts of the world: Europe, Middle East, Africa, Australia, Oceania (and most of Asia).
- GSM-900 uses 890–915 MHz to send information from the mobile station to the base station (uplink) and 935–960 MHz for the other direction (downlink), providing 124 RF channels (channel numbers 1 to 124) spaced at 200 kHz. Duplex spacing of 45 MHz is used. Guard bands 100 kHz wide are placed at either end of the range of frequencies.
- GSM-1800 uses 1.710–1.785 MHz to send information from the mobile station to the base transceiver station (uplink) and 1.805–1.880 MHz for the other direction (downlink), providing 374 channels (channel numbers 512 to 885). Duplex spacing is 95 MHz. GSM-1800 is also called DCS (Digital Cellular Service) in the United Kingdom.
- GSM-850 and GSM-1900 are used in Argentina, Bolivia, Brazil, Canada, the United States and many other countries in the Americas.

13.1.8.2 GSM-R

GSM-R is built on the GSM technology that is used to provide a highly secure and reliable communication system for train operators and signal systems [80]. Existing hardware in a GSM system can be modified by users or manufacturers to work on the GSM-R platform.

The GSM-R standard is based on second generation GSM (2G). The upcoming adoption of faster cellular communication technologies is planned to enhance the quality and reduce the costs of GSM-R networks. As the third generation of GSM evolves towards long term evolution (LTE), GSM-R is expected to evolve as well. That means that GSM-R networks will be able to work with LTE based equipment. This has the potential to greatly reduce costs while improving speed and reliability.

GSM-R mobile terminals operate at frequency bands 876-880 MHz and 921-925 MHz and are only licenced for railway purposes [81].

GSM-R system introduces a number of services to the users:

- Point-to-point calls;
- Predefined operational text messages, for specific situations;
- Broadcast calls and acknowledgments;
- Emergency group calls;
- Route calls automatically from a registered cab radio;
- Automatically change channels;
- Provide call waiting;
- Allow calls to be put on hold;
- Identify who is calling or being called;
- Allow more than one person to use the system;
- Prioritise calls.

An overview of a GSM-R system including the in cab radio and the station links is shown in Figure 53.

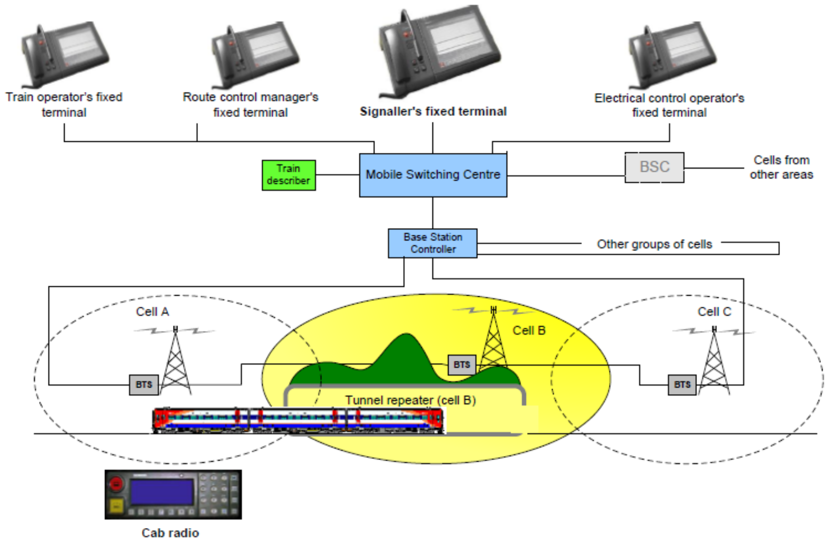

FIGURE 53: GSM-R SYSTEM OVERVIEW [82].

13.1.8.3 3G

3G (third Generation), is the third generation of mobile telecommunications technology. It is based on a set of standards used for mobile devices and mobile telecommunications using services and networks that comply with the International Mobile Telecommunications-2000 (IMT-2000) specifications by the International Telecommunication Union. 3G finds application in wireless voice telephony, mobile internet access, fixed wireless internet access, video calls and mobile TV.

The following standards are typically branded 3G:

- The Universal Mobile Telecommunications System (UMTS), created and revised by the 3GPP, is a full revision from GSM in terms of encoding methods and hardware. The cell phones are typically UMTS and GSM hybrids. Several radio interfaces are offered, sharing the same infrastructure. The original and most widespread interface is called W-CDMA;
  - HSPA is an amalgamation of several upgrades to the original W-CDMA standard and offers speeds of 14.4 Mbit/s down and 5.76 Mbit/s up. HSPA is backward-compatible with, and uses the same frequencies as W-CDMA;
  - HSPA+, a further revision and upgrade of HSPA, can provide theoretical peak data rates up to 168 Mbit/s in the downlink and 22 Mbit/s in the uplink.

Different countries support different UMTS frequency bands – Europe initially used 2100 MHz while most carriers in the US use 850 MHz and 1900 MHz. T-Mobile has launched a network in the US operating at 1700 MHz (uplink) /2100 MHz (downlink), and these bands are also being adopted elsewhere in the Americas.

- The CDMA2000 system, first offered in 2002, standardized by 3GPP2, used especially in North America and South Korea, sharing infrastructure with the IS-95 2G standard. The cell phones are typically CDMA2000 and IS-95 hybrids. The latest release EVDO Rev B offers peak rates of 14.7 Mbit/s downstream.

Currently, CDMA2000 network infrastructure and user devices are available in most of the IMT-2000 frequency bands designated by the ITU, including the 450 MHz, 700 MHz, 800 MHz, 1700 MHz, 1900 MHz, AWS and 2100 MHz bands.

13.1.8.4 4G

ITU created the IMT-Advanced committee where mandatory requirements were defined for a communication standard which could be considered part of the 4G generation.

Among the basic requirements, the most important is related to the maximum transmission speed, so data transmission must be 100 Mbit/s for high mobility and 1 Gbit/s for low mobility. It should be emphasized that the working groups of the ITU are not purely theoretical; the industry is part of the working groups and they study real technologies.

Therefore, the LTE (Long Term Evolution) standard is not 4G, because it does not comply with the requirements defined by the IMT-Advanced committee related to peak data rates and spectral efficiency. However, in 2010 the ITU stated that candidates for 4G, as it was, could be advertised as 4G.

4G is completely based on the IP protocol, and can be used by wireless modems, smartphones and other mobile devices.

LTE radio interface is based on OFDMA for the downlink and SC-FDMA for uplink. The modulation selected for 3GPP technologies makes different antennas (MIMO) have a greater ease of implementation.

The most important features are:

- High spectral efficiency;
- Downlink OFDM is robust against interference;
- DTFS-OFDM (single-Carrier FDMA) for uplink;
- Two different planes for user and control;
- Very low latency; values of 100 ms for the Control-Plane and 10 ms for the User-Plane;
- Adaptive Bandwidth: 1, 4, 3, 5, 10, 15 e 20 MHz;
- It can work in many different frequency bands;
- Simple protocol architecture;
- Compatibility with other 3GPP technologies;
- Peak data rates:
  - Uplink: 86.5 Mbps
  - Downlink: 326.5 Mbps with 4x4 antennas, 172.8 Mbps with 2x2 antennas
- Optimal for displacements up to 15 km/h. Supports up to 500 km/h;
- Optimal cell size 5 km;

- Improvement and flexibility of spectrum use (FDD and TDD);
- Unicast and broadcast services;
- LTE Frequency Bands are shown in Figure 54 and Table 26. Different frequency bands are used depending on the country or area.
  - BC1, LTE Band 1 or Class 1: 2100 MHz.
  - BC2, LTE Band 2 or Class 2: 1900 MHz.
  - BC3, LTE Band 3 or Class 3: 1800 MHz. In Europe, several operators are licensed to band 3, which is currently used for 2G (GSM), so it is not excluded that in the future this band could be divided and distributed for use by both 2G and LTE. Two blocks of 75 MHz: 1710-1785 MHz and 1805-1880 MHz.
  - BC4, LTE Band 4 or Class 4 ó LTE AWS: 1700 MHz for uplink and 2100 MHz for downlink. These bands are mainly used in Canada, Mexico and USA.
  - BC5, LTE Band 5 or Class 5: 850 MHz.
  - BC6, LTE Band 6 or Class 6: 800 MHz.
  - BC7, LTE Band 7 or Class 7: 2600 MHz or 2.6 GHz. LTE is used in those places where the band 1800 is not enough to be very saturated (usually places with large crowds).
  - BC12, LTE Band 12 or Class 12: 700 MHz.
  - BC13, LTE Band 13 or Class 13: 700 MHz
  - BC17, LTE Band 17 or Class 17: 700 MHz.
  - BC20, LTE Band 20 or Class 20: 800 MHz. From 790 MHz to 862 MHz, currently used for broadcasting digital television. Once digital television channels have been moved to lower frequencies, this band will be used for LTE.
  - BC25, LTE Band 25 or Class 25: 1900 MHz.
  - BC28, LTE Band 28 or Class 28: 700 MHz.

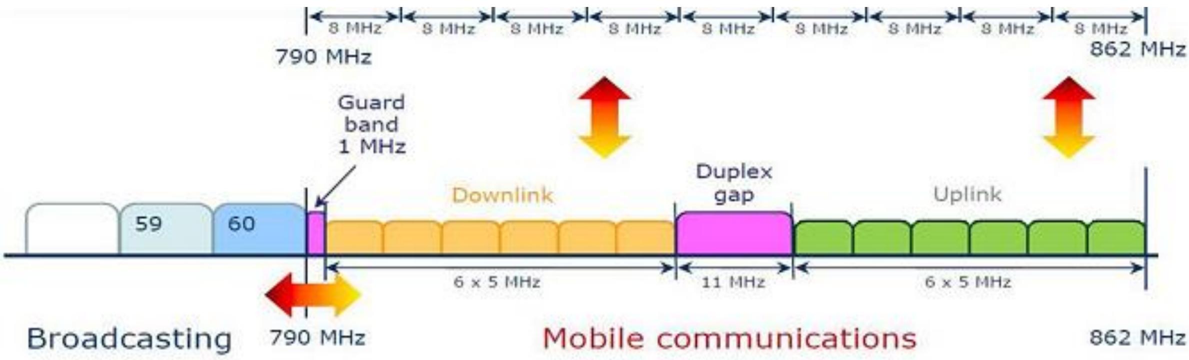

FIGURE 54: LTE BAND 20

TABLE 26: FREQUENCY BANDS AND REGIONS

LTE Bands	Uplink (MHz)	Downlink (MHz)	Duplex Spacing (MHz)	BW (MHz)	Duplex Mode	Deployment in the world
Band 1	1920 -1980	2110 -2170	190	60	FDD	China, Japan, EU, Asia, Australia
Band 2	1850 -1910	1930 -1990	80	60	FDD	North/South America
Band 3	1710 -1785	1805 -1880	95	75	FDD	EU, China, Asia, Australia, Africa
Band 4	1710 -1755	2110 -2155	400	45	FDD	North/South America
Band 5	824 -849	869 -894	45	25	FDD	North/South America, Australia, Asia, Africa
Band 6	830 -840	875 -885	45	10	FDD	Japan
Band 7	2500 -2570	2620 -2690	120	70	FDD	EU, South America, Asia, Africa, Australia
Band 8	880 -915	925 -960	45	35	FDD	EU, South America, Asia, Africa, Australia
Band 9	1749.9 -1784.9	1844.9 -1879.9	95	35	FDD	Japan
Band 10	1710 -1770	2110 -2170	400	60	FDD	North/South America
Band 11	1427.9 -1447.9	1475.9 -1495.9	48	35	FDD	Japan
Band 12	698 -716	728 -746	30	18	FDD	North America
Band 13	777 -787	746 -756	31	10	FDD	North America
Band 14	788 -798	758 -768	30	10	FDD	North America
Band 17	704 -716	734 -746	30	12	FDD	North America
Band 18	815 -830	860 -875	45	15	FDD	North/South America, Australia, Asia, Africa
Band 19	830 -845	875 -890	45	15	FDD	North/South America, Australia, Asia, Africa
Band 20	832 -862	791 -821	41	30	FDD	EU
Band 21	1447.9 -1462.9	1495.9 -1510.9	48	15	FDD	Japan
Band 22	3410 - 3500	3510 - 3600	100	90	FDD	
Band 24	1626.5 -1660.5	1525 -1559	101.5	34	FDD	
Band 33	1900 -1920		N/A	20	TDD	
Band 34	2010 -2025		N/A	15	TDD	China
Band 35	1850 -1910		N/A	60	TDD	
Band 36	1930 -1990		N/A	60	TDD	
Band 37	1910 -1930		N/A	20	TDD	
Band 38	2570 -2620		N/A	50	TDD	EU
Band 39	1880 -1920		N/A	40	TDD	China
Band 40	2300 -2400		N/A	100	TDD	China, Asia
Band 41	2496 -2690		N/A	194	TDD	
Band 42	3400 -3600		N/A	200	TDD	
Band 43	3600 -3800		N/A	200	TDD	

These technologies are based on cellular networks, which means that devices connect to the network by searching for cells in the immediate vicinity. The coverage area of each cell varies according to the implementation environment.

Cell horizontal radius varies depending on antenna height, antenna gain, and propagation conditions from a couple of hundred meters to several tens of kilometers. The longest distance the GSM specification supports in practical use is 35 kilometers. There are also several implementations of the concept of an extended cell, where the cell radius could be double or even more, depending on the antenna system, the type of terrain, and the timing advance.

13.1.8.5 WIMAX

WiMAX is a technology standard for long-range wireless networking. WiMAX equipment exists in two basic forms:

- Base stations, installed by service providers to deploy the technology in a coverage area;

- Receivers, installed in clients.

This technology is based upon the IEEE 802.16 standard enabling the delivery of wireless broadband services anytime, anywhere. WiMAX products can accommodate fixed and mobile usage models across a range of applications. The IEEE 802.16 standard was developed to deliver non-line-of-sight (NLoS) connectivity between a subscriber station and base station.

WiMAX signals can function over a distance of several kilometres with data rates reaching up to 75 megabits per second (Mb/s). A number of wireless signalling options exist ranging anywhere from the 2 GHz range up to 11 GHz.

The main specifications for WiMax are demonstrated in Table 27.

TABLE 27: WIMAX (802.16A) MAIN FEATURES

Feature	WiMax (802.16a)
Primary Application	Broadband Wireless Access
Frequency Band	Licensed/Unlicensed 2 G to 11 GHz
Channel Bandwidth	Adjustable 1.25 M to 20 MHz
Half/Full Duplex	Full
Radio Technology	OFDM (256-channels)
Bandwidth Efficiency	<=5 bps/Hz
Modulation	BPSK, QPSK, 16-, 64-, 256-QAM
FEC	Convolutional Code Reed-Solomon
Encryption	Mandatory- 3DES, Optional- AES

Frequencies commonly used for WiMAX, shown in Figure 55, are higher than 2.4GHz. As most wireless communication in PAN are allocated in sub-Gigahertz frequency ranges, WiMAX signals may not affect other WSN networks.

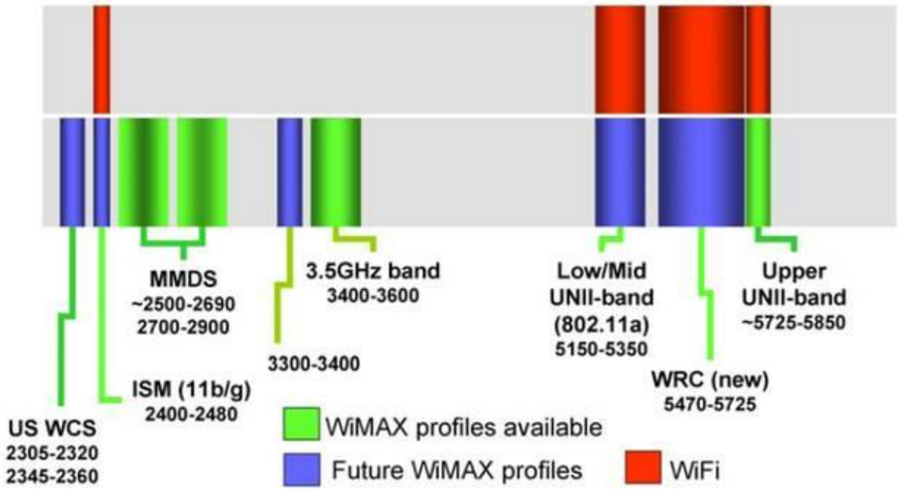

FIGURE 55: FREQUENCY BANDS USED BY WIMAX

13.2 WIRED

This section explores the communication methods that are commonly used in sensing and digital communication for transferring data using physical connections.

13.2.1 SERIAL

13.2.1.1 USB

Universal Serial Bus is a licensed asynchronous communication technique that also carries out the bus power. This method is used to connect devices to computers. There are sensors available with USB protocol. Advantages of this method include the compatibility between USB versions, and the power saving mode feature.

However, due to the low power and high-speed design of USB sensors, they are highly sensitive to noise for distances over 5 meters.

13.2.1.1 SPI AND I2C

Serial Peripheral Interface is a license-free synchronous communication technique that carries a clock signal and two data lines. This method is usually used for microcontrollers/microprocessors to communicate with their peripherals. SD-cards, analogue to digital convertors and serial RAMs are the most common devices that use SPI.

This interface is highly sensitive to noise and requires consideration during system design for optimal performance. Over long distances, the cable introduces propagation delay, therefore without extra line drivers it is not recommended to use this method outside of the printed circuit boards.

I2C is another synchronous interface which is not full-duplex and only needs one clock line and one data line. This has the same usage as SPI in most cases.

13.2.1.2 RS232, RS422 and RS485

RS232 is an asynchronous serial standard that was originally used for telecommunication systems such as modem. It was also widely used for low-speed industrial applications, compared to other serial protocols. The recommended length is about 15 meters and maximum speed is about 2 Mbps.

RS422 is an extended version of the RS232, which transfers the data using differential line drivers where the speed can go up to 10 Mbps for longer distances on a twisted pair cable (maximum 1.5 km).

RS485 is a multi-node extension of RS232, which can go over long distances and can include multiple send and receive nodes. However, in multi-node mode, the cable length should not exceed more than 10 m and the data rate is about 2 Mbps.

13.2.1.1 CAN

Controller area network (CAN) is a communication protocol that is mainly used in the automotive industry. CAN is a multi-node serial bus network which uses differential signals to reduce the effect of common noise. Robustness and fault detection capability in this communication system are the key advantages of this method. The maximum number of nodes is 30 and the length of the bus should be less than 40 m. The data rate varies depending on the distance. At the longest distance the highest signal rate is about 1 Mbps [83].

13.2.2 Ethernet

Ethernet is a computer based network. TCP/IP is the common technique used for communication in this system. This provides a unique identification number for each device. The speed on this network varies from 10 Mbps to 1 Gbps. About 100 m would be the maximum length from one node to another using CAT5/CAT6 cables in this protocol [84].

13.2.3 DSL and ADSL

Digital subscriber line (DSL) and Asymmetric DSL are data communication technologies that are used over telephone lines to transfer data at higher speeds compared to traditional dial-up modems. The distance limits for a DSL system are about 5 km and the speed depends on the distance. For instance, at a distance of 3 km the speed is about 3 Mbps.

13.2.4 Fibre optic

Thin flexible fibres of glass that transmit light signals are mainly used in telecommunication and sound systems [85]. The data rate of 10 Gbps can be attained in a fibre optic cable of around 3 m. For a 2 km distance 100 Mbps is easily achievable [86]. They are not susceptible to electromagnetic noise and fibre optic cable has been used for distances of around 300 km [87].

13.2.5 Evaluation for wired communication technologies

Table 28 shows an evaluation based on the length of the coverage, the ease of installation and maintenance, the susceptibility to electromagnetic noise, the overall cost of the technology and finally its simplicity. The evaluation is based purely on the use of the technology as a communication medium. For example, as previously described, fibre optic systems can be used for both monitoring and data transfer. This is outside the scope of this isolated evaluation, but it can be seen using the combination of the communications and sensing elements of the framework.

TABLE 28: EVALUATION OF WIRED COMMUNICATION TECHNOLOGIES

COMMUNICATIONS										
Ref	Description	Short distance data rate (<10m)	Long distace data rate (> km)	Maintenance	Installation	Immunity to EMC	Multi node capabilty	Cost	technology simplicity	**COMMUNICATION SCORE**
		13%	13%	13%	13%	13%	13%	13%	13%	
C1	USB	10	0	10	5	5	0	10	0	**5.0**
C2	SPI and I2C	5	0	10	10	0	5	10	10	**6.3**
C3	RS232	10	0	10	10	0	0	10	10	**6.3**
C4	RS422	10	5	10	5	5	5	5	10	**6.9**
C5	RS485	10	5	10	5	5	10	5	5	**6.9**
C6	Ethernet	10	5	10	5	5	10	5	5	**6.9**
C7	DSL	10	10	5	5	5	10	0	5	**6.3**
C8	Fibre optics	10	10	5	5	10	10	0	0	**6.3**

13.3 CONCLUSIONS – COMMUNICATIONS

In this section, the most common and practical wireless and wired communication methods were discussed and explained. It was shown that there are communication protocols that are specifically used for certain applications, such as railway signalling or telecommunication. How some of these technologies have evolved and how they could be further improved in the future was also discussed. The data rate, bandwidth and frequency aspect of each technology was set out. The different uses of short range systems for trackside monitoring purposes and GSM-R for railway safety critical applications were explained.

It was also shown how electronic systems can use different communication systems internally and wired connections. The use of longer range wired connections was also explained, although this would require running cables to a central point, from which data could be distributed by other wireless technologies for higher bandwidth and more robust systems.

14 Recommendations / Considerations

This report has considered a number of different aspects of the components and systems required to develop condition monitoring systems using a range of different inspection technologies. In each of the previous sections, technologies have been discussed in order to highlight the key parameters that should be considered in their selection or application. Each technology has been evaluated using a standard form, and individual conclusions relating to the technologies or technology families presented. This section will draw together some of the key observations and considerations associated with each technology.

14.1 Context

During the project, one of the key observations has been the significance of the context in which the monitoring system is to be developed and deployed. Early in the project, other work packages in the subproject were responsible for identifying a number of contextual scenarios for which monitoring systems were to be developed. Prior to the development of the scenarios and thus the requirements for the monitoring systems it was very difficult to evaluate different potential monitoring technologies or solutions. This illustrates the importance of applicational context, and in particular having specific objectives and defined requirements when identifying and developing appropriate monitoring technologies.

14.2 Frameworks

This report has described a number of different technologies and considered their appropriateness for application in a number of scenarios. The work has, therefore, developed a technology catalogue considering current and likely future solutions. In order to do this, impartial identification and evaluation mechanisms have been developed. These mechanisms, and their associated methodologies, can be applied to technologies now, but also in the future, thereby providing a standardised approach to technology evaluation. These frameworks, and the methodologies that go with them, are a key output of this work package.

When developing and using frameworks, such as those found within this work package, it is also important to consider the limitations of such systems. While they can be useful for filtering to select the more appropriate technologies, the context specific nature of the scoring systems means that generic frameworks will not necessarily identify optimum solutions. The weighting of individual scoring elements, should potentially be varied to “tune” the framework to each specific application.

14.3 Sensing technologies

Once the context / application has been identified, and the requirements defined, it is possible to identify technologies suitable for use in the development of solutions. In this work package a technology marketplace chart was used to provide an initial review of the potential usefulness of a technology. The combination of this, with the evaluation framework scores, and the applicational context can be used to drive technology development, as shown in Figure 56.

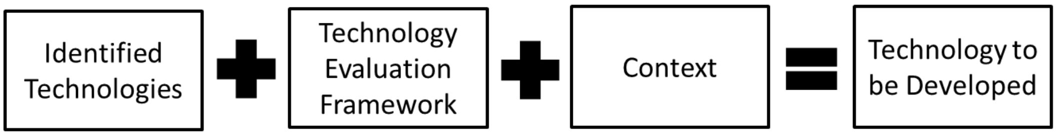

FIGURE 56: FACTORS INFLUENCING TECHNOLOGIES SELECTED FOR DEVELOPMENT

In this document, a number of different types of sensing technologies have been considered and the key parameters associated with their selection and operation discussed. Table 29 summarises the factors that must be considered when considering each technology.

TABLE 29: KEY PARAMETERS USED IN TECHNOLOGY EVALUATION

Technology	Key Factors
Vision	Frame rate Resolution Colour depth / sensitivity Field of vision (lens angle)
Vibration	Range of operation Sensitivity Drift / stability Sampling rate Power consumption Shock tolerance Sensor resonance frequency
Mechanical (Strain)	Bridge configuration Robustness (operating environment) Target geometry Installation method
Environmental (Temperature, Humidity, Wind)	Range of operation Robustness Accuracy vs. cost Size Installation method
Acoustic	Range of operation (sensitivity) Frequency range Directionality Physical limitations (size) Robustness / operating principle
Electrical	Range of operation Sensitivity Bandwidth (inc. AC / DC) Sampling rate Physical limitations (size) Installation method Isolation
Specialist / Multifunction (Fibre)	Operational benefits arising from multi-modal operation (sensing and communications)

14.4 Energy harvesting and storage

The performance of energy harvesting and storage technologies is significantly influenced by the operating environment in which they are used. For example, solar panels would not necessarily be appropriate in a Nordic environment, while a thermogenerator would best be applied in a railway rolling stock context (i.e. around an engine). Chemical energy storage systems are particularly temperature dependent, to the extent that specific chemistries may be inappropriate for certain climates. When selecting energy harvesting technologies, it is important to keep the environment in mind, but also to consider the particular tuning requirements of the application. Vibration based energy harvesting systems are often tuned to their operating environment. This approach often requires preliminary testing / quantification using, for example, vibration monitoring systems to identify the key frequencies to which to tune the system.

Energy harvesting is a range of technologies that are best used in conjunction with support technologies to either compensate for the variance in their output, or to provide storage / smoothing to the output that they can sustain. Energy harvesting technologies are best used with low power sensing and processing systems. These often include periodic rather than continuous operation, and processing in order to minimise any onward communication requirements. Any such processing would need to be optimised for efficiency.

14.5 Processing

Simply recording information from a physical system does not inherently provide any operational benefits. In order to monitor an asset, it is essential to apply processing, ideally automated, to the recorded data. In its simplest form, this could be a comparison to a pre-established threshold, but it is often much more complex. Condition monitoring systems are the combination of sensors, measurement interfaces, processing, and user interfaces. The complexity of the processing generally determines the effectiveness of the system; however, there are other factors that must be considered – for example the power and computational fabric requirements of more complex processing.

The type of processing to be undertaken can also be driven by the use case and the target outputs. For example, if the monitoring system is identifying the condition of a critical component for which the only possible remedial action is to replace the whole element, the system only needs to be able to detect a fault. If on the other hand the component being inspected is modular, it may be that identifying the exact nature of the fault (i.e. fault diagnosis) would allow more appropriate and directed remedial action to be taken. In this report, a number of processing approaches are described. These can broadly be categorised as model-free and model-based which often, although not exclusively, align with the detection and diagnosis scenarios.

14.6 User interface

The user interface is another key element of a condition monitoring system. It is essential that the user is presented with an appropriate level of detail. If too much information is presented, the user may be required to further process the output which would detract from the usability of the system. Alternatively, if too little information is presented the user may not trust the system. A good compromise to this is to present a high level result indicator along with making the supporting data available upon request.

14.7 Processing hardware / architecture

Another consideration when developing a condition monitoring system is the architecture on which the processing algorithms will operate. Ideally, the required outputs of the system would lead to a specification of the algorithm, which would define the processing requirements, which would in turn specify the processing hardware. However, in some cases other criteria might be the key drivers, and this can lead to a different approach. For example, if the hardware is to be installed in a remote location where an energy harvesting based power supply is to be used, it is unlikely that a conventional PC would be practical. In this case a lower power solution would be required and this would either limit the processing capacity, or require the adoption of an alternative architecture where the local hardware acted only as a measurement tool and the processing was undertaken at a more suitable location.

14.8 Communications

The final technology section of this report considers the communications systems used within measurement and monitoring architectures. As with most elements of such systems, there are a number of key parameters which must be considered in balance to develop a suitable system. One of the better understood balances is between the operating range and the bandwidth of the communications media. A good example of this is in wireless communications where long range cellular systems generally have lower bandwidth than local wireless solutions. A similar consideration must be given to communications channel reliability. A railway specific example would be the low bandwidth GSM-R solution which guarantees coverage, compared to a higher bandwidth 3G system which may be intermittently available across the whole network. In addition to these physical considerations, communications protocols are also considered. These are primarily driven by compatibility with the physical elements of the connection, but may also be dependent on supporting sensors with particular interfaces.

14.9 Conclusions

A condition monitoring system consists of multiple components, all of which are intricately linked. While it is moderately straightforward to evaluate one technology or component in isolation, in order to ascertain any real suitability it is necessary to both consider it in the context to which it will be applied, and in the system in which it will be a component. Technology marketplace charts, and technology evaluation frameworks have been developed to try to formalise the technology identification and evaluation processes, but even these require this context in order to be effective.

When designing a condition monitoring system, the interaction between the components and the requirements and constraints that they place upon each other can be as significant as the underlying component selections themselves. When evaluating particular technologies, it is therefore essential to consider them in the context of the whole system in which they are to be implemented.

15 Conclusions

This document has considered how different technologies should be evaluated in order to assess their appropriateness for use within the rail industry. It presents a selection of technologies for sensing and monitoring, and then looks to evaluate them either in terms of their individual merits, or as part of larger sensing and monitoring systems.

The work described in this document has considered a broad range of technologies which are either: (i) currently available in rail but with scope for improvement; (ii) available in other industries and suitable for adoption within rail; or (iii) near-horizon technologies being adopted that may be suitable for railway applications. The technologies considered have not been constrained to any particular target measurement or physical mechanism and have spanned a range of classifications including visual imaging, acceleration, strain, magnetic fields, environmental conditions, electrical, etc. High level general recommendations from other parts of the sub-project have, however, been adopted which has led the work to focus on small, low cost, sensing solutions that on a system level also consider communications and power solutions (often energy harvesting). As the work carried out within the project is focused primarily on the railway infrastructure, some measurement technologies are naturally more appropriate than others, for example the physical elements acceleration, strain, and temperature are naturally prioritised for measurement. Technologies that support multiple aspects of this, such as fibre optic systems that can be used for both measurement and communication have also been considered.

A number of frameworks have been developed within the work package in order to support the ongoing evaluation of technologies and to assess them for use in the railway industry. These include technology marketplace charts which act as a technology identification framework in order to first provide a high level assessment of general suitability. Once technologies, or combinations of technologies, were identified they were then passed through the technology evaluation framework developed within the work package and described in D4.2.1. In some cases it was appropriate to evaluate a technology, but generally the technology evaluation framework is more suitable for considering specific implementations of a technology and so candidate products were selected and evaluated. Where products were being assessed in isolation, rather than as part of a measurement system, the component elements of the framework were used and the technology's performance discussed.

While measurement technologies are obviously important, the work carried out in the work package has also identified the significance of the performance of the measurement system as a whole. To this end, the evaluation frameworks and assessments have been extended to include: (i) the processing fabric / architecture used, and to some extent the type of processing applied; (ii) the solutions available for providing power to any measurement systems; and (iii) the communications requirements and solutions for different measurement and monitoring architectures.

Despite being of limited capacity, energy harvesting technologies are becoming increasingly interesting as solutions to power small sensing nodes. On small scales, solar energy harvesting systems are generally in the higher end of energy generation capability and so are often considered – particularly in southern European countries. Wind based EH systems, often compatible with the air movement caused by the train itself are another popular lineside EH solution. On a smaller scale, or possibly for more direct application, inductive (by mutual induction) or vibration solutions are often favoured. While the levels of energy generated by piezo and thermal sources are still quite limited, a combination of energy harvesting and energy storage systems may lead to more practical solutions where continuous monitoring is required. Additionally, wireless power transmission can be used to send energy “over the air” for a couple of metres without the need for cables. Although it is a relatively new technology, tests in the lab showed stable transmission of about 10 W, which is more than enough for small sensing nodes. This may be particularly suitable for the transmission of energy from one side of the track to the other to support distributed monitoring networks.

While considering the processing algorithm alternatives for different sensing technologies, different computational demands have been identified and this has led to a consideration of the most appropriate computational frameworks for different applications or to support particular sensor types. Microcontrollers and digital signal processors are now considered to be a viable alternative to mainstream processing while being more suitable for field deployment and reducing energy consumption and heat generation. Fully integrated systems with microcontrollers for processing and transceivers for wireless communication are considered to be generally good solutions for adoption as a monitoring architecture.

A number of wireless standards and technologies have been introduced and their advantages and disadvantages discussed. Although wireless communication is desired in most modern applications, in some circumstances, such as when high bandwidth or high integrity are required, wired systems may be preferable. Wired technologies are also of particular use in the local connections within a monitoring system, where the overheads of a wireless solution may not be desirable. Consideration has also been given to electromagnetic noise susceptibility.

In summary, a range of sensing technologies and their applicability to the railway domain have been explored, and sensor and architecture identification and evaluation techniques have been demonstrated. The systems described go beyond basic measurement technologies to consider: signal acquisition, data processing (algorithms), power sources, energy storage solutions, communications systems and overall monitoring system architectures. The interactions between these system components and how they may be considered in isolation and together when designing monitoring systems has also been discussed. This information is captured in recommendations relating to a series of key points for consideration when developing monitoring systems or when considering a technology for potential future adoption within the railway industry.

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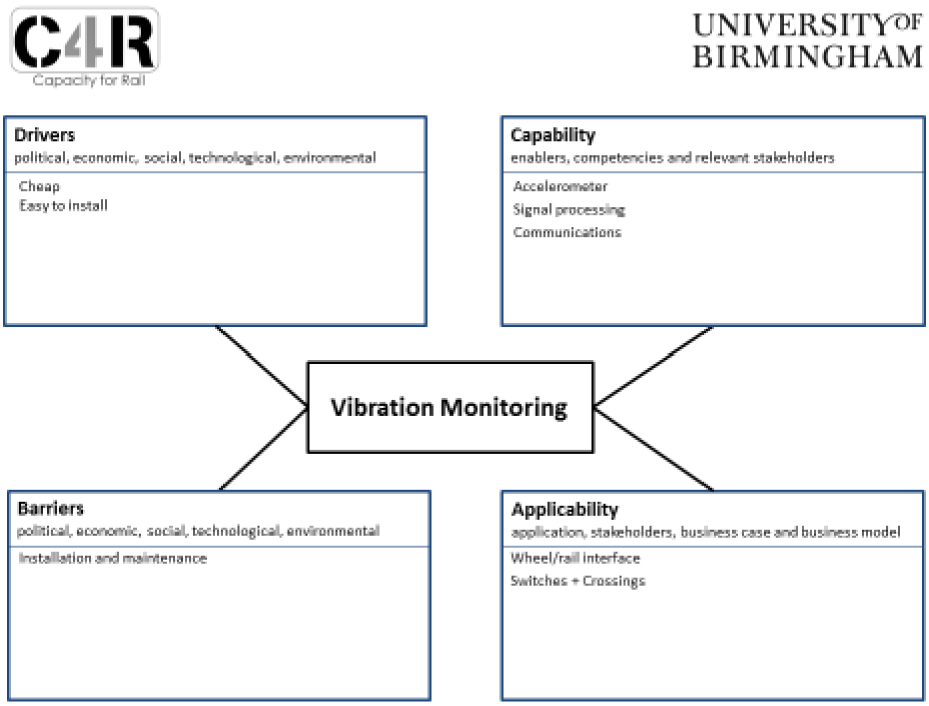
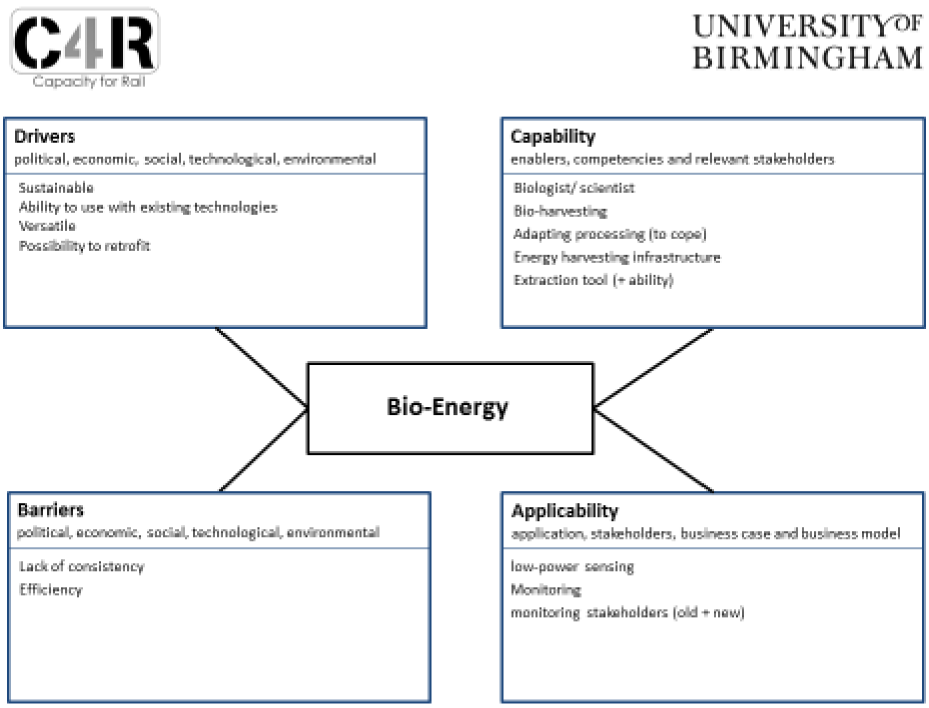
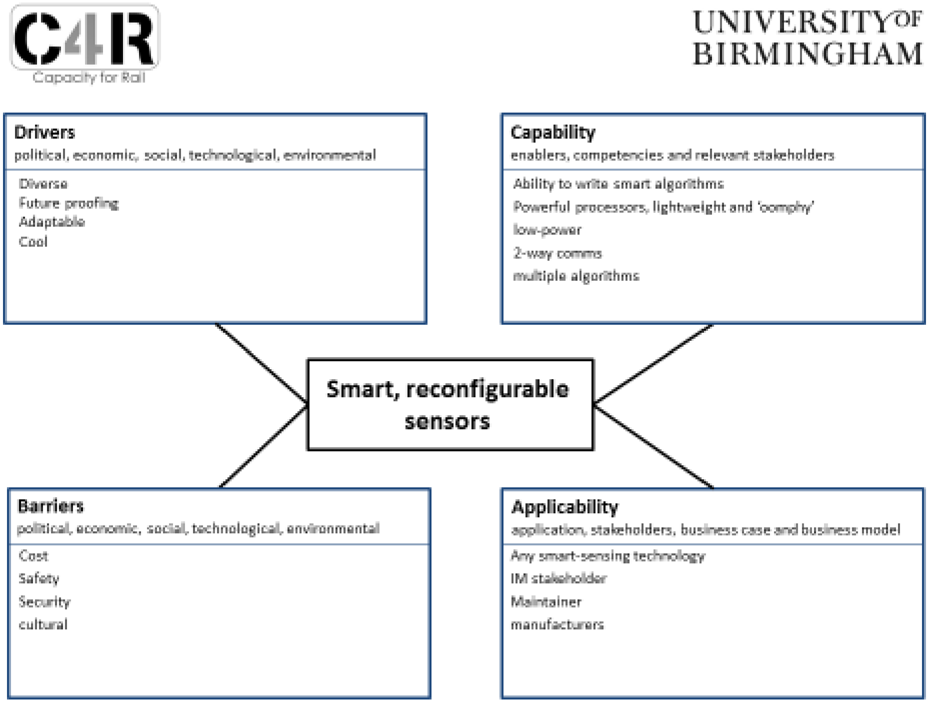
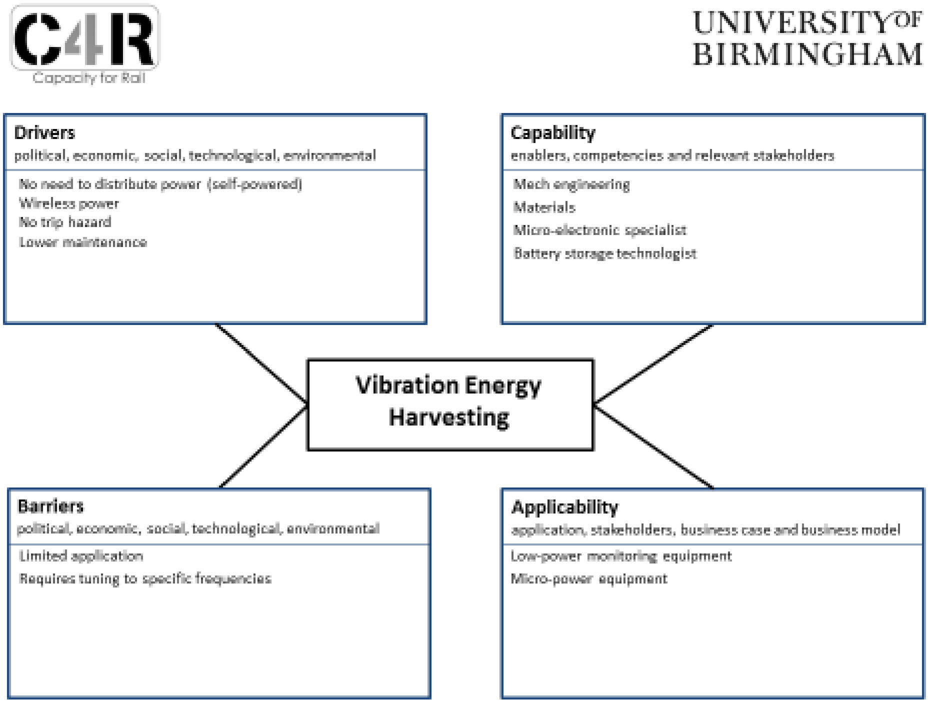
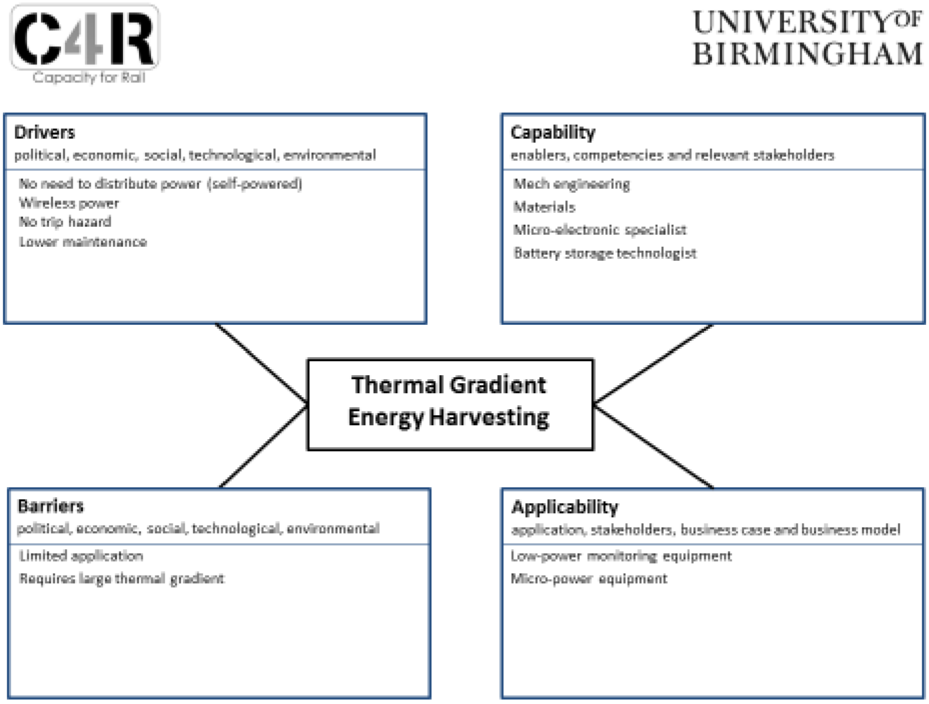
Appendix (A) - Example technology marketplace charts

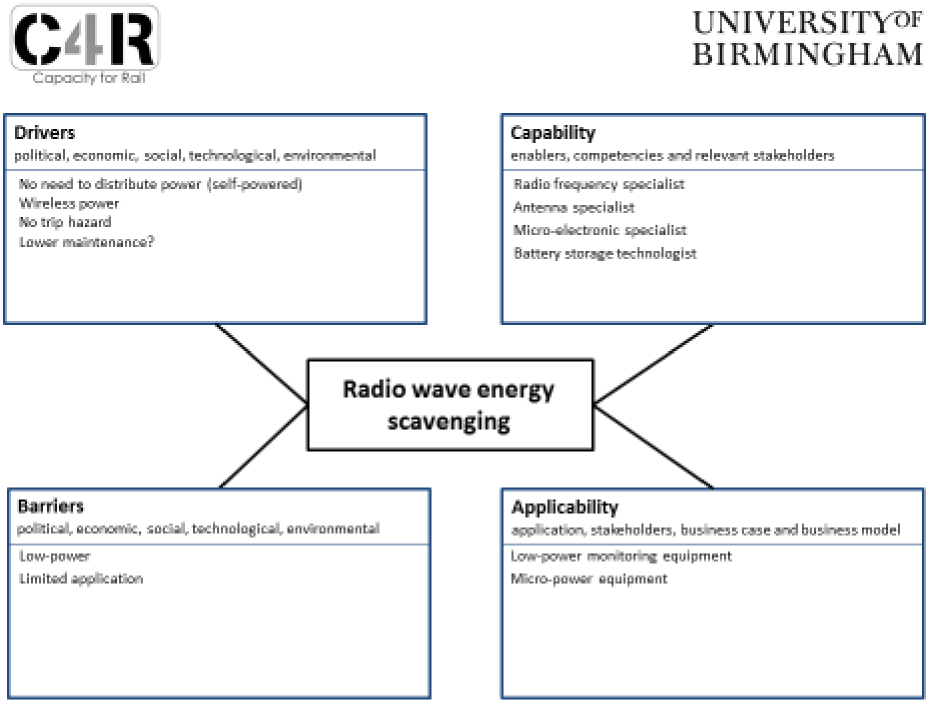


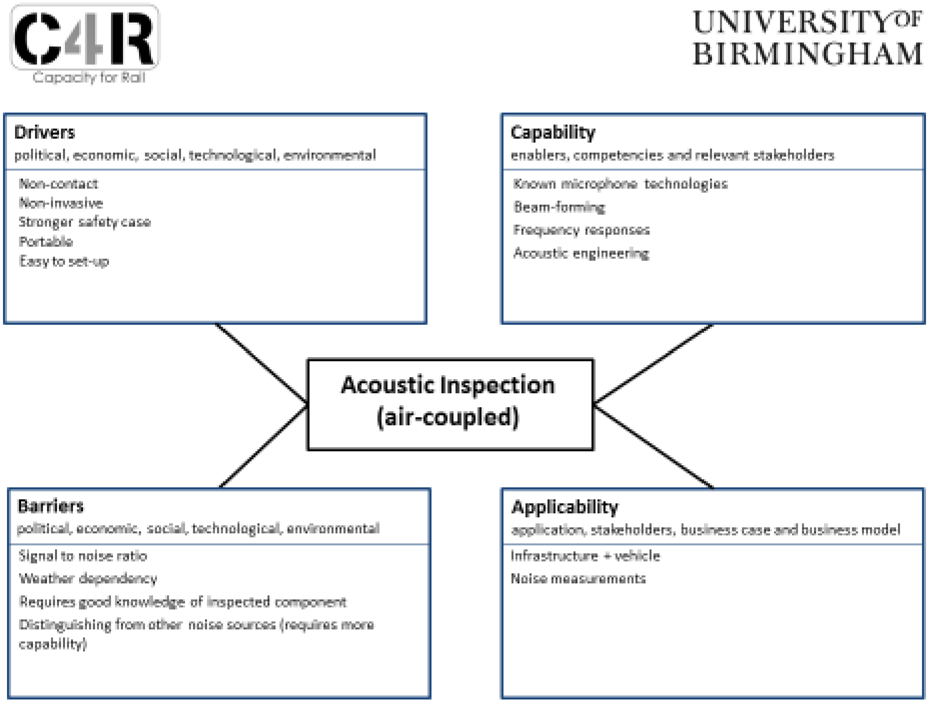


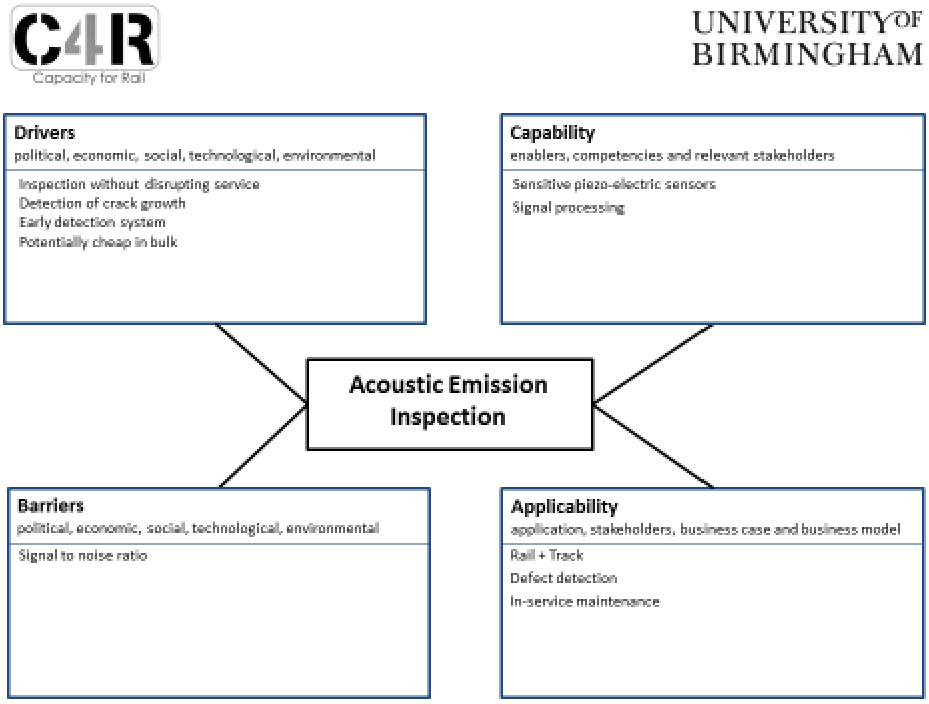

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Diverse
Future proofing
Adaptable
Cool
Capability
enablers, competencies and relevant stakeholders
Ability to write smart algorithms
Powerful processors, lightweight and 'oomphy'
low-power
2-way comms
multiple algorithms
Smart, reconfigurable sensors
Barriers
political, economic, social, technological, environmental
Cost
Safety
Security
cultural
Applicability
application, stakeholders, business case and business model
Any smart-sensing technology
IM stakeholder
Maintainer
manufacturers

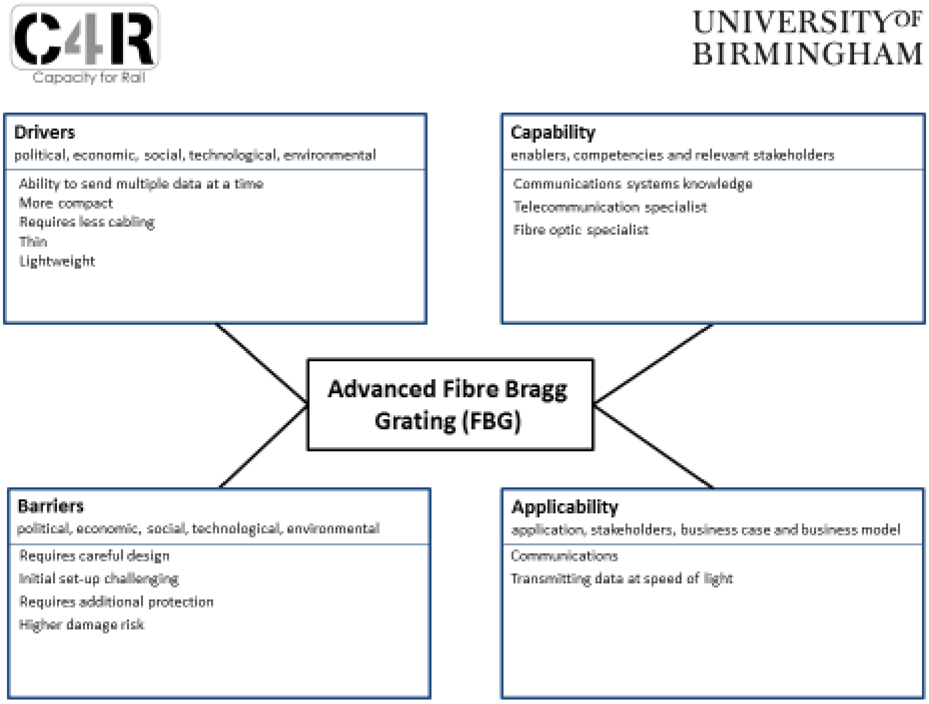

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
No need to distribute power (self-powered)
Wireless power
No trip hazard
Lower maintenance
Capability
enablers, competencies and relevant stakeholders
Mech engineering
Materials
Micro-electronic specialist
Battery storage technologist
Vibration Energy Harvesting
Barriers
political, economic, social, technological, environmental
Limited application
Requires tuning to specific frequencies
Applicability
application, stakeholders, business case and business model
Low-power monitoring equipment
Micro-power equipment

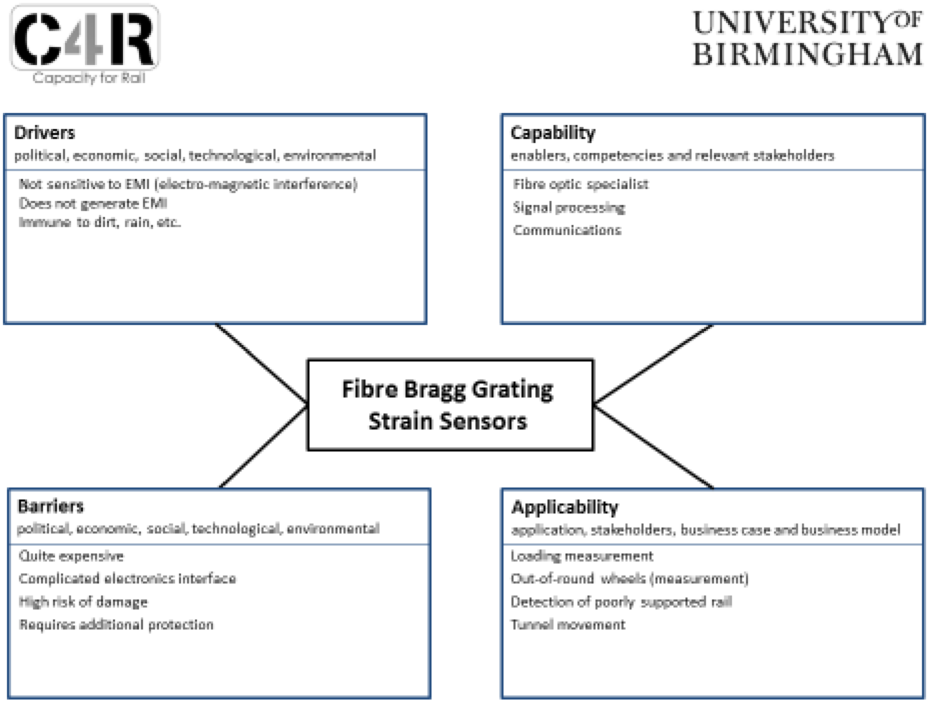

Drivers
political, economic, social, technological, environmental
No need to distribute power (self-powered)
Wireless power
No trip hazard
Lower maintenance
Capability
enablers, competencies and relevant stakeholders
Mech engineering
Materials
Micro-electronic specialist
Battery storage technologist
Thermal Gradient Energy Harvesting
Barriers
political, economic, social, technological, environmental
Limited application
Requires large thermal gradient
Applicability
application, stakeholders, business case and business model
Low-power monitoring equipment
Micro-power equipment

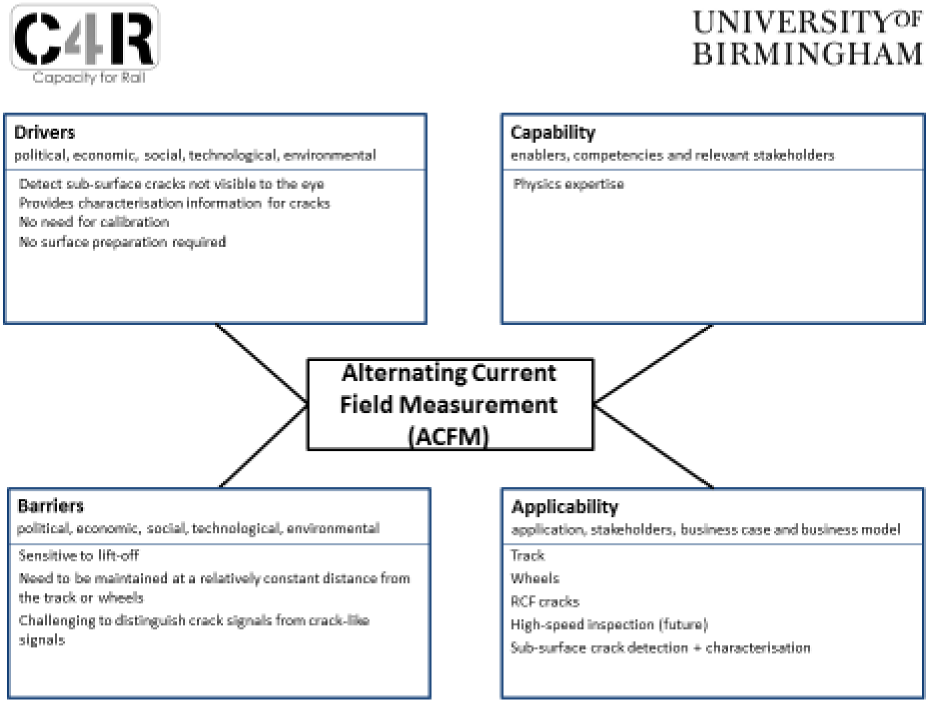

Drivers
political, economic, social, technological, environmental
No need to distribute power (self-powered)
Wireless power
No trip hazard
Lower maintenance?
Capability
enablers, competencies and relevant stakeholders
Radio frequency specialist
Antenna specialist
Micro-electronic specialist
Battery storage technologist
Radio wave energy scavenging
Barriers
political, economic, social, technological, environmental
Low-power
Limited application
Applicability
application, stakeholders, business case and business model
Low-power monitoring equipment
Micro-power equipment

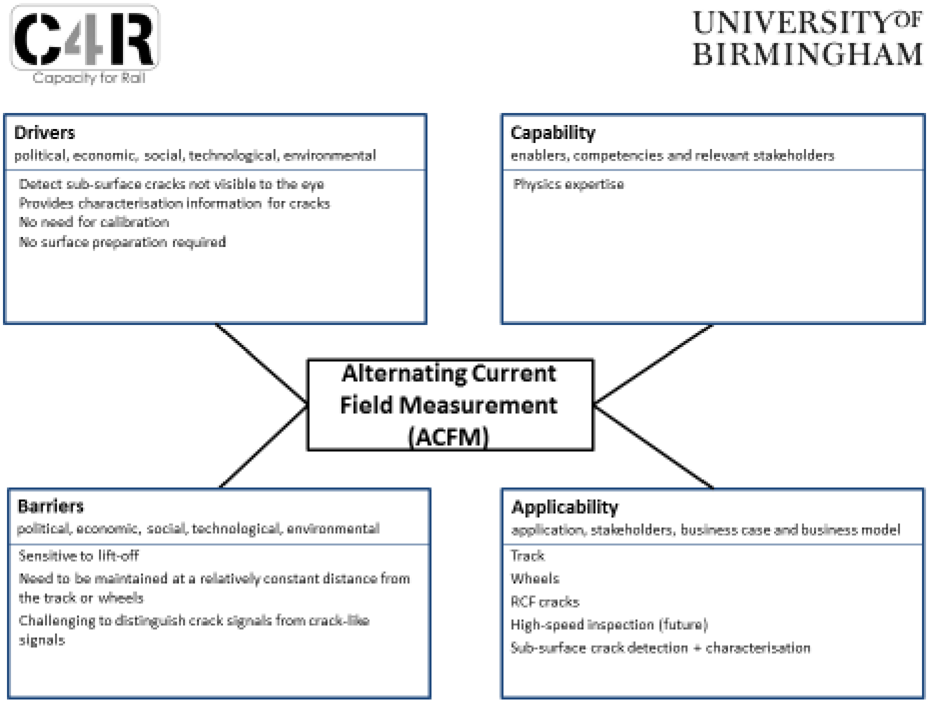

Drivers
political, economic, social, technological, environmental
Non-contact
Non-invasive
Stronger safety case
Portable
Easy to set-up
Capability
enablers, competencies and relevant stakeholders
Known microphone technologies
Beam-forming
Frequency responses
Acoustic engineering
Acoustic Inspection (air-coupled)
Barriers
political, economic, social, technological, environmental
Signal to noise ratio
Weather dependency
Requires good knowledge of inspected component
Distinguishing from other noise sources (requires more capability)
Applicability
application, stakeholders, business case and business model
Infrastructure + vehicle
Noise measurements

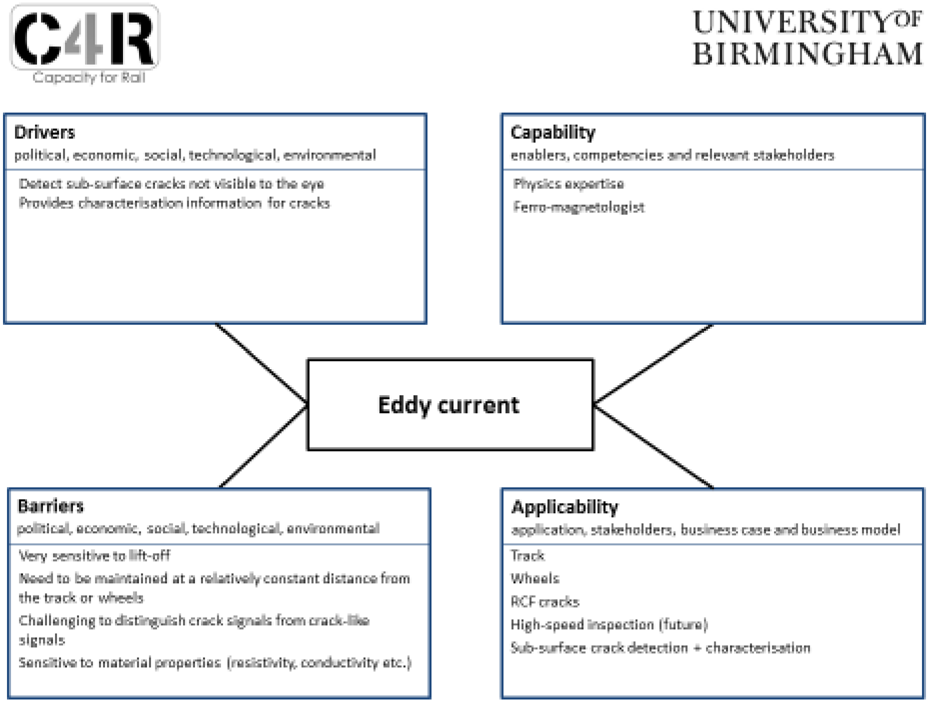

Drivers
political, economic, social, technological, environmental
Inspection without disrupting service
Detection of crack growth
Early detection system
Potentially cheap in bulk
Capability
enablers, competencies and relevant stakeholders
Sensitive piezo-electric sensors
Signal processing
Acoustic Emission Inspection
Barriers
political, economic, social, technological, environmental
Signal to noise ratio
Applicability
application, stakeholders, business case and business model
Rail + Track
Defect detection
In-service maintenance

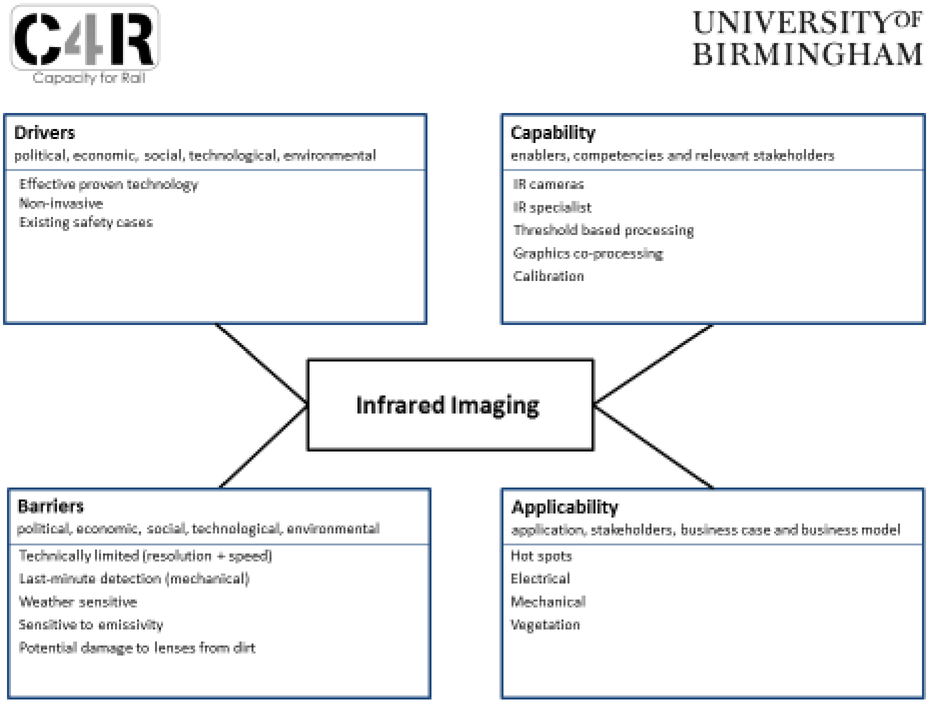

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Ability to send multiple data at a time
More compact
Requires less cabling
Thin
Lightweight
Capability
enablers, competencies and relevant stakeholders
Communications systems knowledge
Telecommunication specialist
Fibre optic specialist
Advanced Fibre Bragg Grating (FBG)
Barriers
political, economic, social, technological, environmental
Requires careful design
Initial set-up challenging
Requires additional protection
Higher damage risk
Applicability
application, stakeholders, business case and business model
Communications
Transmitting data at speed of light

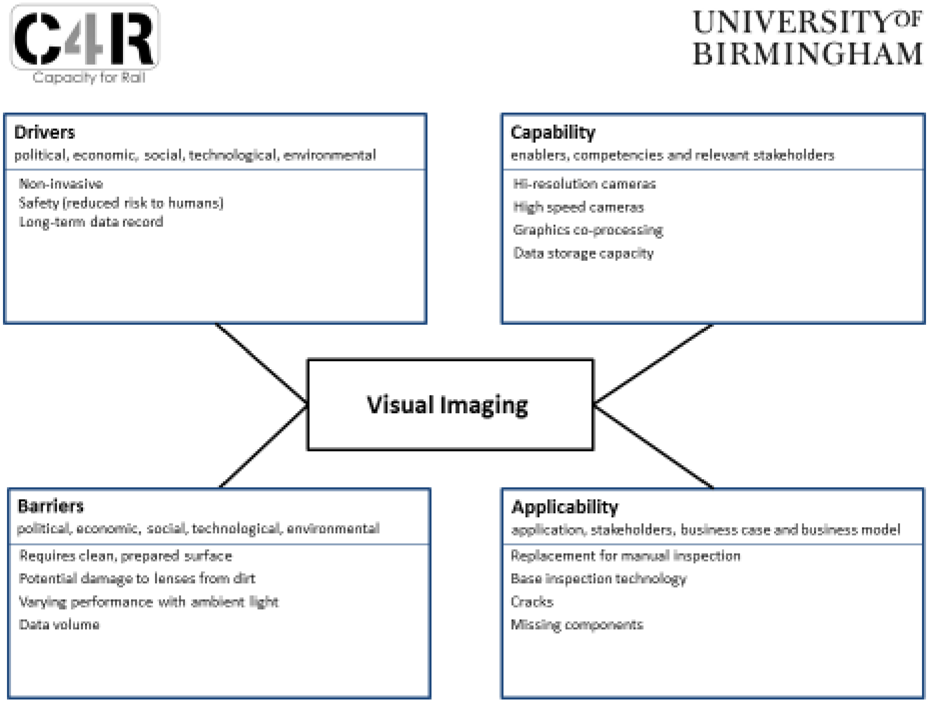

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Not sensitive to EMI (electro-magnetic interference)
Does not generate EMI
Immune to dirt, rain, etc.
Capability
enablers, competencies and relevant stakeholders
Fibre optic specialist
Signal processing
Communications
Fibre Bragg Grating Strain Sensors
Barriers
political, economic, social, technological, environmental
Quite expensive
Complicated electronics interface
High risk of damage
Requires additional protection
Applicability
application, stakeholders, business case and business model
Loading measurement
Out-of-round wheels (measurement)
Detection of poorly supported rail
Tunnel movement

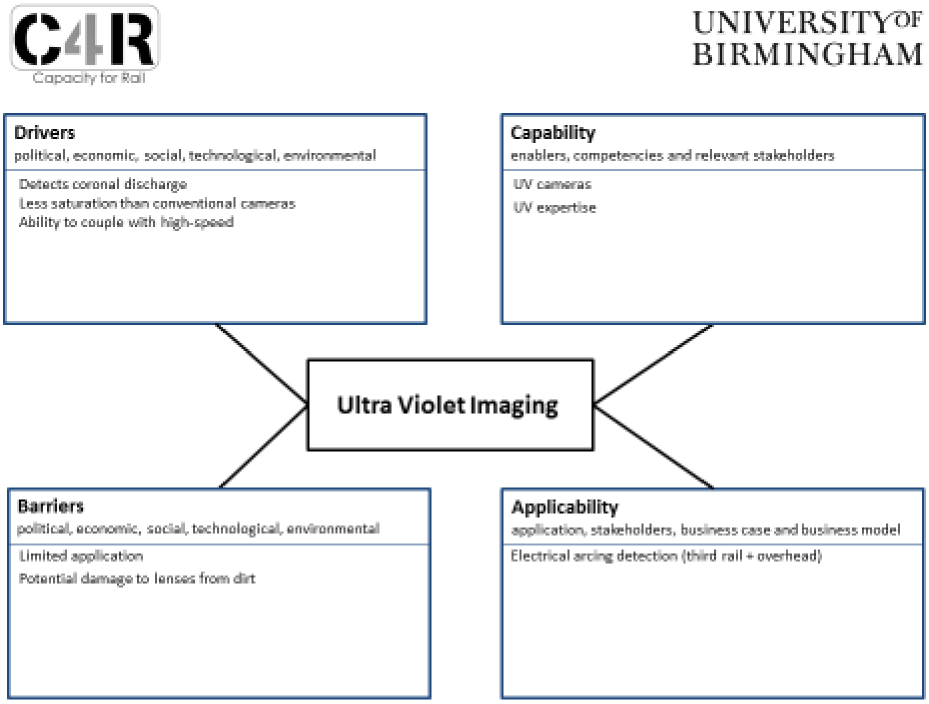

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Detect sub-surface cracks not visible to the eye
Provides characterisation information for cracks
No need for calibration
No surface preparation required
Capability
enablers, competencies and relevant stakeholders
Physics expertise
Alternating Current Field Measurement (ACFM)
Barriers
political, economic, social, technological, environmental
Sensitive to lift-off
Need to be maintained at a relatively constant distance from the track or wheels
Challenging to distinguish crack signals from crack-like signals
Applicability
application, stakeholders, business case and business model
Track
Wheels
RCF cracks
High-speed inspection (future)
Sub-surface crack detection + characterisation

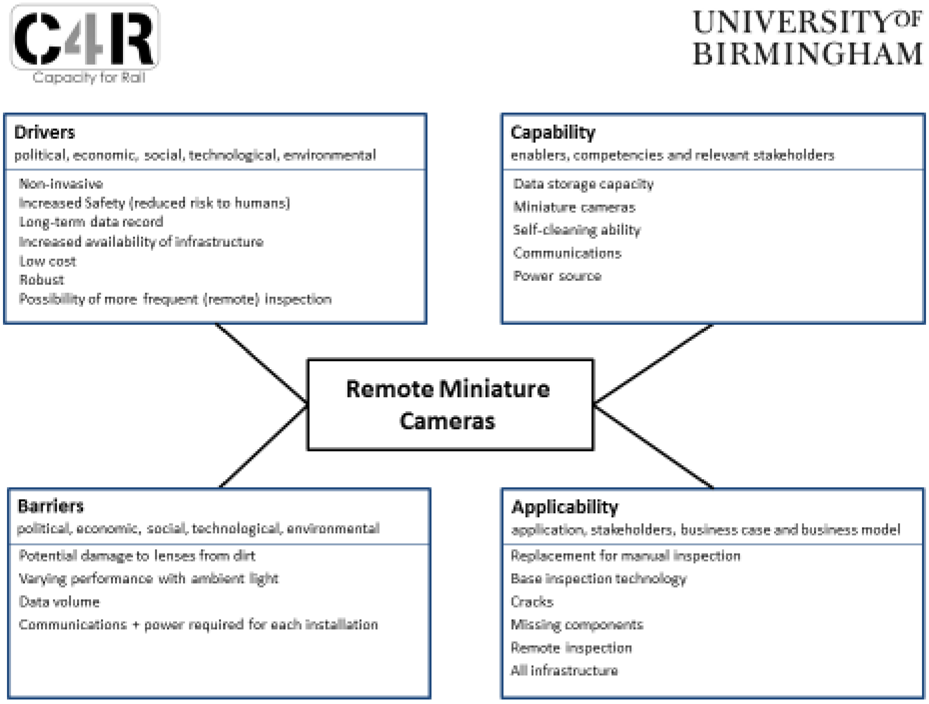

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Detect sub-surface cracks not visible to the eye
Provides characterisation information for cracks
No need for calibration
No surface preparation required
Capability
enablers, competencies and relevant stakeholders
Physics expertise
Alternating Current Field Measurement (ACFM)
Barriers
political, economic, social, technological, environmental
Sensitive to lift-off
Need to be maintained at a relatively constant distance from the track or wheels
Challenging to distinguish crack signals from crack-like signals
Applicability
application, stakeholders, business case and business model
Track
Wheels
RCF cracks
High-speed inspection (future)
Sub-surface crack detection + characterisation

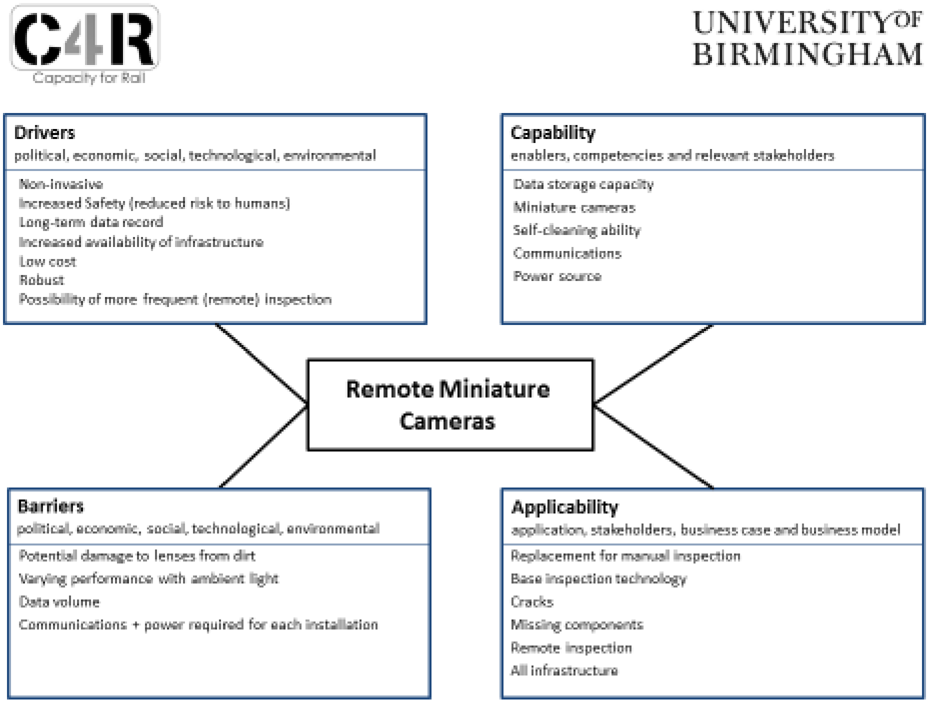

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Detect sub-surface cracks not visible to the eye
Provides characterisation information for cracks
Capability
enablers, competencies and relevant stakeholders
Physics expertise
Ferro-magnetologist
Eddy current
Barriers
political, economic, social, technological, environmental
Very sensitive to lift-off
Need to be maintained at a relatively constant distance from the track or wheels
Challenging to distinguish crack signals from crack-like signals
Sensitive to material properties (resistivity, conductivity etc.)
Applicability
application, stakeholders, business case and business model
Track
Wheels
RCF cracks
High-speed inspection (future)
Sub-surface crack detection + characterisation

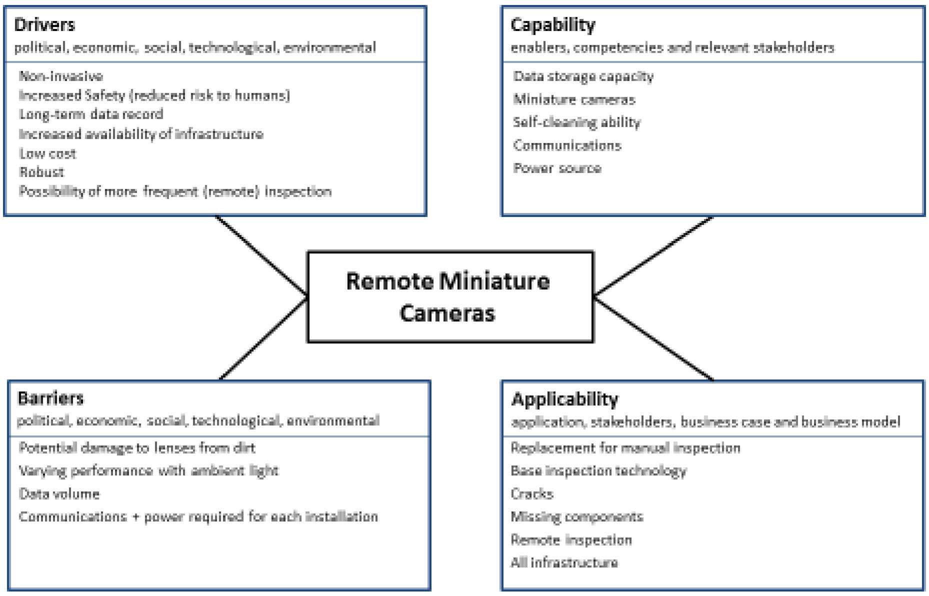

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Effective proven technology
Non-invasive
Existing safety cases
Capability
enablers, competencies and relevant stakeholders
IR cameras
IR specialist
Threshold based processing
Graphics co-processing
Calibration
Infrared Imaging
Barriers
political, economic, social, technological, environmental
Technically limited (resolution + speed)
Last-minute detection (mechanical)
Weather sensitive
Sensitive to emissivity
Potential damage to lenses from dirt
Applicability
application, stakeholders, business case and business model
Hot spots
Electrical
Mechanical
Vegetation

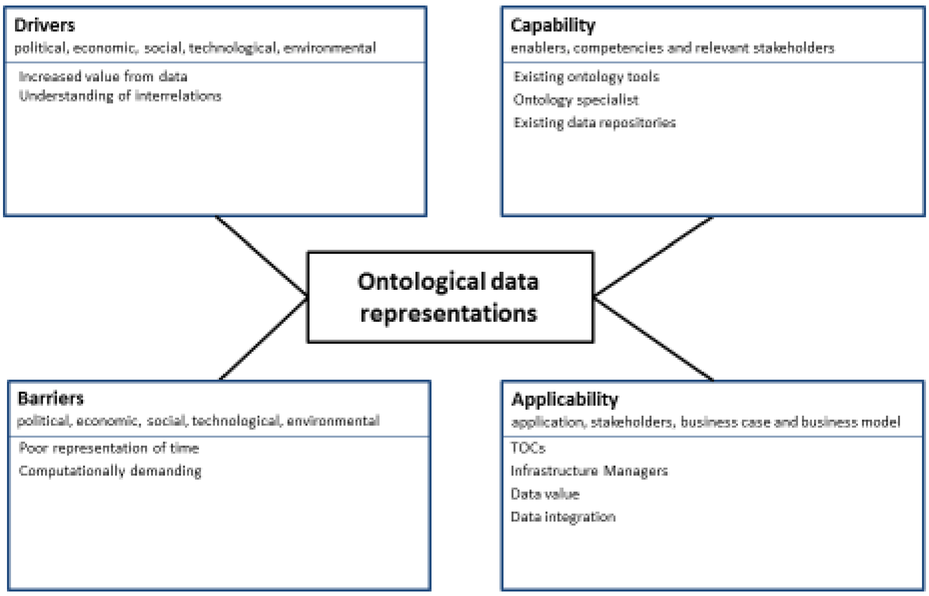

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Non-invasive
Safety (reduced risk to humans)
Long-term data record
Capability
enablers, competencies and relevant stakeholders
Hi-resolution cameras
High speed cameras
Graphics co-processing
Data storage capacity
Visual Imaging
Barriers
political, economic, social, technological, environmental
Requires clean, prepared surface
Potential damage to lenses from dirt
Varying performance with ambient light
Data volume
Applicability
application, stakeholders, business case and business model
Replacement for manual inspection
Base inspection technology
Cracks
Missing components

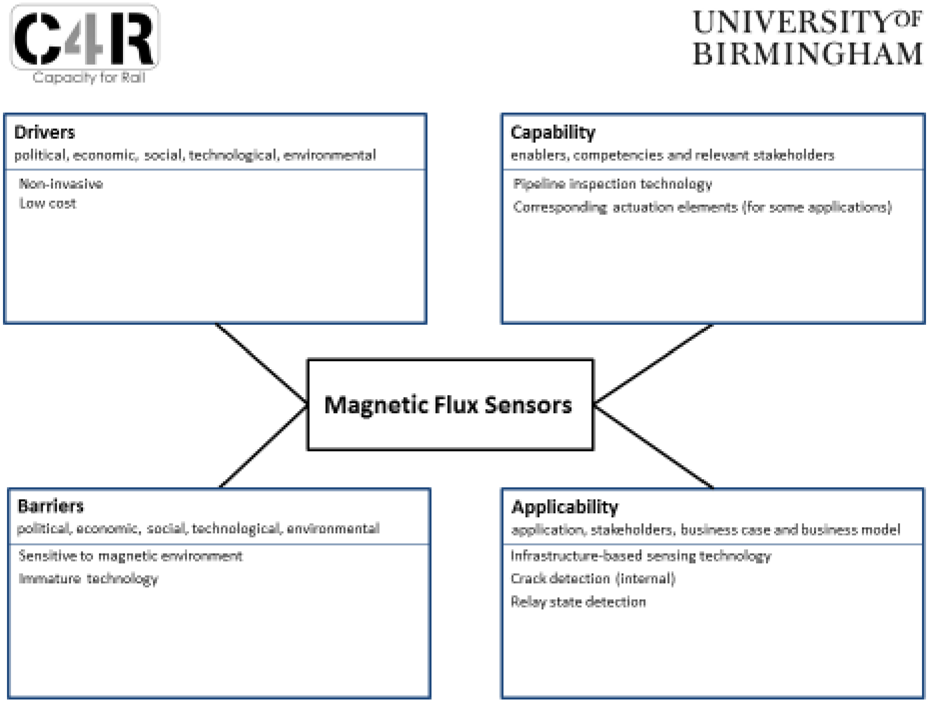

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Detects coronal discharge
Less saturation than conventional cameras
Ability to couple with high-speed
Capability
enablers, competencies and relevant stakeholders
UV cameras
UV expertise
Ultra Violet Imaging
Barriers
political, economic, social, technological, environmental
Limited application
Potential damage to lenses from dirt
Applicability
application, stakeholders, business case and business model
Electrical arcing detection (third rail + overhead)

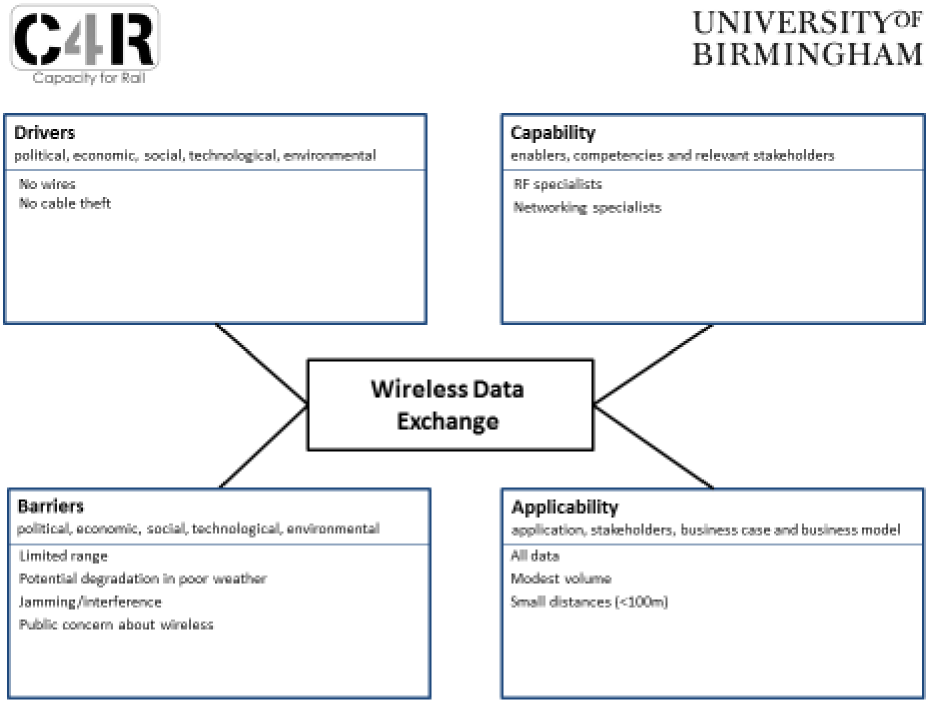

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Non-invasive
Increased Safety (reduced risk to humans)
Long-term data record
Increased availability of infrastructure
Low cost
Robust
Possibility of more frequent (remote) inspection
Capability
enablers, competencies and relevant stakeholders
Data storage capacity
Miniature cameras
Self-cleaning ability
Communications
Power source
Remote Miniature Cameras
Barriers
political, economic, social, technological, environmental
Potential damage to lenses from dirt
Varying performance with ambient light
Data volume
Communications + power required for each installation
Applicability
application, stakeholders, business case and business model
Replacement for manual inspection
Base inspection technology
Cracks
Missing components
Remote inspection
All infrastructure

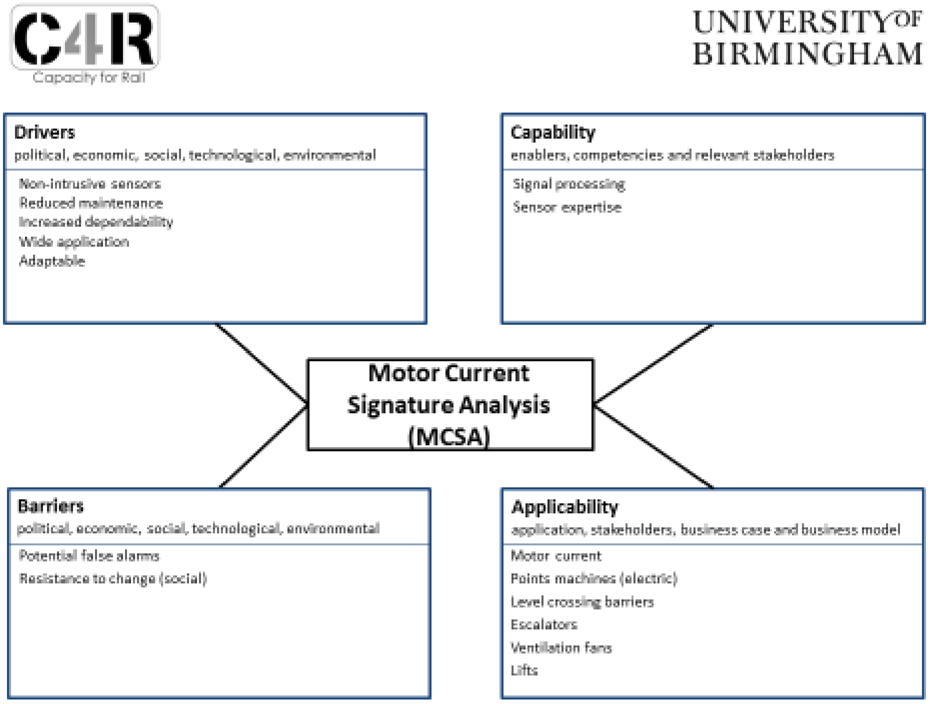

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Non-invasive
Increased Safety (reduced risk to humans)
Long-term data record
Increased availability of infrastructure
Low cost
Robust
Possibility of more frequent (remote) inspection
Capability
enablers, competencies and relevant stakeholders
Data storage capacity
Miniature cameras
Self-cleaning ability
Communications
Power source
Remote Miniature Cameras
Barriers
political, economic, social, technological, environmental
Potential damage to lenses from dirt
Varying performance with ambient light
Data volume
Communications + power required for each installation
Applicability
application, stakeholders, business case and business model
Replacement for manual inspection
Base inspection technology
Cracks
Missing components
Remote inspection
All infrastructure

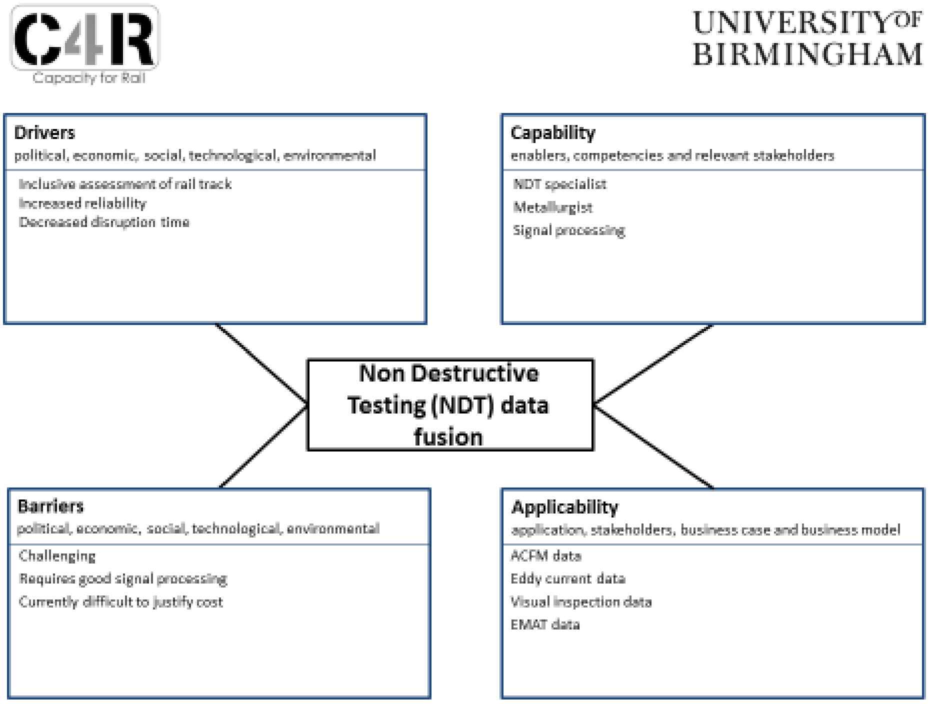

Drivers
political, economic, social, technological, environmental
Non-invasive
Increased Safety (reduced risk to humans)
Long-term data record
Increased availability of infrastructure
Low cost
Robust
Possibility of more frequent (remote) inspection
Capability
enablers, competencies and relevant stakeholders
Data storage capacity
Miniature cameras
Self-cleaning ability
Communications
Power source
Remote Miniature Cameras
Barriers
political, economic, social, technological, environmental
Potential damage to lenses from dirt
Varying performance with ambient light
Data volume
Communications + power required for each installation
Applicability
application, stakeholders, business case and business model
Replacement for manual inspection
Base inspection technology
Cracks
Missing components
Remote inspection
All infrastructure

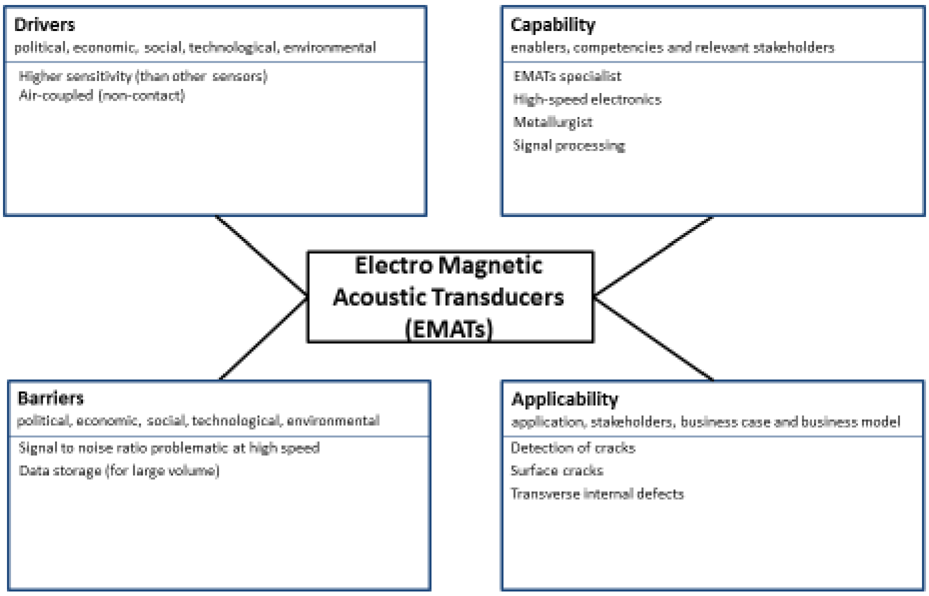

Drivers
political, economic, social, technological, environmental
Increased value from data
Understanding of interrelations
Capability
enablers, competencies and relevant stakeholders
Existing ontology tools
Ontology specialist
Existing data repositories
Ontological data representations
Barriers
political, economic, social, technological, environmental
Poor representation of time
Computationally demanding
Applicability
application, stakeholders, business case and business model
TOCs
Infrastructure Managers
Data value
Data integration

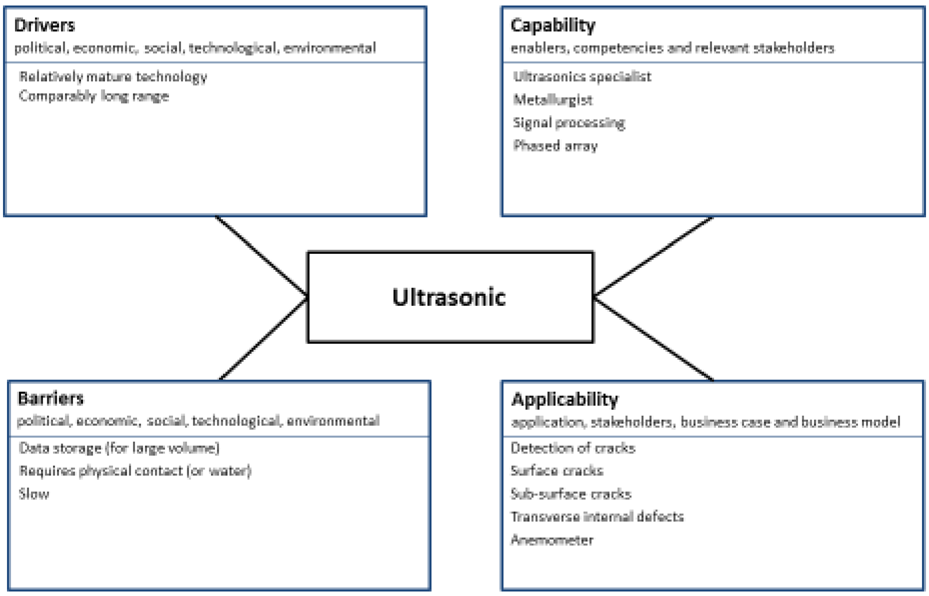

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Non-invasive
Low cost
Capability
enablers, competencies and relevant stakeholders
Pipeline inspection technology
Corresponding actuation elements (for some applications)
Magnetic Flux Sensors
Barriers
political, economic, social, technological, environmental
Sensitive to magnetic environment
Immature technology
Applicability
application, stakeholders, business case and business model
Infrastructure-based sensing technology
Crack detection (internal)
Relay state detection

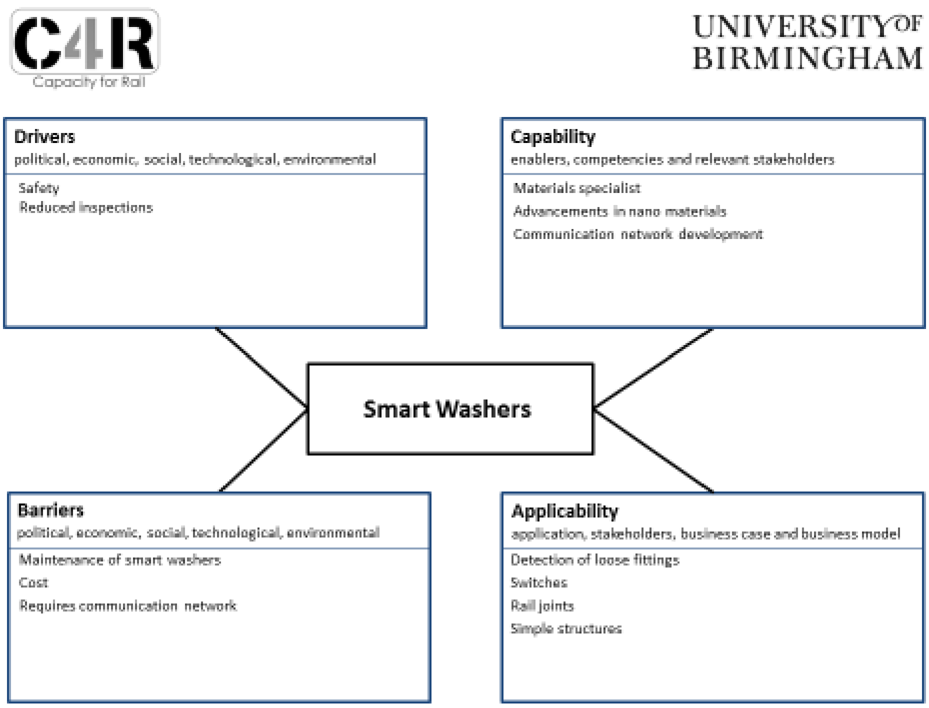

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
No wires
No cable theft
Capability
enablers, competencies and relevant stakeholders
RF specialists
Networking specialists
Wireless Data Exchange
Barriers
political, economic, social, technological, environmental
Limited range
Potential degradation in poor weather
Jamming/interference
Public concern about wireless
Applicability
application, stakeholders, business case and business model
All data
Modest volume
Small distances (<100m)

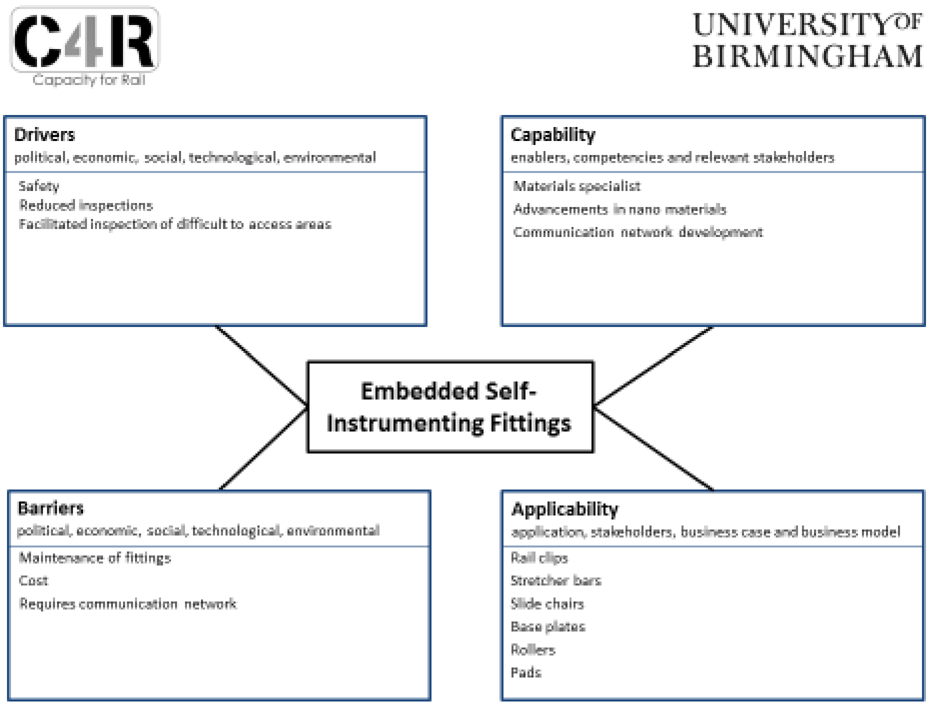

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Non-intrusive sensors
Reduced maintenance
Increased dependability
Wide application
Adaptable
Capability
enablers, competencies and relevant stakeholders
Signal processing
Sensor expertise
Motor Current Signature Analysis (MCSA)
Barriers
political, economic, social, technological, environmental
Potential false alarms
Resistance to change (social)
Applicability
application, stakeholders, business case and business model
Motor current
Points machines (electric)
Level crossing barriers
Escalators
Ventilation fans
Lifts

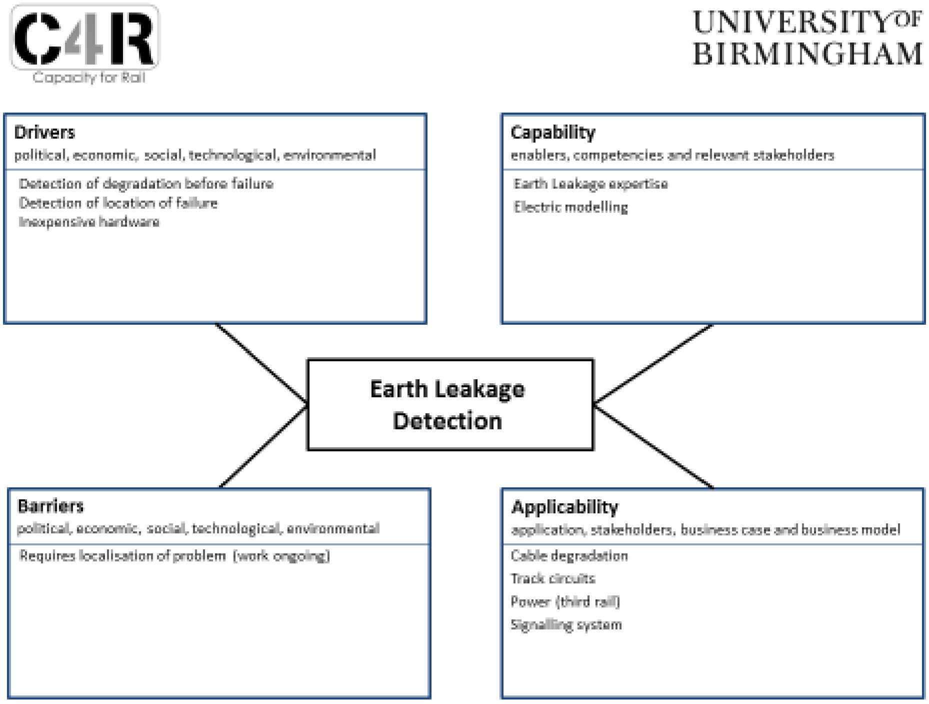

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Inclusive assessment of rail track
Increased reliability
Decreased disruption time
Capability
enablers, competencies and relevant stakeholders
NDT specialist
Metallurgist
Signal processing
Non Destructive Testing (NDT) data fusion
Barriers
political, economic, social, technological, environmental
Challenging
Requires good signal processing
Currently difficult to justify cost
Applicability
application, stakeholders, business case and business model
ACFM data
Eddy current data
Visual inspection data
EMAT data

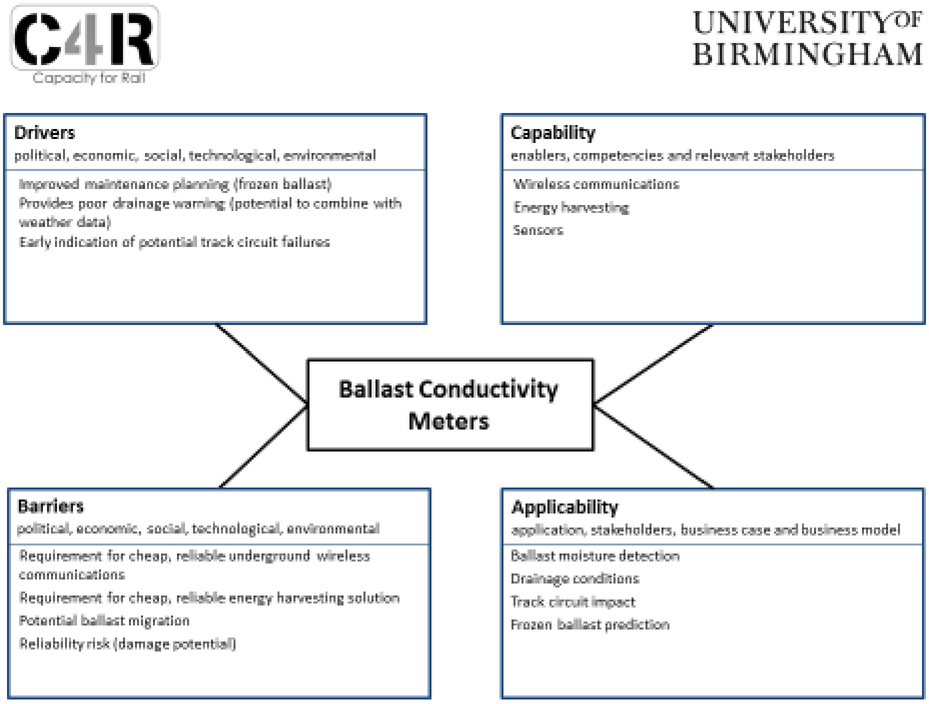

Drivers
political, economic, social, technological, environmental
Higher sensitivity (than other sensors)
Air-coupled (non-contact)
Capability
enablers, competencies and relevant stakeholders
EMATs specialist
High-speed electronics
Metallurgist
Signal processing
Electro Magnetic Acoustic Transducers (EMATs)
Barriers
political, economic, social, technological, environmental
Signal to noise ratio problematic at high speed
Data storage (for large volume)
Applicability
application, stakeholders, business case and business model
Detection of cracks
Surface cracks
Transverse internal defects

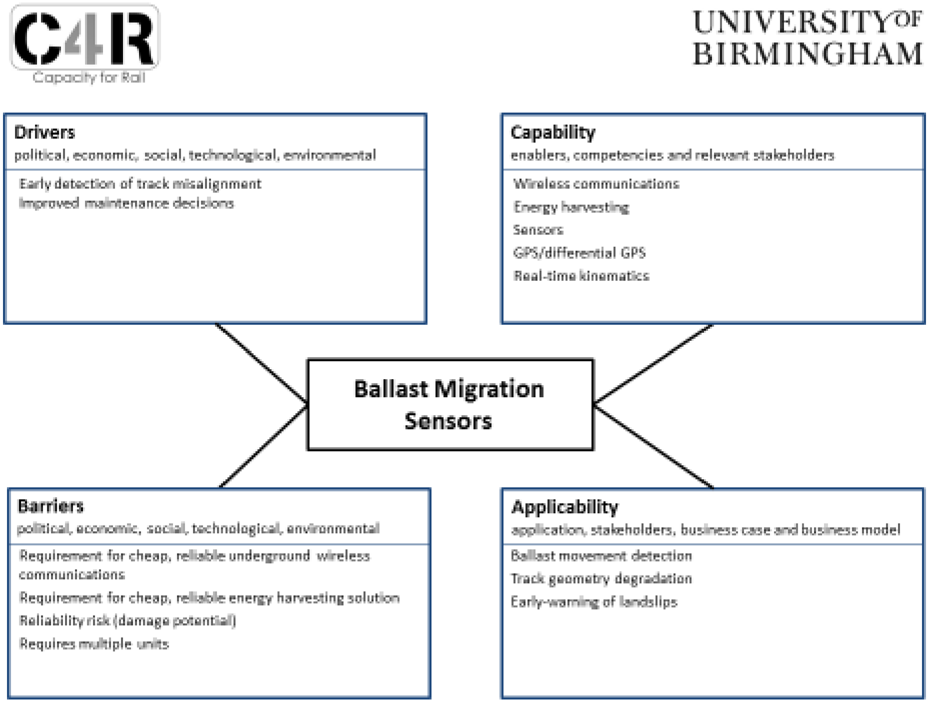

Drivers
political, economic, social, technological, environmental
Relatively mature technology
Comparably long range
Capability
enablers, competencies and relevant stakeholders
Ultrasonics specialist
Metallurgist
Signal processing
Phased array
Ultrasonic
Barriers
political, economic, social, technological, environmental
Data storage (for large volume)
Requires physical contact (or water)
Slow
Applicability
application, stakeholders, business case and business model
Detection of cracks
Surface cracks
Sub-surface cracks
Transverse internal defects
Anemometer

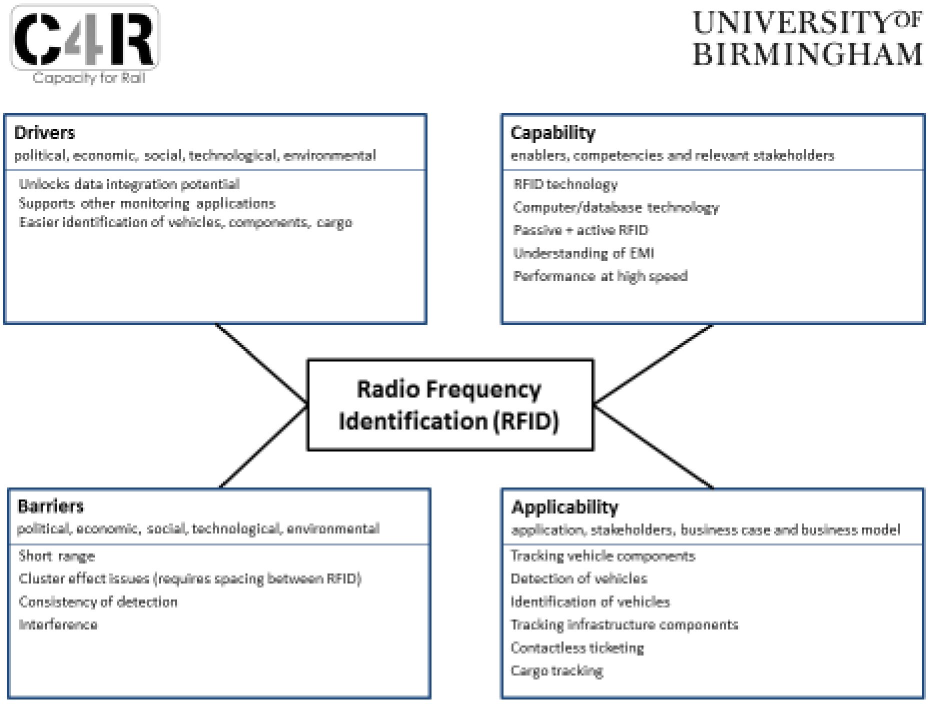

Drivers
political, economic, social, technological, environmental
Safety
Reduced inspections
Capability
enablers, competencies and relevant stakeholders
Materials specialist
Advancements in nano materials
Communication network development
Smart Washers
Barriers
political, economic, social, technological, environmental
Maintenance of smart washers
Cost
Requires communication network
Applicability
application, stakeholders, business case and business model
Detection of loose fittings
Switches
Rail joints
Simple structures

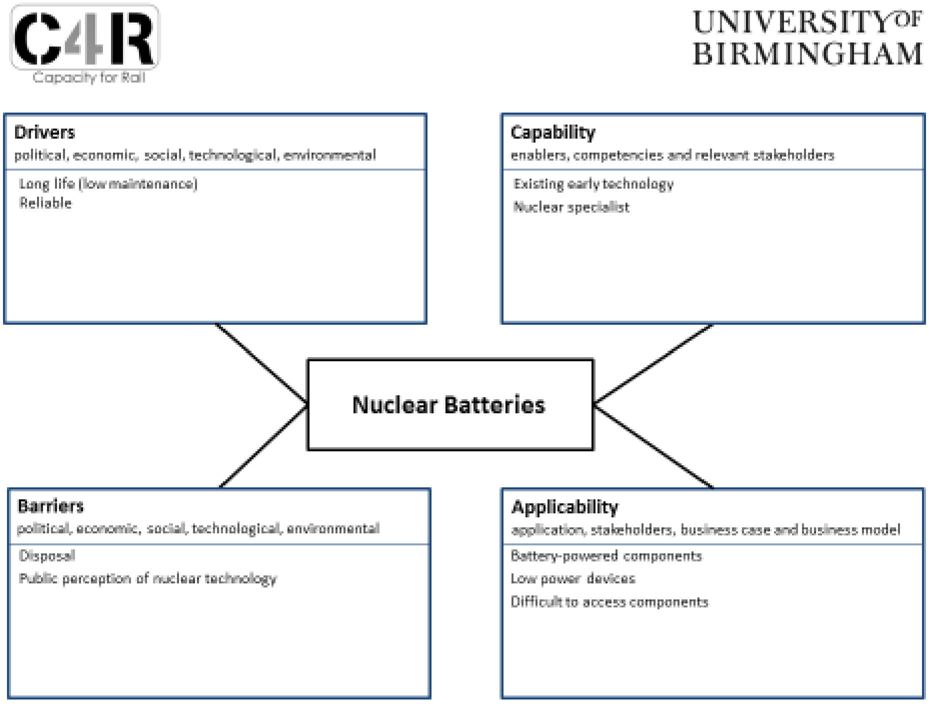

Drivers
political, economic, social, technological, environmental
Safety
Reduced inspections
Facilitated inspection of difficult to access areas
Capability
enablers, competencies and relevant stakeholders
Materials specialist
Advancements in nano materials
Communication network development
Embedded Self-Instrumenting Fittings
Barriers
political, economic, social, technological, environmental
Maintenance of fittings
Cost
Requires communication network
Applicability
application, stakeholders, business case and business model
Rail clips
Stretcher bars
Slide chairs
Base plates
Rollers
Pads

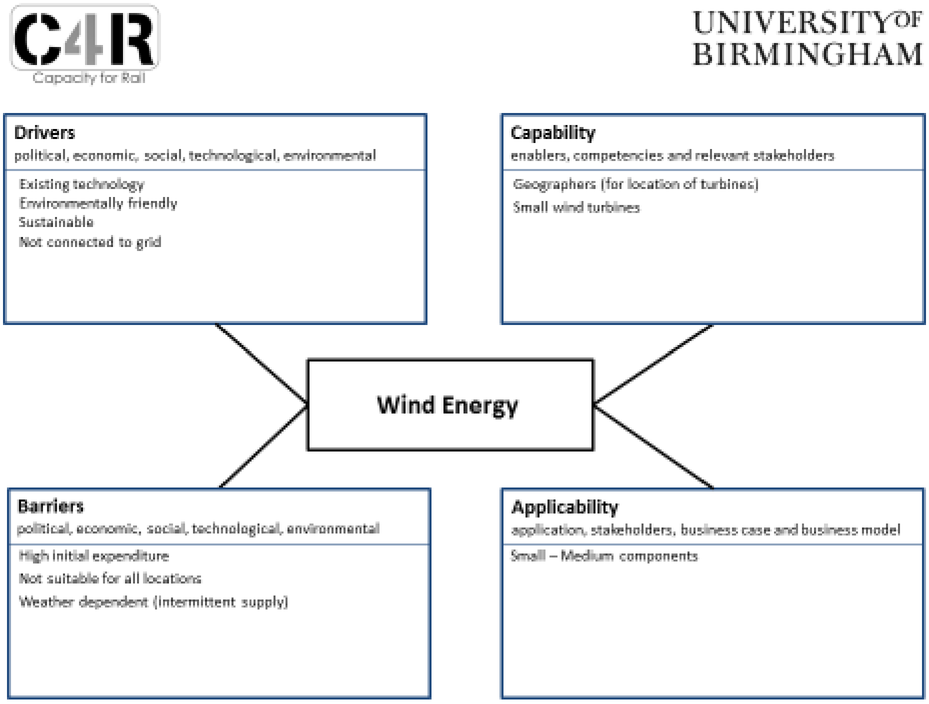

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Detection of degradation before failure
Detection of location of failure
Inexpensive hardware
Capability
enablers, competencies and relevant stakeholders
Earth Leakage expertise
Electric modelling
Earth Leakage Detection
Barriers
political, economic, social, technological, environmental
Requires localisation of problem (work ongoing)
Applicability
application, stakeholders, business case and business model
Cable degradation
Track circuits
Power (third rail)
Signalling system

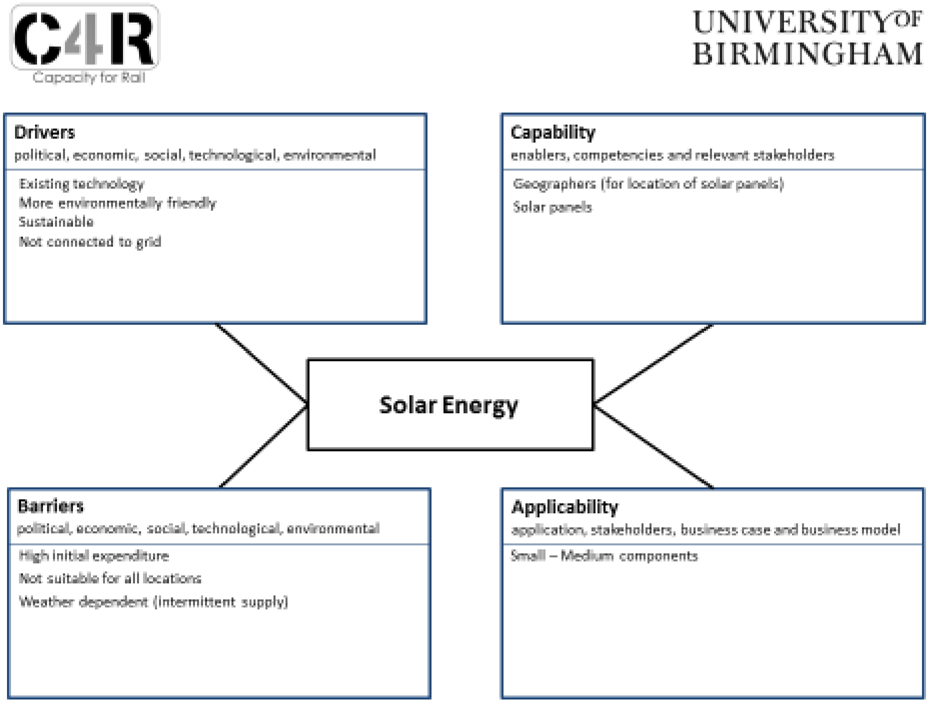

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Improved maintenance planning (frozen ballast)
Provides poor drainage warning (potential to combine with weather data)
Early indication of potential track circuit failures
Capability
enablers, competencies and relevant stakeholders
Wireless communications
Energy harvesting
Sensors
Ballast Conductivity Meters
Barriers
political, economic, social, technological, environmental
Requirement for cheap, reliable underground wireless communications
Requirement for cheap, reliable energy harvesting solution
Potential ballast migration
Reliability risk (damage potential)
Applicability
application, stakeholders, business case and business model
Ballast moisture detection
Drainage conditions
Track circuit impact
Frozen ballast prediction

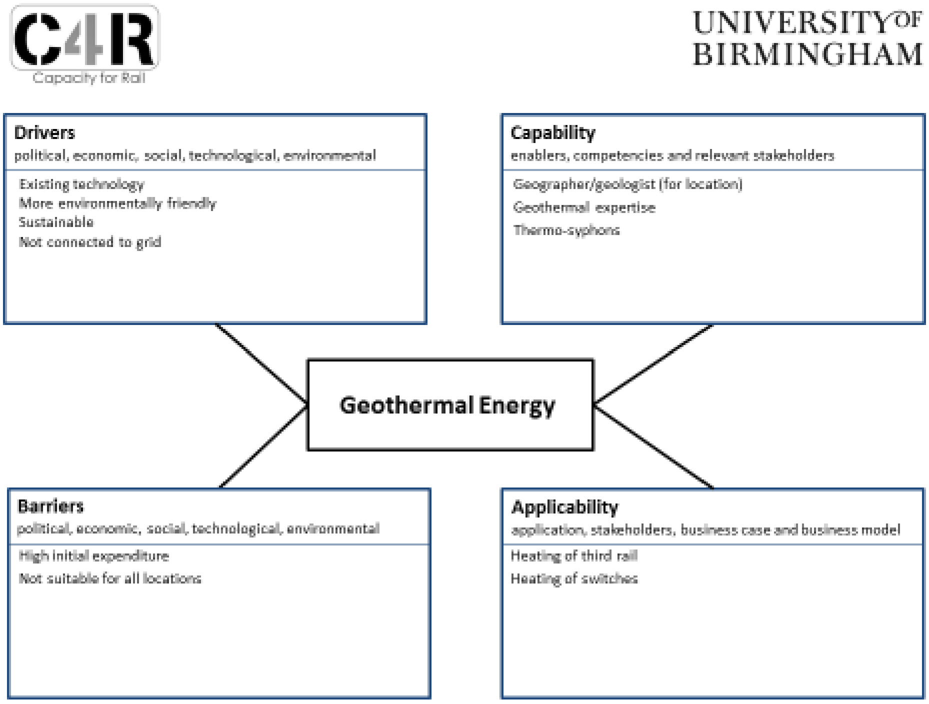

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Early detection of track misalignment
Improved maintenance decisions
Capability
enablers, competencies and relevant stakeholders
Wireless communications
Energy harvesting
Sensors
GPS/differential GPS
Real-time kinematics
Ballast Migration Sensors
Barriers
political, economic, social, technological, environmental
Requirement for cheap, reliable underground wireless communications
Requirement for cheap, reliable energy harvesting solution
Reliability risk (damage potential)
Requires multiple units
Applicability
application, stakeholders, business case and business model
Ballast movement detection
Track geometry degradation
Early-warning of landslips

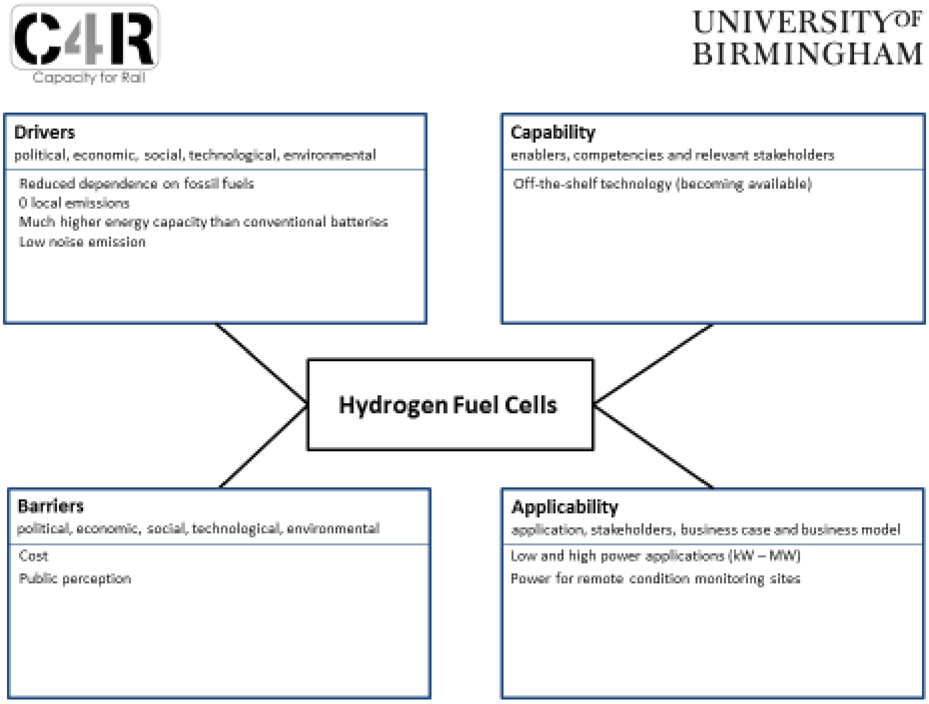

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Unlocks data integration potential
Supports other monitoring applications
Easier identification of vehicles, components, cargo
Capability
enablers, competencies and relevant stakeholders
RFID technology
Computer/database technology
Passive + active RFID
Understanding of EMI
Performance at high speed
Radio Frequency Identification (RFID)
Barriers
political, economic, social, technological, environmental
Short range
Cluster effect issues (requires spacing between RFID)
Consistency of detection
Interference
Applicability
application, stakeholders, business case and business model
Tracking vehicle components
Detection of vehicles
Identification of vehicles
Tracking infrastructure components
Contactless ticketing
Cargo tracking

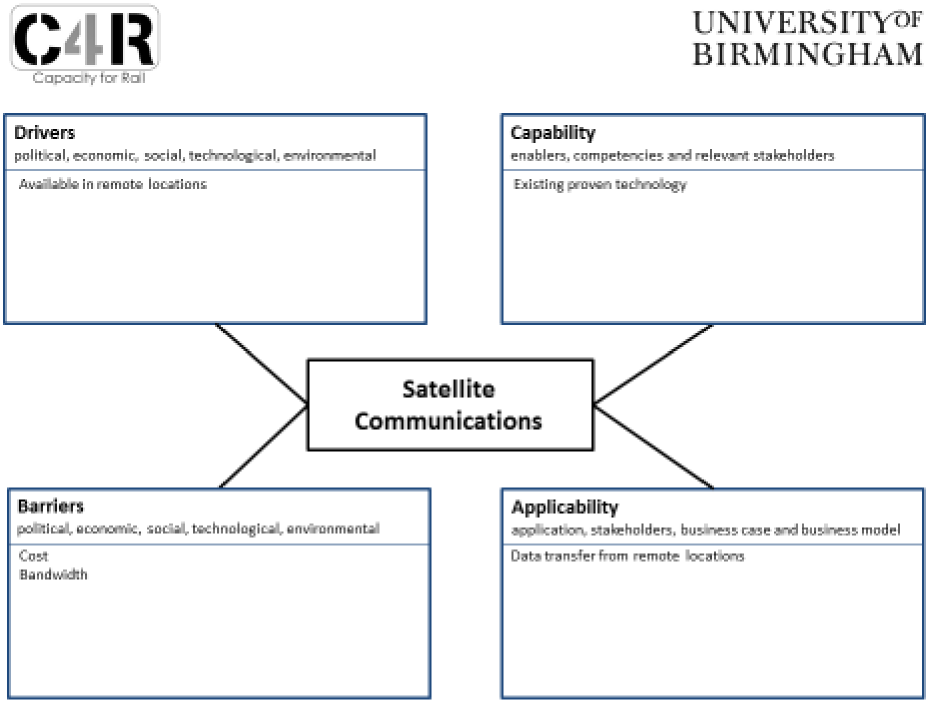

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Long life (low maintenance)
Reliable
Capability
enablers, competencies and relevant stakeholders
Existing early technology
Nuclear specialist
Nuclear Batteries
Barriers
political, economic, social, technological, environmental
Disposal
Public perception of nuclear technology
Applicability
application, stakeholders, business case and business model
Battery-powered components
Low power devices
Difficult to access components

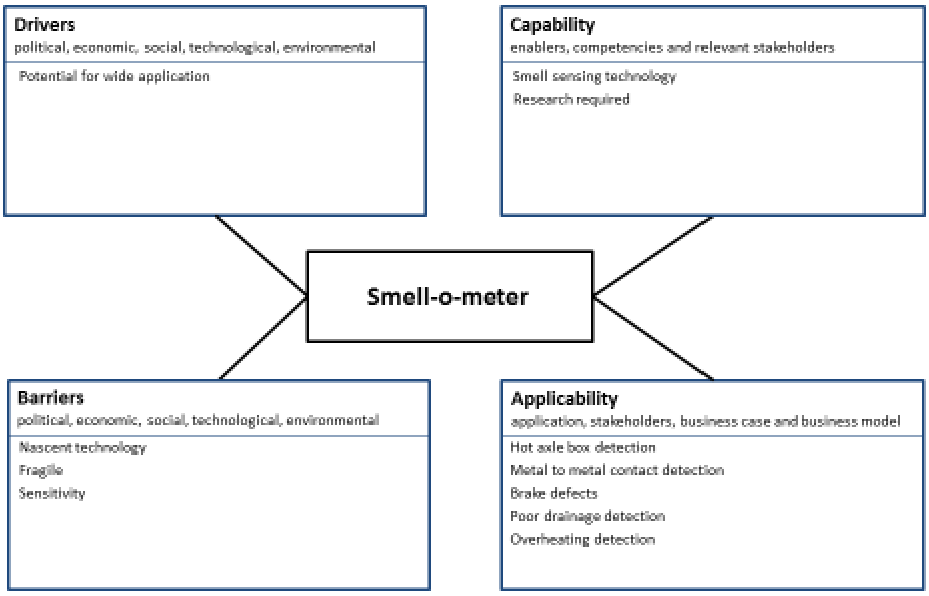

C4R
Capacity for Rail
UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Existing technology
Environmentally friendly
Sustainable
Not connected to grid
Capability
enablers, competencies and relevant stakeholders
Geographers (for location of turbines)
Small wind turbines
Wind Energy
Barriers
political, economic, social, technological, environmental
High initial expenditure
Not suitable for all locations
Weather dependent (intermittent supply)
Applicability
application, stakeholders, business case and business model
Small – Medium components


Drivers
political, economic, social, technological, environmental
Existing technology
More environmentally friendly
Sustainable
Not connected to grid
Capability
enablers, competencies and relevant stakeholders
Geographers (for location of solar panels)
Solar panels
Solar Energy
Barriers
political, economic, social, technological, environmental
High initial expenditure
Not suitable for all locations
Weather dependent (intermittent supply)
Applicability
application, stakeholders, business case and business model
Small – Medium components


Drivers
political, economic, social, technological, environmental
Existing technology
More environmentally friendly
Sustainable
Not connected to grid
Capability
enablers, competencies and relevant stakeholders
Geographer/geologist (for location)
Geothermal expertise
Thermo-syphons
Geothermal Energy
Barriers
political, economic, social, technological, environmental
High initial expenditure
Not suitable for all locations
Applicability
application, stakeholders, business case and business model
Heating of third rail
Heating of switches


UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Reduced dependence on fossil fuels
0 local emissions
Much higher energy capacity than conventional batteries
Low noise emission
Capability
enablers, competencies and relevant stakeholders
Off-the-shelf technology (becoming available)
Hydrogen Fuel Cells
Barriers
political, economic, social, technological, environmental
Cost
Public perception
Applicability
application, stakeholders, business case and business model
Low and high power applications (kW – MW)
Power for remote condition monitoring sites


UNIVERSITY OF BIRMINGHAM
Drivers
political, economic, social, technological, environmental
Available in remote locations
Capability
enablers, competencies and relevant stakeholders
Existing proven technology
Satellite Communications
Barriers
political, economic, social, technological, environmental
Cost
Bandwidth
Applicability
application, stakeholders, business case and business model
Data transfer from remote locations


Drivers
political, economic, social, technological, environmental
Potential for wide application
Capability
enablers, competencies and relevant stakeholders
Smell sensing technology
Research required
Smell-o-meter
Barriers
political, economic, social, technological, environmental
Nascent technology
Fragile
Sensitivity
Applicability
application, stakeholders, business case and business model
Hot axle box detection
Metal to metal contact detection
Brake defects
Poor drainage detection
Overheating detection