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Technical specification for infrastructure monitoring by wireless sensor network

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Tongji University

Wisen Innovation (UK) Ltd

Shanghai Institute of Disaster Prevention and Relief

The Hong Kong University of Science and Technology

Norwegian Geotechnical Institute

Shanghai Rail Transit Maintenance Support Co., Ltd.

Yunnan Xuanhui Expressway Co., Ltd

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0 Introduction

Infrastructure safety faces critical challenges in design, construction, and operation due to inherent uncertainties in surrounding geological environments, compounded by the escalating impacts of geo-disasters such as landslides, debris flows, and ground subsidence. These hazards have become increasingly frequent and destructive under the combined effects of climate change and intensive human activities. Such geo-disasters not only exacerbate the instability of geological conditions but also serve as hidden triggers that amplify the vulnerability of structural systems. Consequently, infrastructure assets often suffer from insufficient real-time state perception and adaptive control, resulting in performance degradation throughout their service life and, in severe cases, catastrophic safety incidents.

Traditional monitoring techniques, including manual measurement, wired systems, and fiber-optic sensors, face significant challenges due to complex installation procedures, high maintenance demands, and limited adaptability to large-scale or long-term monitoring. Over the past fifteen years, wireless sensor network (WSN) has emerged as a promising alternative technology for infrastructure monitoring. Characterized by real-time sensing, autonomous energy supply, and strong environmental adaptability, WSN has been widely applied in infrastructure health monitoring projects worldwide.

This specification seeks to promote consistency and interoperability among WSN-based monitoring systems, ensure data accuracy and system robustness, and support the safe, intelligent, and sustainable development of civil and geotechnical infrastructure monitoring.

1 Scope and objective

1.1 Scope

1.1.1 In order to standardize the monitoring work of wireless sensor network (WSN) for infrastructure, achieve advanced technology, reasonable economy, reliable system, and ensure the safety of infrastructure and surrounding environment, this specification is formulated.

1.1.2 This specification is applicable to the wireless sensor network monitoring during the construction and operation periods of infrastructures such as tunnel, underground utility tunnel, excavation engineering, pipeline, bridge, slope, airport and road engineering, and railway engineering. Other infrastructures can be implemented by reference.

1.1.3 The monitoring work of wireless sensor network for infrastructure should not only comply with this specification, but also comply with the provisions of the current relevant national standards.

1.2 Objective

1.2.1 The objective of this specification is to provide general principles and requirements for the design, implementation, and management of wireless sensor network monitoring of infrastructure, ensuring technical advancement, economic feasibility, system reliability, and the safety of infrastructures and their surrounding environments.

1.2.2 The standard specifies general principles and requirements for the following:

- Design principles;

- Technical configuration and system reliability;

- Monitoring procedures and data management;

- Safety and performance assurance during construction and operation.

2 References

The main and directly relevant documents referred to in this standard are listed in Table 2.

Table 2 References

Title	Authors / Document code
Low-rate wireless personal area networks	IEEE 802.15.4
Wideband transmission systems (2.4 GHz)	EN 300 328
Short range devices (SRD)	EN 300 220
Degrees of protection provided by enclosures (IP code)	IEC 60529
Quality management systems	ISO 9001
A best practice guide: Wireless sensor networks for civil infrastructure monitoring	Rodenas Herráiz, Kenichi Soga, Paul R. A. Fidler, Nicholas de Battista
Code for engineering surveying	GB 50026
Information technology – Sensor networks	GB/T 30269.301
Technical code for monitoring of building excavation engineering	GB 50497
Technical code for urban utility tunnel engineering	GB 50838
Code for monitoring measurement of urban rail transit engineering	GB 50911
Technical code for monitoring of building and bridge structures	GB 50982
Research monitoring and control in tunnel construction	AITES/ITA WG2
Smart community infrastructures - Operation and maintenance of utility tunnels	ISO 37175
Geotechnical design - Part 1: General rules	EN 1997-1 Eurocode 7
Geotechnical design - Part 2: Ground investigation and testing	EN 1997-2 Eurocode 7
Improvement of structural integrity monitoring for drinking water mains	EPA/600/R-05/038
Petroleum and natural gas industry - Pipeline transportation systems - Pipeline integrity assessment specification	ISO 22974
Structural design of buried pipelines under various conditions of loading - Part 1: General requirements	EN 1295-1
Technical code for monitoring of urban water supply network operation safety risk	DB31/T 1333
Eurocode - Basis of structural design	EN 1990
Bridge construction specifications	AASHTO LRFD BDS-10
Technical specification for structural safety monitoring systems of highway bridges	JT/T 1037

Geotechnical investigation and testing - Geotechnical monitoring by field instrumentation	ISO 18674
Mechanical vibration - Road surface profiles - Reporting of measured data	ISO 8608
Mechanical vibration, shock and condition monitoring	ISO/TC 108
Theoretical maximum specific gravity (GMM) and density of asphalt mixtures	AASHTO T209
Electrical indication of concrete's ability to resist chloride ion penetration	AASHTO T277
Railway applications - Track geometry quality	ISO 23054
Manual for railway engineering	AREMA -
Railway applications - Track - Track geometry quality	EN 13848

3 Terminology and abbreviations

The following terms are used in this specification.

3.1 Terminology

3.1.1 Wireless sensor network (WSN)

A network formed by organizing and combining sensor nodes in a free style through wireless communication technology.

3.1.2 WSN node (Node)

A collective term for the sensing units that use wireless communication protocols for data perception, acquisition, transmission, relay, and visualization in a WSN.

3.1.3 WSN sensor node (S-Node)

A WSN node with a built-in sensing module.

3.1.4 WSN interface node (I-Node)

A WSN node equipped with a data acquisition module and a power supply function for external sensing modules.

3.1.5 Tilt sensor array

An assembly of multiple tilt sensors connected in series or array format, designed for distributed measurement of structural movement, including tilt, settlement and convergence. It requires an I-Node to power and sample the data.

3.1.6 WSN visual node (V-Node)

A WSN node with an on-site visual warning module capable of issuing on-site alerts through sound, light, or other means.

3.1.7 WSN camera node (C-Node)

A WSN node capable of remotely transmitting on-site image information to the service center.

3.1.8 Gateway (GW)

A switching unit that connects one network to another.

3.1.9 Mesh networking (Mesh)

An embedded microprocessor communication protocol.

3.1.10 Relay

A cooperative function in a mesh network where a node forwards data on behalf of other nodes to extend network coverage and ensure robust communication. A node performing this function is a Relay Node. Each instance of this forwarding process is counted as one Relay Hop.

3.1.11 Sampling frequency

The number of monitoring measurements performed per unit time.

3.1.12 Radio frequency

The division of radio frequency bands used for wireless communication.

3.1.13 Packet loss rate

The ratio of data packets lost during transmission to the total number of data packets sent.

3.1.14 Time synchronization

The process by which all nodes and gateways in a WSN reach a unified system time scale through precise local clock operation and management.

3.1.15 Timestamp

A complete and verifiable data mark that indicates the existence of a data record at a specific time, usually represented as a unique sequence of characters identifying a particular moment.

3.1.16 Mesh timeout

In a WSN system, the time required from the start of a monitoring cycle to the completion of data transmission by all nodes within the network.

3.1.17 Signal threshold

The minimum radio signal strength required for a node to access a WSN.

3.1.18 Relay factor

In a WSN, the defined time duration during which one node assists other nodes in relaying information.

3.1.19 Industrial scientific medical band (ISM band)

A frequency band defined by the Radiocommunication Bureau of the International Telecommunication Union (ITU) for use in industrial, scientific, and medical applications.

3.1.20 Static Mesh

An ultra-low-power, self-organized mesh network protocol designed for long-term monitoring of gradual structural trends with high reliability and extended battery life.

3.1.21 Trigger Mesh

An event-driven mesh network protocol designed for instantaneous detection and response to abrupt events, capable of autonomous on-site warning independent of backend connectivity.

3.1.22 Dynamic Mesh

A time-synchronized, high-throughput mesh network protocol designed for short-term acquisition and transmission of high-volume or high-frequency data.

3.1.23 Serial number (SN)

The unique identification code assigned to a device.

3.1.24 Electromagnetic Interference (EMI):

The disturbance generated by an electromagnetic source that impairs the performance of an electrical or electronic device, circuit, or system.

3.1.25 Multipath Effect

A phenomenon in wireless communication where signals travel from transmitter to receiver via multiple paths due to reflection, diffraction, or scattering. This results in signal fading, phase shifts, and potential data corruption, particularly in confined or structurally complex environments.

3.1.26 Line of Sight (LoS)

A direct, unobstructed radio propagation path between a transmitting and receiving antenna. LoS conditions are typically required for optimal signal strength and minimal path loss in wireless links.

3.1.27 Path Loss

The reduction in power density of a radio wave as it propagates through a specific space, expressed in decibels (dB). It is a key parameter in the radio link budget calculation for predicting wireless system range and reliability.

3.1.28 Mesh Link Budget

An engineering planning process that evaluates the radio-frequency (RF) reachability and connectivity within a WSN. It assesses the maximum allowable path loss between nodes and gateways, determines the optimal number of relay hops, and guides the placement of network elements to achieve reliable mesh communication under site-specific propagation conditions.

3.1.29 Server Link Budget

An assessment of the communication capabilities and reliability of the backhaul link between gateways and the remote monitoring server. It evaluates available connection options (e.g., cellular, Wi-Fi, Ethernet) in terms of signal coverage, bandwidth, latency, and operational cost to ensure continuous and stable data transmission to the central server.

3.1.30 Power Budget

A systematic analysis and planning of the energy supply and consumption for the entire WSN system or its individual components. It estimates the power requirements of nodes and gateways based on project duration, sampling rates, communication intervals, and available power sources (e.g., batteries, solar, external DC), ensuring the system operates reliably throughout the intended monitoring period.

3.1.31 Over-The-Air function

A method of remotely distributing firmware updates, configuration parameters, or software patches to wireless devices via the network, without requiring physical access.

3.2 Abbreviations

3.2.1 η — Battery capacity reduction factor

3.2.2 ΔD — Variation of tunnel horizontal convergence

3.2.3 $\Delta\theta_1$, $\Delta\theta_2$ — The inclination variation at the installation point of the left and right standard blocks

3.2.4 L — The distance from the turning point A of the standard block to the intersection point B of the inner surface and the horizontal diameter

3.2.5 α — The intersection angle between the vertical line of AB and the horizontal line

3.2.6 ΔH — The relative settlement variation of the tilt sensor array

3.2.7 Δh_i — The relative settlement of the i^{th} tilt sensor array unit

3.2.8 l — The length of the tilt sensor array unit

3.2.9 θ_i — The inclination variation of the i^{th} tilt sensor array unit

3.2.10 *RSSI* — Receive Signal Strength Indication

3.2.11 CE — Conformité Européenne (European Conformity)

3.2.12 FCC — Federal Communications Commission (United States)

3.2.13 UKCA — United Kingdom Conformity Association

3.2.14 SRMC — State Radio Monitoring Center (China)

3.2.15 IC — Innovation, Science and Economic Development Canada

3.2.16 ACMA — Australian Communications and Media Authority

3.2.17 RoHS — Restriction of Hazardous Substances

3.2.18 REACH — Registration, Evaluation, Authorisation and Restriction of Chemicals

4 Basic requirements

4.1 The WSN shall be self-organizing and support multi-hop mesh topology.

4.2 The WSN shall support the wireless communication protocol integrating Static Mesh, Trigger Mesh, and Dynamic Mesh.

4.3 The overall WSN shall have the characteristic of low power consumption, and the average power consumption of wireless node should not be greater than 0.5 mW.

4.4 The data packet loss rate of wireless transmission in WSN should be less than 1‰ in congested environments.

4.5 A single gateway shall be capable of accommodating more than 100 WSN nodes working properly.

4.6 WSN nodes should adopt the self-powered mode, and gateway may adopt the self-powered mode. When AC power supply conditions are available on site, gateway may use an external power supply.

4.7 The basic monitoring requirements, such as monitoring parameter, deployment planning, sampling frequency and alarm triggers, should be implemented according to the requirements of the corresponding design documents. The initial value (reference value) of the monitoring content should be measured, and the reference point should be set for the displacement measurement.

4.8 Safety and health regulation and training (project specific) must always be treated as the highest priority.

4.9 Battery safety usage must be trained and future recycling scheme must be planned.

4.10 Equipment selection and networking shall take environmental impacts into account.

4.11 When monitoring nodes are damaged, they should be repaired or supplemented in a timely manner and verified against previous monitoring results.

4.12 Automated monitoring shall be combined with manual verification to ensure data accuracy and economic efficiency. Collected multi-dimensional data shall comply with operational safety standards.

5 Monitoring items, methods and requirements

5.1 The monitoring items should be determined according to design requirements, functional requirements and related technical requirements, and may include stress and strain, displacement and deformation, differential settlement, inclination, crack, water leakage, vibration and other environmental factors monitoring.

5.2 Monitoring parameters shall be divided into static parameters and dynamic parameters. The selection of monitoring parameters should meet the requirements for normal monitoring, early warning and evaluation of the state of the infrastructure. Static parameters should be those for long-term safety and health monitoring when the deformation trends occur gradually over extended period. Dynamic parameters should be those related to abrupt geo-hazard, where deformation changes can be rapid over relatively short period of time, or those requiring high-volume data transmission.

5.3 Strain should be monitored by strain monitoring components such as resistance strain gauges and vibrating wire strain gauges.

5.4 Stress should be monitored by strain gauges or stress gauges installed inside or on the surface of the structure.

5.5 Deformation monitoring should be divided into horizontal displacement monitoring, vertical displacement monitoring, three-dimensional displacement monitoring and other displacement monitoring, and benchmark value measurement should be carried out. The results of deformation monitoring should be modified in conjunction with the results of environmental and effect monitoring.

5.6 Inclination should be monitored by tilt sensor nodes, and the layout of the tilt sensor node should be determined according to the rigidity and deformation characteristics of the structure.

5.7 Cracks or joints should be monitored by vibrating wire displacement gauges, strain gauges, and laser rangefinders. The measuring direction of the sensor should be perpendicular to the direction of the crack, and the following requirements should be complied with:

(1) When measuring a structure that has cracked, it is advisable to monitor the change in the width of the crack;

(2) When measuring a structure that has not yet cracked, it is advisable to monitor the change in the strain of the structure.

5.8 The water leakage should be monitored by the temperature gradient method or the electrode method. The water leakage monitoring indicators may include the location of the water leakage, the area of the water leakage, etc.

5.9 Vibration monitoring should include vibration response monitoring and vibration excitation monitoring. Monitoring parameters could include acceleration, velocity, displacement and strain, etc.

5.10 Temperature and humidity monitoring should include environmental and component temperature monitoring and environmental humidity monitoring.

5.11 Wind and wind-induced response monitoring shall be carried out for wind-sensitive structures. The monitoring parameters of wind and wind-induced response should include wind pressure, wind speed, wind direction and wind-induced vibration response. The monitoring parameters of wind and wind-induced response of bridge structures may include wind attack angle.

5.12 WSN should meet the requirements of real-time monitoring, and the frequency of static monitoring should be from once per second to once per day, which may be dynamically adjusted according to the monitoring requirements. The dynamic monitoring quantity should be determined according to the dynamic load and the vibration characteristics of the measured object. During the monitoring process, when the monitoring data value reaches the early warning trigger value or abnormal deformation occurs, the monitoring frequency should be increased.

6 WSN Monitoring System

6.1 General requirements

6.1.1 The system should operate reliably in temperature ranges from -40°C to +85°C. The system should meet a minimum IP66 rating for dust and water resistance.

6.1.2 The time synchronization error shall not exceed 20ms for static monitoring and 1.0ms for dynamic monitoring.

6.1.3 The system shall consist of four layers: Sensing, Transmission, Processing, and Application:

(1) The Sensing Layer should include gateways, sensor nodes, interface nodes, relay nodes, and combinations thereof;

(2) The Transmission Layer should comprise mesh communication protocols;

(3) The Processing Layer should handle data storage, analysis, and backup;

(4) The Application Layer should provide visualization, reporting, alarm management, and user control.

6.2 Sensing layer

6.2.1 Nodes shall be selected based on measurement type, environmental conditions, service life, and power consumption. The system should support MEMS-based, Vibrating Wire (VW), analog, digital, laser distance, and camera sensors.

6.2.2 All sensors should be certified to relevant international standards (e.g., RoHS, REACH, CE, UKCA, FCC, and other relevant certifications). For further details, please refer to Appendix B.

6.2.3 Gateway and node dimensions should not exceed 350 × 250 × 200mm, and shall be appropriate for the spatial constraints of the installation site.

6.2.4 The system shall support primary batteries, external DC, solar, and AC/DC adapters.

6.2.5 Battery life shall be monitored, with early warnings issued at predetermined voltage thresholds. Batteries shall be stored and disposed of in accordance with environmental regulations.

6.2.6 Equipment selection shall account for challenging operational environments, where specified devices should possess capabilities such as fire resistance, explosion-proofing, resistance to salt spray and carbon monoxide, and tolerance to acids and alkalis. For further details, please refer to Appendix A.

6.3 Transmission Layer

6.3.1 The WSN should support no less than 4 hops in scenarios requiring long-distance data transmission.

6.3.2 The static mesh, trigger mesh and dynamic mesh should be adopted based on the monitoring purpose:

(1) Static Mesh protocol shall be used for long-term structural health monitoring;

(2) Trigger Mesh protocol shall be used for rapid event detection and response;

(3) Dynamic Mesh protocol shall be used for high-data-rate applications.

6.3.3 Gateway shall support multiple backhaul communication protocols, including 5G/4G cellular, Wi-Fi, and Ethernet, to ensure reliable connectivity to the remote server.

6.3.4 The design and deployment of the transmission layer shall also account for critical factors affecting signal integrity and range, such as frequency band selection in compliance with local regulations, core radio link budget principles. For further details, please refer to Appendix A.

6.3.5 The impact of various environmental and technical factors on signal integrity shall be taken into consideration. These factors include, but are not limited to, environmental attenuation (e.g., rain, fog, salt spray), EMI, multi-path propagation effects, non-line-of-sight (NLoS) conditions, and path loss.

6.4 Processing Layer

6.4.1 The server shall support multiple communication protocols including 5G/4G, WiFi, and Ethernet. System availability shall exceed 99.9% uptime.

6.4.2 Data shall be encrypted during transmission and storage.

6.4.3 Data shall include node serial number, sensor readings, timestamp, node health status, and alarm triggers.

6.4.4 Data shall be stored locally and transmitted to a central server with redundancy.

6.5 Application Layer

6.5.1 The platform shall provide real-time data tables, historical plotting, and remote configuration. Role-based access control and multi-language support shall be included.

6.5.2 It shall support automated reporting, multi-level alarms, and data export via URL API, FTP, SFTP, MQTT, etc.

6.5.3 For both aboveground and underground infrastructure monitoring, the system shall provide on-site visual and audible warnings.

6.5.4 Visual LED indicators should support multiple colors and flashing patterns. Auditory alarms should have a minimum sound level of 110dB. Camera units should have a minimum resolution of 2MP and night vision capability.

6.6 Equipment storage requirement

6.6.1 Equipment should be stored in a stable, clean environment with temperature and humidity control. Device enclosures shall be stored with lids slightly tightened and include desiccant.

6.6.2 Primary lithium batteries shall be stored between +5°C and +10°C in moisture-proof packaging.

6.6.3 Shelf life for unopened devices shall not exceed 12 months from manufacture date.

7 System Planning and Onsite Installation

7.1 Project Planning Framework

7.1.1 A detailed installation plan shall be developed, including project timeline, site layout, and equipment placement.

7.1.2 The Mesh Link Budget shall evaluate radio reachability and determine optimal gateway and node placement. The Server Link Budget shall assess available communication links (cellular, WiFi, Ethernet, RS-232/485). A Power Budget shall be developed based on project duration, sampling rate, and available power sources.

7.1.3 A Site-Specific Assessment shall document environmental factors, EMI risks, and installation constraints.

7.2 Installation preparation

7.2.1 A comprehensive site survey shall be conducted, including RF environment assessment. Safety and health training shall be provided to all installation personnel. Battery safety and recycling procedures shall be established.

7.3 Node installation

7.3.1 Installation method shall be selected based on structure type, environment, and monitoring duration. Installation should be performed in a way that does not significantly disrupt the normal operation of the project.

7.3.2 Each device shall have a unique serial number and be securely fixed without affecting structural integrity. Antenna placement shall ensure clear signal transmission without obstructions.

7.4 Gateway installation

7.4.1 Gateways shall be installed before sensor nodes, typically near the center of the mesh network. Installation should be performed in a way that does not significantly disrupt the normal operation of the project.

7.4.2 Gateway location shall ensure reliable cellular or network connectivity to the remote server.

7.4.3 Signal availability shall be verified on-site using a mobile phone with the same service operator as the gateway SIM.

7.5 Detailed procedures and considerations for project planning and site deployment are provided in the comprehensive checklist included in Appendix A.

8 Underground infrastructure WSN monitoring

8.1 General requirements

8.1.1 The underground infrastructure should include tunnel, utility tunnel, excavation and pipeline.

8.1.2 The maximum distance of wireless node for underground infrastructure WSN monitoring should be determined according to the site environment, the related guidance is provided in Appendix A. The wireless transmission distance should be tested on site, and the layout of WSN should be optimized according to the site test results.

8.1.3 The monitoring frequency under specific mesh should be closely coordinated with the construction progress, and should be set according to different geological conditions, construction methods, construction procedures, and environmental conditions. The optimal monitoring frequency should be reasonably determined according to monitoring demand, safety level, monitoring cycle, sensor service life, and power supply method.

8.1.4 During the construction period, the sampling frequency on underground infrastructure structure, surrounding ground condition and environment should be once per hour. For key locations and construction period, the sampling frequency should be once every 3 minutes to 30 minutes. When under special needs, the sampling frequency should be further increased. The optimal sampling frequency should be determined according to factors of monitoring plan, safety level requirement, overall monitoring period, sensor service life, power supply method, etc.

8.1.5 During the operation period, the sampling frequency of underground infrastructure monitoring should be comprehensively determined according to the cumulative change and incremental change due to surrounding environmental disturbance. The sampling frequency should not be less than once per hour in the first year after operation, not less than once per 4 hours in the second year, and not less than once per day after two years.

8.1.6 Emergency monitoring should be targeted to deploy more dense monitoring nodes, apply faster sampling frequency or observe increasing types of sensor parameters.

8.1.7 The sampling frequency of dynamic monitoring should be determined according to the dynamic load and vibration characteristics of the monitoring object.

8.2 Tunnel

8.2.1 The monitoring content, section selection and measuring point layout by using WSN for tunnel should comply with the relevant provisions of local standards, and may be referenced in accordance with “Monitoring and control in tunnel construction” by AITES/ITA WG2.

8.2.2 Monitoring sections and measuring points in the tunnel should be focusing in the places with complex geological conditions, structural type change, structural deformation joints, etc., and the factors such as adjacent important buildings (structures), underground pipelines, loading and unloading should be considered for more dense deployment.

8.2.3 The contents of monitoring and the selection of wireless sensors should be considered according to table 8.2.3.

Table 8.2.3 Tunnel wireless monitoring content and sensor selection

Monitoring Content	Monitoring Items	Sensor Type	Node Type
Structural deformation	Convergence	Laser distance sensor / Tilt sensor	S-Node
	Longitudinal differential settlement	Static level / Electric horizontal beam / Hydrostatic settlement gauge / Tilt sensor array	I-Node
	Crown settlement		
	Invert uplift		
	Lining inclination	Tilt sensor	S-Node
	Lining crack	Crack meter	I-Node
	Joint open	Laser distance sensor	S-Node
Structural internal force	Stress of lining reinforcement	Steel bar stress meter	I-Node
	Stress of concrete	Surface strain gauge or embedded steel stress / strain gauge	I-Node
	Stress of connecting bolt	Strain gauge	I-Node
Ground pressure	Earth pressure	Earth pressure sensor	I-Node
	Water pressure	Pore water pressure gauge / Piezometer	I-Node
Environment monitoring	Temperature and humidity	Temperature and humidity sensor	I-Node
	Water leakage	Water leakage sensor	I-Node
	Vibration	Acceleration sensor	S-Node
	Smoke / CO concentration	Smoke / CO concentration sensor	I-Node
	Gas	Gas concentration sensor	I-Node
	Adjacent structure inclination	Tilt sensor	S-Node
	Adjacent structure settlement	Hydrostatic settlement gauge / Tilt sensor array	I-Node

8.2.4 Wireless tilt sensor nodes can be used to monitor the inclination of lining and the convergence of tunnel.

8.2.5 Monitoring segments should be selected according to the importance of cross section and the complexity of geological environment for the layout of wireless tilt sensor node in shield tunnel, and the following requirements should be complied:

(1) It should be laid on sensitive segments at key positions;

(2) The layout position should be away from bolt hand hole and grouting hole, and away from the joint position; When the inclination angle conversion is adopted for tunnel convergence, the provisions in article 8.2.6 of this specification should be followed.

8.2.6 When the horizontal convergence of circular shield tunnel is measured by wireless tilt sensor node conversion, the convergence variation should be calculated according to the following formula, and the optimal installation position should be determined by mechanical calculation or numerical simulation (Fig. 8.2.6).

$$\Delta D = L(\Delta\theta_1 - \Delta\theta_2)\cos(\alpha) \tag{8.2.6}$$

where ΔD is variation of horizontal convergence of tunnel (m); $\Delta\theta_1$, $\Delta\theta_2$ are inclination change value (rad) at the installation point of left and right standard blocks; L is the distance from the rotation point A of the standard block to the intersection point B of the inner surface and the horizontal diameter (m); α is the intersection angle (rad) between the vertical line and the horizontal line of AB.

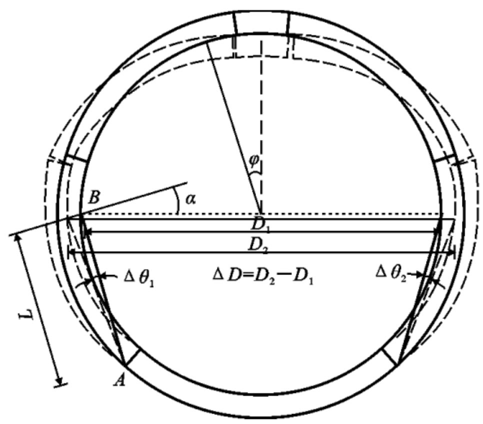

Fig. 8.2.6 Calculation model of horizontal diameter convergence deformation for angle conversion

8.2.7 The tilt sensor array shall be used to measure the longitudinal differential settlement, and the relative settlement change should be calculated according to the following formula (Fig. 8.2.7)

$$\Delta H = \sum_{i=1}^{n} \Delta h_i = \sum_{i=1}^{n} l \sin(\theta_i) \qquad (8.2.7)$$

where ΔH is relative settlement variation of tilt sensor array (m); Δh_i is relative settlement of the i^{th} tilt sensor array unit (m); L is length of tilt sensor array unit (m); θ_i is inclination change value (rad) of the i^{th} tilt sensor array unit.

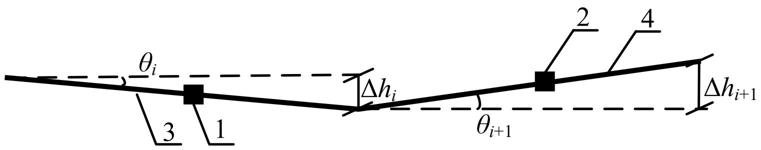

Fig. 8.2.7 Calculation model of longitudinal differential settlement

8.2.8 For node installation in tunnel monitoring during the construction phase, safe and environmentally suitable monitoring positions shall be selected in consideration of the impacts of rockfall, dust and other interferences, and corresponding protective measures shall be properly implemented.

8.2.9 During construction period, monitoring section of tunnel face and adjacent area should be arranged in mobile method by following the advancing of tunnel face, and the layout scope should not be less than 3 times of tunnel diameter.

8.2.10 When the tunnel passes through the gas section, the gas concentration level should be monitored wirelessly. The sensor layout should consider the uneven spatial distribution of gas concentration, and the number of measuring points in each section should not be less than 2.

8.3 Utility tunnel

8.3.1 The layout of the monitoring section of the utility tunnel should comply with the relevant provisions of local standards, and may be referenced in accordance with "Smart community infrastructures - Operation and maintenance of utility tunnels" ISO 37175:2024.

8.3.2 The gateway in the utility tunnel can be connected to the communication optical cable or wireless network. When there is no communication optical cable and wireless communication signal available in the urban underground utility tunnel structure, the wireless gateway should be set at the vent or feeding entrance of the utility tunnel, and should then be connected to the mobile operator network.

8.3.3 When the wireless sensor signal cannot penetrate the middle wall of the multi cabin underground utility tunnel, each cabin sensor network should be set with separate gateway for networking.

8.3.4 The monitoring content and wireless sensor selection of the utility tunnel can be selected according to table 8.2.3.

8.3.5 The layout of relay node in the utility tunnel should meet the requirements of system data communication, and should be comprehensively determined according to the partition of fire compartment, monitoring section and gateway location.

8.3.6 The node layout should be determined comprehensively by considering the space requirements of pipes.

8.4 Deep excavation

8.4.1 The layout of WSN monitoring section and measuring points of excavation should comply with the relevant provisions of local standards, and may be referenced in accordance with the European standard "Eurocode 7: Geotechnical design - Part 1: General rules" EN 1997-1:2004 and "Eurocode 7 - Geotechnical design - Part 2: Ground investigation and testing" EN 1997-2:2007.

8.4.2 The monitoring content of excavation and the selection of wireless sensor should be selected according to table 8.4.2.

Table 8.4.2 Wireless monitoring content and sensor selection of excavation

Monitoring Content	Monitoring Item	Sensor Type	Node Type
Deformation	Retaining wall / Slope Top settlement	Static level / Electric horizontal beam / Tilt sensor array	I-Node
	Deep horizontal displacement		
	Vertical displacement of inner column		
	Uplift of excavation bottom		
Internal Force	Internal force of support	Surface strain gauge / Axial force sensor	I-Node
	Internal force of column	Surface strain gauge / Steel stress gauge (embedded) / Strain gauge (embedded)	I-Node
	Internal force of anchor bolt / soil nail	Steel stress gauge (embedded) / Strain gauge (embedded)	I-Node
Underground Water	Groundwater level	Water level sensor	I-Node
	Pore water pressure	Pore water pressure gauge / Piezometer	I-Node
Environmental Monitoring	Vertical displacement of surrounding surface	Static level / Electric horizontal beam / Tilt sensor	I-Node

		array	
	Adjacent structure inclination	Tilt sensor	S-Node

8.4.3 Static leveling wireless sensor equipment can be used for vertical displacement monitoring of retaining wall, top of excavation slope or surrounding structures.

8.4.4 In the initial stage of monitoring, the stable data of two to three days should be collected, and the monitoring reference data should be taken when the data tends to be stable. The initial data sampling should not be less than three times, and should meet other relevant monitoring requirements.

8.4.5 Wireless tilt sensor array or wireless automatic servo motor inclinometer can be used for horizontal displacement monitoring of retaining structure or deep soil.

8.4.6 Vibrating wire stress gauge can be used for internal force monitoring of supporting structure, and wireless interface node should be installed. The interface node should be installed at the position which is not easy to be affected by construction and does not interfere with normal engineering activities, and protection device should be installed when necessary.

8.5 Pipeline

8.5.1 The monitoring content and measuring point layout for pipeline shall comply with the relevant provisions of local standards, and may be referenced in accordance with "Petroleum and natural gas industry - Pipeline transportation systems - Pipeline integrity assessment specification" ISO 22974:2023, "Structural design of buried pipelines under various conditions of loading - Part 1: General requirements" EN 1295-1:2021, "Improvement of Structural Integrity Monitoring for Drinking Water Mains" EPA/600/R-05/038 and the Shanghai local standards "Technical Code for Monitoring of Urban Water Supply Network Operation Safety Risk" DB31/T 1333-2021.

8.5.2 Monitoring of pipeline can be classified into protective monitoring and preventive monitoring according to different purposes:

(1) Protective monitoring focuses on potential structural damage that may result from external activities such as adjacent construction, overloading, or other environmental disturbances. It evaluates the impact of such activities on the structural integrity and operational stability of the pipelines through real-time observation and measurement.

(2) Preventive monitoring concentrates on the routine operational safety. Its

objective is to identify early signs of anomalies or adverse conditions that could affect the normal operation or pose safety risks, thereby enabling timely detection and prevention of potential incidents through continuous monitoring.

8.5.3 Pipeline monitoring integrates three monitoring categories: operating status monitoring, structural monitoring, and environmental monitoring. The indicators of monitoring should be considered according to table 8.5.3.

Table 8.5.3 Monitoring content for Pipeline

Monitoring Content	**Monitoring Item**	**Sensor Type**	**Node Type**
Operational Condition	Operating pressure	Pressure sensor	I-Node
	Flow rate	Flow sensor	I-Node
Structural Condition	Vertical displacement	GNSS/ Displacement sensor/ Tilt sensor array	I-Node
	Horizontal displacement		
	Differential settlement	Static level / Electric horizontal beam / Hydrostatic settlement gauge / Tilt sensor array	I-Node
	Deformation of pipeline	Strain gauge	I-Node
	Joint deformation	Tilt sensor	S-Node
	Pipe corrosion	Thickness Sensor	I-Node
	Pipe damage/ Leakage	Leak noise sensor/ Gas sensor	I-Node
Environmental Condition	Overburden soil pressure on pipe crown	Earth pressure sensor	I-Node
	Lateral soil pressure	Earth pressure sensor	I-Node
	Groundwater level	Water level sensor	I-Node
	Pore water pressure	Pore water pressure gauge / Piezometer	I-Node
	Internal temperature	Temperature sensor	I-Node
	Soil temperature around pipeline	Temperature sensor	I-Node
	Soil corrosivity	Soil corrosivity sensor	I-Node
	Meteorological conditions	Weather station	I-Node
	Ambient noise	Noise sensor	S-Node
	Vehicular traffic information	Vibration Sensor / Inductive Loop Sensor	S-Node/ I-Node

8.5.4 The layout of monitoring points should ensure accurate, timely, and comprehensive reflection of the network's operational condition, structural behavior, and service environment. The number and distribution of monitoring points shall be determined in accordance with the management requirements, the current condition of the network, and results of risk assessment.

8.5.5 Strategic monitoring point deployment focuses on locations with material changes, diameter changes, special joints, pipeline intersections, overlapping pipeline areas, and zones subject to alternating loads.

8.5.6 For adjacent construction scenarios, monitoring protocols require initiation fifteen days prior to construction commencement and continuation for minimum three months post-completion until pipeline deformation stabilizes.

8.5.7 The operating frequency used for buried pipeline monitoring shall use 433.05-434.79MHz, 470-510MHz, 865-868MHz or 920-925MHz, with remote frequency tuning capability within the same band to avoid co-channel interference, and should comply with local laws and regulations.

9 Aboveground infrastructure WSN monitoring

9.1 General requirements

9.1.1 The aboveground infrastructure should include bridge, slope, subgrade, rail and other infrastructure whose main structures are on the ground.

9.1.2 The maximum distance of wireless node for aboveground infrastructure WSN monitoring should be determined according to the site environment, and should comply with Appendix A. The transmission distance of wireless nodes should be tested on site, and the layout of WSN should be optimized according to the site test results.

9.1.3 The monitoring frequency under specific mesh should be closely coordinated with the construction progress, and should be set according to different geological conditions, construction methods, construction procedures, weather and environmental conditions. The optimal monitoring frequency should be reasonably determined according to monitoring demand, safety level, monitoring cycle, sensor service life, and power supply method.

9.1.4 During the construction period, the static mesh should be recommended with monitoring frequency of aboveground infrastructure suggested by once per hour. For key locations and key construction periods, the monitoring frequency should be once every three minutes to thirty minutes. The monitoring frequency should be increased under special requirements.

9.1.5 During the operation period, the static mesh should be recommended depending on the monitoring frequency. The monitoring frequency of aboveground infrastructure for static mesh should be comprehensively determined according to the cumulative change and incremental change rate of surrounding environmental disturbance. The monitoring frequency should not be less than once per hour in the first year after operation, once per four hours in the second year, and once per day in the following years.

9.1.6 For emergency monitoring during unexpected risk events, the trigger mesh should be applied with more monitoring points and intensive frequency, or additional monitoring items should be added.

9.1.7 AC power supply should be provided for on-site gateways. Solar panels or battery sets can also be used. When solar panels are adopted, their installation should not affect traffic or safety.

9.1.8 The influence of actual site operation conditions should be considered in aboveground infrastructure wireless monitoring. Protective measures under severe weather conditions should be implemented for monitoring equipment, instruments, and monitoring points. All major instruments and equipment should be verified or calibrated before use, and key devices should be regularly checked or compared with monitoring data during operation.

9.2 Bridge

9.2.1 The selection of wireless monitoring sections and the layout of measuring points should be designed according to monitoring objectives, the actual site conditions and should comply with the local standard, and may be referenced in accordance with the Eurocode EN 1990-1999, AASHTO LRFD BDS-10-2024 and Chinese Technical Specification for Highway Bridge Structure Safety Monitoring System (JT/T 1037).

9.2.2 Wireless monitoring of bridge structures should consider monitoring in the life-cycle period including construction and operation as a whole. Complete details on IDs of the monitoring points, positions, and monitoring data during the construction period should be clearly indicated in the final construction drawings submitted by the construction company.

9.2.3 The monitoring objects and items of bridge structures should comply with the regional standard. The monitoring objects during operation should also include the following:

- Bridges with special structure, materials, construction technology, or special requirements;
- Bridges with complex geological conditions or changed geological units;
- Important bridges with increased load levels or strengthened structures;
- Heavy traffic bridges;
- Bridges affected by construction activities within the bridge protection area;
- Bridges significantly influenced by topography;
- Important super large bridges.

9.2.4 For wireless monitoring systems focusing on the overall technical state of a bridge, systematic monitoring including environmental loads, overall structural response, and local response of the structure should be recommended. For systems focusing on special technical states, monitoring contents should be determined according to the characteristic indicators of the special technical state, as follows:

- For monitoring the overturning stability of a single-column pier bridge: beam inclination, end bearing reaction, relative lateral displacement, and relative vertical displacement of piers and beams;

- For monitoring the lateral creep of curved beams: relative lateral displacement of pier beams, relative lateral displacement of adjacent beams, bearing reaction force, and environmental temperature;

- For monitoring plane rotation disease of inclined bridges: relative longitudinal and transverse displacement of adjacent beams, and environmental temperature;

- For monitoring foundation settlement in poor geological conditions: vertical displacement and inclination of piers and abutments.

9.2.5 For bridges with large traffic flow, heavy vehicles, or traffic exceeding design capacity, dynamic traffic load monitoring should be carried out.

9.2.6 Dynamic monitoring and early warning of vehicle collisions and ship collisions should be implemented for bridges at risk of vehicle or ship impacts.

9.2.7 Bridge wireless monitoring contents and sensor selection should follow Table 9.2.7.

Table 9.2.7 Bridge Wireless Monitoring Content and Sensor Selection

Monitoring Content	Monitoring Item	Sensor Type	Node Type
Load and environment	Temperature and Humidity	Temperature and humidity sensor	I-Node
	Wind load	Wind speed and direction	I-Node
	Vehicle load	Piezoelectric sensor	I-Node
	Vehicle and ship identification	Video sensor / Infrared sensor	I-Node
Overall response of structure	Main girder alignment	GPS / Static level/ Tilt sensor array	I-Node
	Deflection of main girder	Laser distance sensor / Tilt sensor	S-Node
	Bearing settlement	Laser distance sensor / Tilt sensor	S-Node
		Hydrostatic settlement gauge / Tilt sensor array	I-Node
	Inclination	Tilt sensor	S-Node
	Vibration	Acceleration sensor	I-Node
Local	Strain of steel structure	Steel bar stress meter	I-Node

response of structure	Concrete strain	Surface strain gauge / Stress gauge (embedded) / Strain gauge (embedded)	I-Node
	Cable force	Anchor cable meter/ Magnetic flux sensor	I-Node
		Acceleration sensor	S-Node
	Crack	Crack meter	I-Node
		Laser distance sensor	S-Node
	Corrosion	Corrosion meter	I-Node
	Support reaction	Pressure ring / Load bearing	I-Node
	Foundation scour	Scour sensor	I-Node

9.3 Slope

9.3.1 The selection of wireless monitoring sections and the layout of measuring points for slope should be designed according to geological and hydrological conditions, surrounding environment, design scheme, construction characteristics, slope monitoring level, control requirements and should comply with the local standard, and may be referenced in accordance with the ISO 18674, Eurocode 7 (EN 1997).

9.3.2 Monitoring content should be selected to meet requirements of slope protection structure safety and surrounding environmental protection. The content should be comprehensively determined according to slope design, surrounding environment, and management requirements. Wireless sensing monitoring content and sensor selection should follow Table 9.3.2.

Table 9.3.2 Slope Wireless Monitoring Content and Sensor Selection

Monitoring Content	Monitoring Item	Sensor Type	Node Type
Load and Environment	Groundwater level	Water level gauge	S-Node
		Multi parameter automatic monitor	I-Node
	Underground pore water pressure	Pore water pressure gauge / Piezometer	I-Node
	Rainfall	Rain gauge	I-Node
Structural Deformation Response	Surface deformation	Displacement meter / Tilt sensor array	I-Node
	Subsurface horizontal displacement	Tilt sensor array	I-Node
	Subsurface settlement	GNSS / Static level / Layered settlement meter / Frost heaving meter / Hydrostatic settlement gauge / Tilt sensor array	I-Node

	Surface crack	Extensometer / Crack sensor	I-Node
		Laser distance sensor	S-Node
	Slope seepage	Pore water pressure gauge / Piezometer	I-Node
Structural Stress Response	Soil pressure	Earth pressure gauge	I-Node
	Ground stress	Strain gauge (embedded) / Stress meter (embedded)	I-Node
	Stress of supporting structure		
	Anchor tension	Anchor cable meter/ Stress / strain gauges	I-Node
	Blasting vibration	Acceleration sensor	S-Node
Rockfall	Impact	Acceleration sensor	S-Node

9.3.3 Slope wireless monitoring should be combined with manual inspection and synchronized with manual measurement results for comparison.

9.3.4 The location and quantity of monitoring points in the WSN should reflect the safety status of the slope structure and surrounding environment.

9.3.5 The embedding positions of monitoring points should facilitate observation, not affect the normal stress of retaining and reinforcement structures, or hinder construction progress. Monitoring points should be firmly installed, clearly marked, and effectively protected.

9.4 Subgrade

9.4.1 The monitoring scheme for subgrade should be prepared according to the engineering geological conditions, design scheme, and construction characteristics, and should comply with the local standard, and may be referenced in accordance with the ISO 18674, ISO 8608, ISO/TC 108, AASHTO T209,T277 and Eurocode 7 (EN 1997).

9.4.2 Wireless monitoring content and sensor selection for subgrade should follow Table 9.4.2.

Table 9.4.2 Wireless Monitoring Content and Sensor Selection of Subgrade

Monitoring Content	Monitoring Item	Sensor Type	Node Type
Deformation Response	Subgrade settlement	GNSS / Static level / Layered settlement meter / Frost heaving meter / Hydrostatic settlement gauge / Tilt sensor array	I-Node
	Horizontal displacement	GNSS / Displacement sensor	I-Node

	of Subgrade	/ Tilt sensor array	
	Horizontal displacement of Deep Foundation	Inclinometer / Tilt sensor array	I-Node
Stress Response	Subgrade earth pressure	Earth pressure gauge	I-Node
	Pore water pressure of Subgrade	Pore water pressure gauge / Piezometer	I-Node
Environment	Subgrade temperature	Temperature sensor	I-Node
	Soil moisture content	Humidity sensor	I-Node

9.4.3 The layout of surface settlement observation sections should meet the following requirements:

(1) Observation sections should be arranged every 100 m;

(2) In sections where the preloading height reaches the limit height, observation sections should be arranged every 50 m;

(3) For structures with spans greater than 30 m, adjacent embankment sections at both ends should each have one observation section; for spans less than 30 m, only one end requires a section;

(4) Observation sections should be densified in areas with poor foundation conditions or significant topographic changes.

9.5 Rail

9.5.1 The monitoring scheme for rail shall be developed according to the geological conditions, track design specifications, construction characteristics, and operational safety requirements and should comply with the local standard, and may be referenced in accordance with the ISO 18674, ISO 23054, AREMA Manual for Railway Engineering, Eurocode 7 (EN 1997) and EN 13848.

9.5.2 Monitoring system composition shall include, but not be limited to, track geometry monitoring, environmental parameter monitoring and structural stress response monitoring.

9.5.3 Wireless monitoring content and sensor selection for rail should follow Table 9.5.3.

Table 9.5.3 Wireless Monitoring Content and Sensor Selection of Rail

Monitoring	**Monitoring Item**	**Sensor Type**	**Node**

Content			Type
Track geometry	CANT	Tilt sensor	S-Node
	Twist		
	Longitudinal settlement	Tilt sensor	S-Node
		Tilt sensor array	I-Node
	Horizontal movement	Laser distance sensor	S-Node
	Vertical displacement	Linear Voltage Displacement Transducer (LVDT)	I-Node
Environment	Temperature	Temperature sensor	I-Node
	Vibration	Vibration sensor	S-Node
Structural Stress	Rail stress	Strain gauge	I-Node
	Ballast pressure	Earth pressure sensor	I-Node

10 System operation and maintenance

10.1 General requirements

10.1.1 The system shall be continuously monitored for hardware and software health status.

10.1.2 Remote maintenance and on-site maintenance shall be performed as required to ensure operational integrity.

10.2 Operation analysis

The system shall automatically analyze and report the parameters: battery voltage, power supply status, internal temperature of nodes, signal strength (RSSI) and packet loss rate, network topology and node connectivity.

10.3 Maintenance

10.3.1 Remote maintenance should include routine status checks via the cloud platform and Firmware updates performed via Over-The-Air (OTA) function.

10.3.2 On-site maintenance should include physical inspection of equipment at least every six months and battery replacement when the voltage falls below the predetermined threshold.

10.3.3 Sensor calibration should be performed at intervals not exceeding three years, or as per the manufacturer's recommendation.

11 Monitoring data management and reports

11.1 General requirements

11.1.1 The monitoring data should be backed up in real time, and redundant backup may be made every month.

11.1.2 Daily snapshots of the database should be made, and snapshots may be kept for ten days or more.

11.1.3 The original data should be backed up on the local server at the same time.

11.2 Data management

11.2.1 The management of monitoring data should include three levels of data management: node, gateway and server.

11.2.2 Monitoring data may be stored separately according to date, and redundant backup should be made.

11.2.3 Retest and analysis should be carried out for abnormal data. When the equipment is disturbed by the unexpected factors and produces abnormal data, equipment maintenance and abnormal data processing should be carried out.

11.2.4 The system platform may display data information intuitively in the form of tables and charts.

11.2.5 The system platform should provide alarm threshold setting and display for all data, and should keep its setting log.

11.2.6 The system platform should be set to automatically increase the monitoring sampling frequency when the alarm is triggered and automatically reduce the monitoring sampling frequency after the alarm is released.

11.2.7 After the system platform obtains the real-time data, it may be parsed into the corresponding format and saved according to the database requirements.

11.2.8 The system platform should provide data analysis and operation interface, and should be able to display and download data analysis results from the platform.

11.2.9 After the monitoring project ends, the basic information and data of the project should be kept for more than twelve months.

11.3 Monitoring reports

11.3.1 WSN monitoring for infrastructure should customize different types of monitoring reports on the software platform according to different monitoring stages and monitoring purposes.

11.3.2 Monitoring reports could be divided into daily reports, weekly reports, alert reports, periodic reports, and summary reports. The monitoring report should be expressed intuitively and clearly using words, tables, graphs, photographs, etc.

11.3.3 The contents of the monitoring report should include text description, attached drawings, attached tables, videos, and image data.

11.3.4 Early warning and alarm shall include network system early warning and alarm and infrastructure data early warning and alarm.

11.3.5 The network system early warning and alarm should be given based on parameters such as equipment status and network quality.

11.3.6 For WSN monitoring for infrastructure, the level and standard of early warning and alarm for infrastructure monitoring should be established based on the engineering characteristics, control values of the monitoring project, local experience, etc., and the authority of different management and alarm-receiving personnel should be set according to different alarm levels.

11.3.7 When one of the following situations occurs, an alarm should be triggered immediately, the monitoring sampling frequency should be increased, and the monitoring plan should be adjusted:

(1) Abnormal changes occur in the monitoring parameter value or rate;

(2) Monitoring parameter value or rate reaches or exceeds the alarm value.

11.3.8 The early warning management system should be established based on early warning levels and standards, and should include the target receiver, time, method, and process of alert sending for different early warning levels.

Appendix A: Practical Guide for WSN System Planning, Equipment Selection, and Deployment

This appendix provides consolidated practical guidance for the planning, equipment selection, and deployment of Wireless Sensor Networks (WSN) in infrastructure monitoring. It integrates the technical, regulatory, and logistical considerations essential for a successful project monitoring.

Note: Equipment manufacturers, system integrators, and end-users must comply with the specific regulations and certification requirements of the target country or region's radio spectrum authority prior to designing, deploying, and operating any WSN system.

A.1 Frequency Band Selection and Regulatory Compliance

A.1.1 Overview of Common Unlicensed Frequency Bands

The practical communication distances are indicative and vary based on real-world conditions. Key influencing factors include environmental conditions and antenna performance.

Table A.1.1: Characteristics and Application Reference for Common Unlicensed Bands

Frequency Band	Typical Certification	Typical Regions of Use	Typical Radio Propagation Distance (Ideal Conditions*)	Key Consideration
433 MHz	CE	Europe	In Air: 1-3 km In Soil: 0.5-2 m In Water: Very high attenuation	Long wavelength provides good diffraction and penetration through non-metallic obstacles. Subject to strict duty cycle and power limits.
470 MHz	SRMC	China (Mainland)	In Air: 1-2 km In Soil: 0.5-2 m In Water: Very high attenuation	In China, a dedicated band. Excellent penetration. Pay strict attention to country-specific sub-band allocations and power limits.
868 MHz	CE, UKCA	Europe, United Kingdom	In Air: 0.5-2 km In Soil: 0.3-1 m In Water: Very	Primary WSN band in Europe. Better diffraction than

			high attenuation	2.4GHz. Strict duty cycle limitations (e.g., 1%) often apply.
915 MHz	FCC, IC, ACMA	United States, Canada, Australia,	In Air: 0.5-2 km In Soil: 0.3-1 m In Water: Very high attenuation	Primary sensing band in the Americas. Regulations (e.g., FCC) typically permit higher EIRP than 868 MHz band.
2.4 GHz	CE, SRMC, UKCA, FCC, IC, ACMA	Most countries worldwide	In Air: 0.1-0.5 km In Soil/Water: Very poor penetration; signal largely absorbed	Globally harmonized, high data rate. High interference potential (Wi-Fi, Bluetooth), poor diffraction.

* Dependent on specific device power, antenna, and radio environment

A.1.2 Compliance Mandate

(1) Table A.1.1 provides general guidance only.

(2) Before deployment, it is mandatory to consult the local radio spectrum authority (e.g., SRRC, FCC, Ofcom) to confirm the legality of frequency, transmit power, duty cycle, and out-of-band emissions.

(3) The total system's Equivalent Isotropically Radiated Power (EIRP) must not exceed the regulatory limit.

A.2 Core Radio Link and Antenna Principles

A.2.1 The Radio Link Budget

A fundamental tool for predicting wireless link viability is the Link Budget, which calculates the maximum permissible path loss.

(1) Governing Formula

- The Link Margin indicates link robustness (a margin >10-20 dB is recommended).

- Maximum Allowable Path Loss (dB) = Transmit Power (dBm) + Tx Antenna Gain (dBi) + Rx Antenna Gain (dBi) - Coaxial Cable Loss @Tx (dB) - Coaxial Cable Loss @Rx (dB) - Receiver Sensitivity (dBm)

(2) Application of this Governing Formula

- Calculate Allowed Path Loss: Sum all system gains and subtract all losses as per the formula.

- Estimate Environmental Path Loss: Use empirical models or site measurements for the specific distance and environment.

- Determine Link Margin: Link Margin = Allowed Path Loss - Estimated Environmental Path Loss. A positive margin indicates a viable link.

A.2.2 Key Antenna Selection Factors

(1) Polarization Matching

- For optimal power transfer, the polarization of transmitting and receiving antennas must be aligned.

- Mismatched polarization can cause significant signal loss (typically 20-30 dB). Consistent vertical polarization is recommended for static infrastructure WSN.

(2) Antenna Gain and Type

- Antenna Gain (dBi): A measure of directivity. The chosen gain must comply with the total EIRP limit: EIRP = Transmit Power + Antenna Gain - Cable Loss.

- Omni-directional antennas (e.g., 3-5 dBi) provide 360° coverage, suitable for mesh nodes.

- Directional antennas (e.g., 8-15 dBi) focus energy for point-to-point links. Generally, not recommended for multi-node mesh networks.

A.3 Equipment Selection and Configuration Guide

A.3.1 Node Selection Criteria

(1) Sensor Interface: Match the node's input type (VW, Analog, Digital, RS-485, SDI-12) to the sensor.

(2) Power Consumption: Prioritize ultra-low-power nodes for long-term monitoring. Consider power availability for high-data-rate applications.

(3) Ingress Protection (IP) Rating: IP66 is standard for outdoor and dusty environments. Specify IP68 for permanent immersion, burial, or corrosive environments.

(4) Form Factor: Consider size constraints for mounting.

A.3.2 Gateway Selection Criteria

(1) Backhaul Connectivity: Primary choice is Cellular (4G/5G). Use WiFi or Ethernet where available. RS-232/485 for remote serial devices.

(2) Power Source: Use AC/DC adapter where possible. For remote sites, use internal battery with solar supplement.

(3) Processing Needs: Verify if edge computing capabilities are required.

A.3.3 Antenna Selection Guidelines

(1) Mesh Radio Antenna (on Nodes/Gateways)

- Standard Whip Antenna: Good all-rounder for general use.
- High-Gain Omni Antenna: For extending range in open areas.
- Small/Stubby or Internal Antenna: For space-constrained or high-impact-risk locations (accepting potential range reduction).

(2) Cellular Antenna (on Gateways)

- Ensure the antenna supports the cellular bands of the SIM provider.

A.3.4 Power System Configuration

(1) Battery Life Estimation: Use manufacturer calculators, inputting sampling rate, radio interval, and sensor current draw.

(2) Solar Sizing: Size panel and battery based on site solar insolation, gateway consumption, and required uptime.

(3) Cabling: Use appropriately rated cables, considering voltage drop over distance.

A.4 Project Planning and Site Deployment Checklist

This checklist guides the project planning phase, referencing principles from Sections A.1-A.3.

A.4.1 Preliminary Planning and Radio Network Design

(1) Project start date and timeline defined.

(2) Scale map/drawing of the monitoring area available.

(3) Target frequency band and regulatory limits confirmed for the region (Ref: Section A.1).

(4) Proposed gateway locations marked (considering cellular signal for backhaul).

(5) Proposed node locations marked.

(6) Inter-device distances estimated.

(7) Required number of mesh hops calculated (≤6 recommended for sub-GHz, ≤10 for 2.4GHz).

(8) Preliminary link budget calculated for critical links (Ref: Section A.2.1).

(9) Radio environment (obstructions, interference sources) assessed.

A.4.2 Equipment Specification and Procurement

(1) Node type, quantity, and sensor interfaces finalized (Ref: Section A.3.1).

(2) Gateway type and backhaul method selected (Ref: Section A3.2).

(3) Antenna type (gain, form factor) selected for nodes and gateways based on plan (Ref: Sections A2.2 & A3.3).

(4) Power solution (battery, solar, external DC) defined for all devices (Ref: Section 3.4).

(5) Estimated battery life for all devices calculated and deemed acceptable.

(6) All equipment certifications (SRMC, CE, FCC, etc.) verified for target market (Ref: Section A1.2).

A.4.3 Site-Specific Assessment and Logistics

(1) EMI sources identified; mitigation planned (⩾ 2-3m distance from nodes).

(2) Corrosive environments identified; protective measures specified.

(3) Vibration, weather, and submersion risks assessed.

(4) Special installation requirements documented (e.g., custom brackets, low-profile antennas).

(5) Safety and health plan for installation developed.

(6) Installation team trained on system and safety procedures.

(7) Battery handling and recycling plan in place.

(8) Site access arrangements confirmed.

A.4.4 Installation and Commissioning

(1) Gateways installed first, with cellular/network connectivity verified.

(2) Nodes installed securely with antennas properly oriented.

(3) Network connectivity and data flow from all nodes to server verified.

(4) System operational parameters (sampling rate, alarms) configured and tested.

(5) As-built network topology and device locations documented.

Appendix B: Wireless Sensor Network Equipment Certifications and Standards

B.1 Environmental Standards

RoHS Compliance:

[1] Commission Directive (EU) 2015/863 amending Annex II to Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment.

REACH Compliance:

[2] Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), including the list of Substances of Very High Concern (SVHC) as updated by ECHA.

B.2 Safety Standards

[3] IEC 62368-1:2018: Audio/video, information and communication technology equipment - Part 1: Safety requirements;

[4] BS EN IEC 62368-1:2020+A11:2020: Audio/video, information and communication technology equipment - Part 1: Safety requirements;

[5] EN IEC 62368-1:2020+A11:2020: Audio/video, information and communication technology equipment - Part 1: Safety requirements;

[6] BS EN IEC 62311:2020: Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz to 300 GHz);

[7] EN IEC 62311:2020: Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz to 300 GHz);

[8] AS/NZS 60950.1:2011+A1:2015: Information technology equipment - Safety - Part 1: General requirements;

[9] GB 4943.1-2022: Audio/video, information and communication technology equipment; Part 1: Safety requirements.

B.3 Electromagnetic Compatibility (EMC) Standards

[10] EN 301 489-1 V2.2.3: ElectroMagnetic Compatibility (EMC) standard for radio

equipment and services; Part 1: Common technical requirements;

[11] EN 301 489-3 V2.1.2: ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 3: Specific conditions for Short-Range Devices (SRD) operating on frequencies between 9 kHz and 246 GHz;

[12] EN 301 489-3 V3.2.4: ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 3: Specific conditions for Short-Range Devices (SRD) operating on frequencies between 9 kHz and 246 GHz;

[13] EN 301 489-17 V3.2.4: ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 17: Specific conditions for Broadband Data Transmission Systems;

[14] EN 301 489-17 V3.3.1 (2024-10): ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 17: Specific conditions for Broadband Data Transmission Systems;

[15] EN 301 489-52 V1.2.1: ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 52: Specific conditions for Cellular Communication Stations (CCS);

[16] EN 301 489-52 V1.3.1 (2024-11): ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 52: Specific conditions for Cellular Communication Stations (CCS);

[17] BS EN 55032:2015/A11:2020: Multimedia equipment - Emission requirements;

[18] EN 55032:2015/A11:2020: Multimedia equipment - Emission requirements;

[19] BS EN IEC 61000-3-2:2019/A1:2021: Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤16 A per phase);

[20] EN IEC 61000-3-2:2019/A1:2021: Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤16

A per phase);

[21] EN IEC 61000-3-2:2019/A2:2024: Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤16 A per phase);

[22] BS EN 61000-3-3:2013/A2:2021: Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤16 A per phase and not subject to conditional connection;

[23] EN 61000-3-3:2013/A2:2021/AC:2022: Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤16 A per phase and not subject to conditional connection;

[24] BS EN 55035:2017/A11:2020: Multimedia equipment - Immunity requirements;

[25] EN 55035:2017/A11:2020: Multimedia equipment - Immunity requirements;

[26] AS/NZS CISPR 32:2015: Information technology equipment - Multimedia equipment and digital equipment - Emission requirements;

[27] ICES-003 Issue 7, October 2020: Limits and methods of measurement of radio disturbance characteristics of information technology equipment;

[28] GB/T 9254.1-2021: Information technology equipment, multimedia equipment and receivers - Electromagnetic compatibility; Part 1: Emission requirements.

B.4 Radio Frequency (RF) & Telecommunications Standards

[29] EN 300 220-1 V3.1.1: Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 1: Technical characteristics and test methods;

[30] EN 300 220-2 V3.2.1: Short Range Devices (SRD) operating in the frequency range 25 MHz to 1000 MHz; Part 2: Harmonised Standard for access to radio spectrum;

[31] EN 300 440 V3.2.1: Short Range Devices (SRD) operating in the frequency range 1 GHz to 40 GHz; Part 1: Technical characteristics and test methods;

[32] EN 300 328 V2.2.1: Wideband transmission systems; Data transmission equipment operating in the 2,4 GHz band; Harmonised Standard for access to radio spectrum;

[33] EN 300 328 V2.2.2: Wideband transmission systems; Data transmission equipment operating in the 2,4 GHz band; Harmonised Standard for access to radio spectrum;

[34] EN 301 511 V12.5.1: Global System for Mobile Communications (GSM); Harmonised Standard for access to radio spectrum;

[35] EN 301 906-1 V13.1.1: IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 1: Introduction and common requirements;

[36] EN 301 908-1 V11.1.1: IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 1: Introduction and common requirements;

[37] EN 301 908-1 V15.2.1 (2023-01): IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 1: Introduction and common requirements;

[38] EN 301 908-2 V11.1.2: IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 2: CDMA Direct Spread (UTRA FDD) User Equipment (UE);

[39] EN 301 908-2 V13.1.1: IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 2: CDMA Direct Spread (UTRA FDD) User Equipment (UE);

[40] EN 301 908-13 V11.1.2: IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 13: Evolved Universal Terrestrial Radio Access (E-UTRA) User Equipment (UE);

[41] EN 301 908-13 V13.1.1: IMT cellular networks; Harmonised Standard for access to radio spectrum; Part 13: Evolved Universal Terrestrial Radio Access (E-UTRA) User Equipment (UE);

[42] EN 301 908-13 V13.3.1 (2024-10): IMT cellular networks; Harmonised Standard

for access to radio spectrum; Part 13: Evolved Universal Terrestrial Radio Access (E-UTRA) User Equipment (UE);

[43] AS/NZS 4268:2017: Radio equipment and systems (RES) - Land mobile service - Technical characteristics and test conditions for radio equipment intended for the transmission of data (and speech) and using an integral antenna;

[44] AS/NZS 2772.2:2016: Human exposure to radio frequency fields - Part 2: Principles and methods of measurement and calculation - 3 kHz to 300 GHz;

[45] AS/CA S042.1:2015: Radio Frequency (RF) Land Mobile and Fixed Equipment - ACS and ATS;

[46] AS/ACIF S042.3:2005: Technical requirements for connection to an air interface of a Telecommunications Network - Part 3: GSM Customer Equipment;

[47] AS/CA S042.4:2010: Technical requirements for connection to an air interface of a Telecommunications Network - Part 4: IMT-2000 Customer Equipment;

[48] ETSI TS 151 010-1 V12.8.0 (2016-05): Global System for Mobile Communications (GSM); Mobile Station (MS) conformance specification; Part 1: Conformance specification;

[49] RSS-102: Radio Standards Specification - Radio Frequency (RF) Exposure Compliance of Radiocommunication Apparatus (All Frequency Bands);

[50] RSS-247 Issue 2, February 2017: Radio Standards Specification - Devices Using Digital Modulation Techniques in the Frequency Bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz;

[51] RSS-Gen Issue 5, Amendment 2, February 2021: Radio Standards Specification - General Requirements and Information for the Certification of Radio Apparatus;

[52] FCC 47 CFR Part 15: Code of Federal Regulations Title 47; Part 15 - Radio Frequency Devices;

[53] MIIT Regulation on Radio Transmission Equipment Type Approval: Technical requirements for micro-power short-range radio transmitting equipment (covering

frequency bands, transmit power, occupied bandwidth, frequency tolerance, and spurious emissions).

B.5 Cybersecurity Standards

[54] EN 18031-1:2024: Information technology - Security techniques - Encryption algorithms; Part 1: General.