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Harsh-Environment LoRa / LPWAN Wireless Communication Systems: Technical Landscape and Field-Validation Opportunities in Kazakhstan and China

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Abstract

This technical report examines the feasibility and research value of deploying harsh-environment LoRa/LPWAN wireless communication systems across Kazakhstan and China, with particular attention to conditions that go well beyond ordinary cold-weather or industrial-noise testing. In addition to thermal extremes, electromagnetic interference, and difficult terrain, the report addresses three categories of especially severe operating conditions relevant to both countries: (1) underground mine environments, where signal attenuation through rock is severe and where roof falls, rock bursts, or seismic events can physically sever communication infrastructure mid-operation; (2) mountainous terrain, where ridge lines and valleys create diffraction losses and shadow zones that a simple gateway deployment cannot overcome; and (3) acute-hazard and specialized monitoring — methane and other toxic gas accumulation, fire and spontaneous combustion, structural roof collapse, seismic activity, snow loading and avalanche risk, general environmental (air, water, and ecological) monitoring, uranium-mining radiological and radon monitoring, and nuclear power facility monitoring — where the communication system itself becomes part of a life-safety, regulatory, or environmental-stewardship function rather than simply an operational-efficiency tool.

Drawing on the published engineering and field-research literature, the report surveys established solutions from the underground mining industry (leaky feeder cable, through-the-earth low-frequency systems, and post-disaster survivable network design mandated in some jurisdictions since the mid-2000s), from mountainous and alpine deployments (ridge-line repeater placement, Fresnel-zone-aware gateway siting, and standardized battery-powered relay extensions), and from hazard-monitoring research (avalanche sensor arrays, geotechnical roof-collapse instrumentation, and multi-gas early-warning networks). It then maps these solution patterns onto the specific terrain, industrial base, and climate of Kazakhstan and China, identifies priority field-validation use cases — including gas monitoring, fire detection, roof-collapse and seismic monitoring, snow/avalanche monitoring in mountainous mining regions, general environmental monitoring, uranium-mining radiological monitoring, and nuclear power facility monitoring — and sets out a non-profit cooperation framework through which the Euro-Eurasia Environmental Science & Education Foundation (EESEF) can support academic field-validation research without acquiring or claiming any commercial or intellectual-property interest in the underlying technology.

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1. Executive Summary

Low-Power Wide-Area Network (LPWAN) technology, and LoRa in particular, has become one of the principal wireless communication solutions for the Internet of Things (IoT) over the last decade, owing to its combination of long range, low power consumption, and minimal supporting infrastructure. Industry analysts project that LoRa will account for the majority of LPWAN connections globally by 2026 ^[2], and the technology has moved firmly into industrial, agricultural, logistics, and smart-city deployments worldwide ^[2,3].

However, LoRa's performance is materially affected by the conditions in which it is deployed. Extreme temperatures, industrial electromagnetic interference, complex terrain, and long unattended operating periods all degrade signal quality, reduce effective range, and shorten the working life of field-deployed sensor networks. These are precisely the conditions found across large parts of Kazakhstan and China — from sub-arctic winter steppe to high-altitude desert and dense industrial or mining sites — which makes both countries unusually well suited as real-world validation environments for next-generation harsh-environment LoRa systems.

This report surveys the technical challenges of deploying LoRa/LPWAN systems in harsh environments, reviews the existing research literature on cold-climate and industrial-interference performance, and sets out the specific climatic, industrial, and regulatory conditions in Kazakhstan and China that are relevant to field validation of such systems. It concludes by identifying priority use cases and candidate test environments, and by outlining a non-profit, research-only cooperation framework through which the Euro-Eurasia Environmental Science & Education Foundation (EEEESEF) can support academic field-validation work in the region — in partnership with local universities — without acquiring or claiming any commercial or intellectual property interest in the underlying technology.

The report is intended as a technical orientation document for EEEEESEF's own internal use and for shared reference with academic partners considering harsh-environment field trials. It does not describe, reproduce, or evaluate any specific proprietary system, and all technical claims are drawn from the published, publicly available research literature cited in Section 16.

2. Purpose and Scope

EEEESEF is a UK-registered (England & Wales) non-profit foundation supporting applied environmental, industrial, and technology research across Central Asia and beyond, principally through academic partnership, independent assessment, and publication. This report was prepared to build EEEEESEF's own technical understanding of harsh-environment LoRa/LPWAN systems and to establish a shared factual basis ahead of any future academic cooperation involving field validation of such systems in Kazakhstan and, where relevant, China.

The scope of this report is limited to:

- A general technical overview of LoRa and LPWAN principles relevant to harsh-environment performance, drawn from the public research literature;
- A survey of documented environmental and industrial stressors that affect LoRa performance (thermal extremes, electromagnetic interference, terrain, and power constraints);
- A description of the climatic, industrial, and infrastructure conditions in Kazakhstan and China that are germane to harsh-environment field validation, independent of any specific commercial project;
- Identification of candidate test environments and priority research use cases; and
- A proposed non-profit cooperation model through which EEEEESEF, together with regional university partners, could support future field-validation research.

This report deliberately does not address the commercial development, ownership, licensing, or intellectual property status of any specific harsh-environment communication system. EEEEESEF's role in any future cooperation is limited to research facilitation, in-country field access, academic partnership-building, and publication — consistent with its non-profit purpose. Any commercial development, manufacturing, or licensing activity connected to a specific technology would, if it occurs, be pursued separately by the relevant commercial parties and falls entirely outside EEEEESEF's mandate.

3. Introduction to LoRa and LPWAN Technology

3.1 Physical Layer Fundamentals

LoRa ("Long Range") is a proprietary spread-spectrum modulation scheme operating in unlicensed sub-GHz industrial, scientific, and medical (ISM) radio bands — typically around 868 MHz in Europe and parts of Central Asia, and 433 MHz or 470-510 MHz in various configurations used in China. LoRa uses chirp spread spectrum (CSS) modulation, in which the transmitted signal frequency is swept across a defined bandwidth. This modulation approach gives LoRa a large link budget and strong resilience to multipath fading and narrowband interference, which is a major reason it performs relatively well in outdoor, long-range, and moderately noisy environments compared with alternative narrowband IoT technologies [2].

LoRaWAN is the open media-access-control (MAC) layer and network architecture commonly built on top of the LoRa physical layer, standardized by the LoRa Alliance. It defines how end devices, gateways, and network servers interact, and introduces the concept of Adaptive Data Rate (ADR), which allows a network to dynamically trade off range, data rate, and power consumption according to link conditions [2,9].

3.2 Network Topologies: Star vs. Mesh

The conventional LoRaWAN architecture uses a star topology: end devices communicate directly with one or more gateways, which relay data to a central network server. This is simple to deploy and manage, but it has a known weakness in harsh or complex terrain — coverage gaps in valleys, behind ridgelines, or across large industrial sites can leave end devices unable to reach any gateway reliably. Recent research has explored LoRa-mesh architectures, in which nodes can relay traffic for one another over multiple hops, as a way of extending coverage and improving resilience in environments where a simple star topology struggles [4]. Mesh approaches introduce additional complexity — particularly around scheduling, latency, and interoperability with other industrial protocols — but they are increasingly seen as a relevant option for large, geographically dispersed, or topographically difficult deployments such as open-pit mines, pipeline corridors, or remote steppe monitoring networks [4].

Figure 1. Star vs. Mesh Network Topology for LoRa/LoRaWAN Deployments

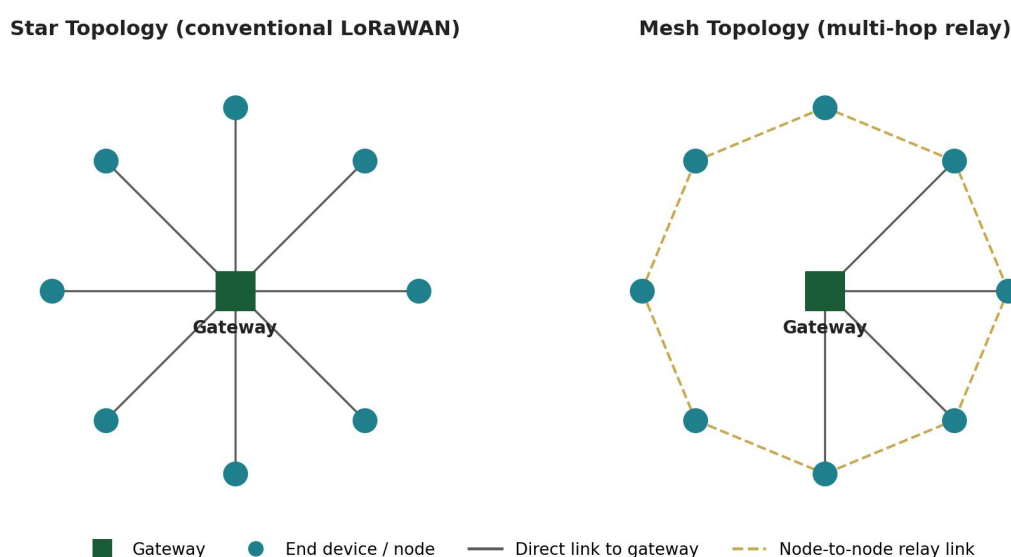


Figure 1. Star vs. mesh network topology for LoRa/LoRaWAN deployments. In a mesh configuration, nodes can relay traffic for one another, extending effective coverage without requiring every node to reach the gateway directly [4].

3.3 Key Performance Parameters

Several parameters determine how well a LoRa link performs under given conditions, and all of them are affected, to varying degrees, by environmental and industrial stressors:

- Spreading Factor (SF): controls the tradeoff between range/robustness and data rate and airtime. Higher spreading factors extend range and improve resilience to noise at the cost of longer transmission times and higher energy use.
- Signal-to-Noise Ratio (SNR) and Received Signal Strength Indicator (RSSI): the primary link-quality metrics used to judge whether a given link is degrading.
- Packet Error Rate (PER): the proportion of transmitted packets that fail to arrive correctly, a key measure of reliability in noisy or interference-heavy settings.
- Forward Error Correction (FEC) coding rate: LoRa's built-in error correction can be tuned to recover a meaningful portion of the SNR lost to noise, at the cost of additional airtime ^[1].

The table below summarizes the general tradeoffs across spreading factors that are relevant when designing a harsh-environment deployment.

Spreading Factor	Relative Range	Data Rate	Airtime / Power Use	Typical Use Case
SF7	Shortest	Highest	Lowest	Dense gateway coverage, short-range industrial sensors
SF9	Moderate	Moderate	Moderate	Mixed urban/peri-urban deployments
SF10-11	Long	Low	High	Rural, remote infrastructure monitoring
SF12	Longest	Lowest	Highest	Extreme range, sparse infrastructure, harsh remote sites

Table 1. General spreading-factor tradeoffs in LoRa deployments (illustrative, based on published LoRa Alliance and research-literature parameters) [1,2].

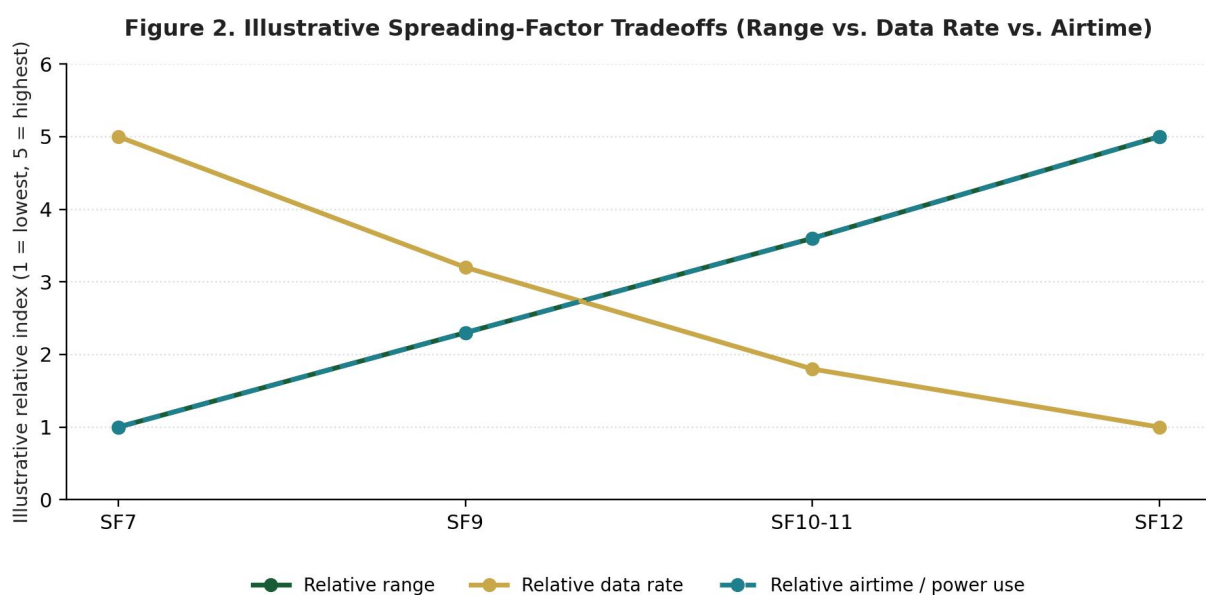


Figure 2. Illustrative spreading-factor tradeoffs between relative range, data rate, and airtime/power use. Values are a qualitative index for illustration, not measured field data.

3.4 Regional Frequency Bands and Regulatory Context

LoRa operates in unlicensed ISM bands, but the specific frequency allocation differs by region and is set by national telecommunications regulators rather than by the LoRa Alliance itself. The 868 MHz band is the common allocation across much of Europe and is also frequently used in Central Asian deployments including Kazakhstan, while China permits LoRa operation in several bands, most commonly around 470-510 MHz alongside other regional allocations, reflecting different national spectrum-planning decisions. A field-validation programme spanning both countries therefore needs to treat frequency-band selection as a first design decision rather than an afterthought, since propagation characteristics, permitted transmit power, and duty-cycle restrictions all vary by band and by jurisdiction. This report does not attempt to state current Kazakhstani or Chinese spectrum allocations definitively, as these are regulatory facts that should be confirmed directly with the relevant national authority immediately prior to any physical field deployment, rather than derived from general technical literature.

4. Harsh-Environment Performance Challenges

The published research literature identifies four broad categories of environmental and operational stressors that materially affect LoRa/LPWAN performance in the field. These categories frame the technical case for structured, real-world validation rather than laboratory or simulation testing alone.

4.1 Thermal Extremes

Both very high and very low temperatures degrade receiver sensitivity and transmitter stability, which in turn reduces effective range and signal quality [7]. Cold-climate field studies are particularly relevant to the Kazakhstan and northern-China context. A widely cited case study of a real LoRaWAN deployment in subarctic northern Sweden found that colder weather actually improved signal-to-noise ratio in that deployment, while warmer weather caused end devices using Adaptive Data Rate to select lower spreading factors to conserve airtime — showing that temperature affects not just raw signal quality but also the network's own adaptive behavior [9]. Other field research on remote hydrological sensor networks recorded a rise in sensor downtime once temperatures fell below approximately -15°C, illustrating that hardware reliability, not just radio-frequency performance, becomes a limiting factor in extreme cold [10]. Separately, research into LoRa-based transceivers for Antarctic and Arctic deployments has confirmed the fundamental suitability of the technology's sub-GHz frequency bands and chirp spread spectrum modulation for long-duration, low-power polar sensor links, provided hardware is adequately cold-rated [8].

4.2 Electromagnetic Interference (EMI)

Industrial environments introduce electromagnetic noise from heavy machinery, generators, variable-frequency drives, welding equipment, and other wireless systems operating in overlapping frequency bands, all of which can disrupt LoRa communication and increase data loss [11]. Simulation-based research evaluating LoRa in industrial settings has shown a measurable degradation in packet error rate compared with a clean noise-only environment, but has also shown that forward error correction and additional filtering (infinite or finite impulse response filters) can recover a meaningful part of the lost signal-to-noise margin — indicating that industrial-grade LoRa deployments are technically feasible but require deliberate engineering attention to coding and filtering choices rather than a default configuration [1].

4.3 Terrain and Signal Propagation

Complex terrain — valleys, mountainous regions, dense urban clutter, or large industrial complexes with significant structural shielding — creates coverage gaps that a simple star-topology network struggles to overcome. Field research on LPWAN deployments in headwater catchments recorded reduced signal strength in topographic valleys even though actual field performance sometimes exceeded model predictions, underlining that propagation in difficult terrain is not fully captured by standard planning tools and benefits from direct field measurement [10]. This is one of the strongest arguments for mesh or hybrid network topologies in geographically dispersed harsh-environment deployments such as open steppe, desert, or mountainous mining regions [4].

4.4 Power, Battery Life, and Remote Maintainability

A core value proposition of LoRa/LPWAN is multi-year battery life with minimal maintenance, which is what makes it attractive for remote, hard-to-access infrastructure [2]. However, this advantage is partly eroded in harsh environments: cold temperatures reduce battery efficiency and capacity, higher spreading factors required for extended range increase per-transmission energy use, and difficult terrain or extreme weather can make physical maintenance visits costly, infrequent, or seasonally impossible [10].

Any harsh-environment system intended for Kazakhstan's remote steppe or China's high-altitude western regions needs empirical, multi-season field data on real battery performance — not laboratory ratings alone — to be credible to prospective industrial or government end users.

5. Underground Mine Communication: Extracting Data From Depth and Through Collapse

Open-pit mining and surface industrial sites are demanding but tractable environments for LoRa/LPWAN — the stressors are cold, EMI, and terrain, all of which can be mitigated with conventional radio engineering. Underground mining is a categorically harder problem: RF signals attenuate rapidly through rock, tunnels bend and branch in ways that defeat line-of-sight planning entirely, and the single worst-case event a communication system must survive — a roof fall, rock burst, or seismic collapse — is also the event most likely to physically destroy part of the network at the exact moment it is needed most. This section surveys how the underground mining industry has historically solved this problem, and what it implies for any future LoRa/LPWAN deployment intended to operate at depth.

5.1 Signal Attenuation Through Rock and the Limits of Direct RF

Conventional VHF/UHF and microwave radio bands do not propagate usefully through more than a short distance of rock or coal, and multiple engineering studies have found that direct radio-to-radio communication in irregular tunnel geometry is unreliable beyond short distances — field trials of short-range wireless sensor protocols in underground tunnels have reported reliable communication only to roughly 120 metres in straight sections, with performance degrading further at bends and junctions ^[20]. This is why underground mines cannot simply scale up a surface LoRaWAN star-topology deployment: even LoRa's relatively strong link budget cannot overcome the combination of rock attenuation, tunnel bends, and metallic equipment clutter over distances of multiple kilometres, which is the scale of a typical modern underground mine.

5.2 Established Solutions: Leaky Feeder and Distributed Relay Infrastructure

The underground mining industry's long-standing answer to this problem is the leaky feeder cable: a coaxial cable strung throughout the mine's tunnels that intentionally radiates and receives signal along its entire length, effectively turning the cable itself into a continuous, distributed antenna ^[17]. A radio anywhere within range of the cable can communicate with any other point connected to it, including the surface, without needing line-of-sight to a fixed base station ^[17]. Leaky feeder systems are typically organized into overlapping power cells linked in a tree structure, with in-line amplifiers boosting signal at intervals to counteract the cable's own transmission loss ^[16]. More recent comparative work has found that helical antenna systems, which use circular rather than linear polarization, can outperform traditional leaky feeder cable in some tunnel geometries by reducing multipath interference and polarization mismatch, offering an alternative or complementary distributed-coverage approach ^[16].

These are mature, purpose-built solutions for continuous voice and data coverage, but they are expensive to install and require physical cable runs that must be maintained and repaired as the mine grows ^[16,17]. A LoRa/LPWAN sensor layer for gas, structural, or environmental monitoring does not need to replace this backbone — it is far more likely to ride on top of it, using leaky feeder or fixed relay infrastructure as a backhaul path from underground LoRa gateways back to the surface network server, while individual LoRa end-devices at the working face communicate short distances to the nearest underground gateway or repeater node.

5.3 Through-the-Earth and Low-Frequency Systems for Post-Collapse Survivability

The hardest requirement in underground communication is not routine operation but survivability after a disaster: a system that only works when the mine is intact is of limited value in exactly the scenario — a roof collapse, explosion, or inundation — where knowing whether trapped miners are alive matters

most. Following a series of underground mining disasters, U.S. federal law (the 2006 MINER Act) required underground coal mine operators to install wireless two-way post-accident communication systems capable of remaining operational after a disaster, which drove widespread adoption of leaky feeder and related systems specifically engineered for this survivability requirement [19]. Separately from leaky feeder, low-frequency (LF) and medium-frequency (MF) through-the-earth radio systems — operating well below conventional VHF/UHF bands, in the tens to hundreds of kilohertz range — can couple to a mine's own natural rock and seam structure as a waveguide, with documented attenuation rates below roughly 5 dB per 100 feet in coal and potash seams and below roughly 16 dB per 100 feet through host rock in metalliferous mines [18]. Because this transmission path relies on the bulk rock and coal seam itself rather than an installed cable, a meaningful portion of the network can survive the initial structural effects of a severe mine event that would sever a physical leaky feeder cable, which is precisely the emergency-communication advantage that motivated early development of this technology [18].

5.4 Implications for LoRa/LPWAN Deployment Underground

Drawing these threads together, a credible underground LoRa/LPWAN deployment for a Kazakhstan or China mining field trial would need to be designed in layers rather than as a single flat network: (1) a routine-operation sensor layer of LoRa end-devices (gas, temperature, vibration, structural sensors) reporting to underground gateways at intervals along the tunnel network; (2) a backhaul layer — most plausibly leaky feeder or a fixed relay chain — connecting those underground gateways back to the surface, since LoRa alone cannot span multi-kilometre tunnel distances through rock [16,17,20]; and (3) a survivability layer, informed by the LF/MF and post-disaster design principles above, ensuring that at least critical gas and structural-alarm data has a chance of reaching the surface even if part of the primary network is physically destroyed by the event it was monitoring for [18,19]. Mesh-capable LoRa nodes (Section 3.2) are directly relevant here: a mesh-relay chain along a drift can re-route around a single failed node in a way that a simple star topology cannot, which is exactly the resilience property needed after a partial collapse.

Figure 5. Underground Relay-Chain Resilience Before and After a Roof-Collapse Event

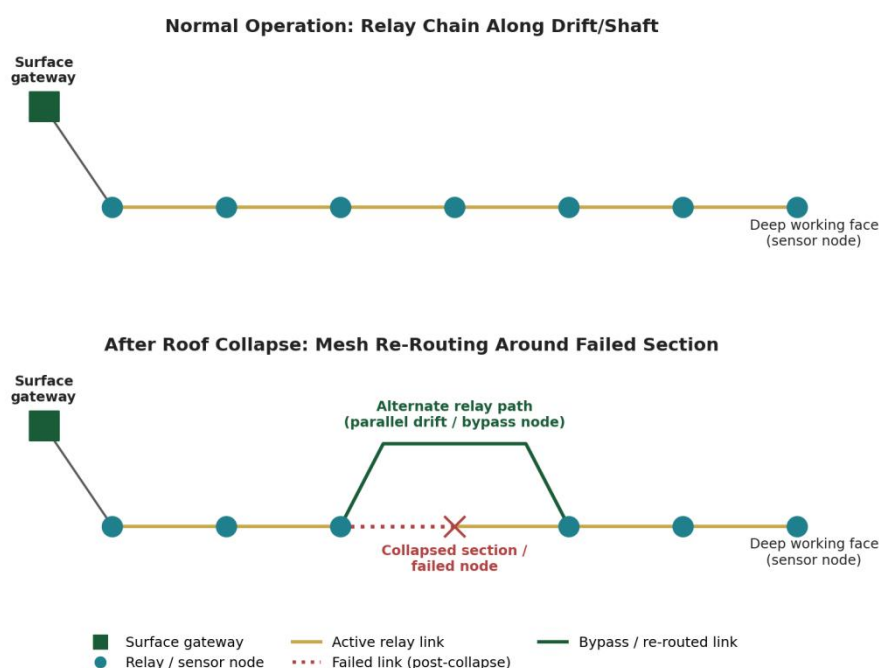


Figure 3. Illustrative underground relay-chain resilience: under normal operation (top), a chain of relay nodes carries data from the working face to the surface gateway; after a roof-collapse event severs one link (bottom), a mesh-capable network can re-route via an alternate node or parallel drift, provided the network was designed with that redundancy from the outset [18].

6. Mountainous Terrain: RF Propagation Challenges and Mitigation

Both Kazakhstan (the Tian Shan and Altai ranges) and China (the Tibetan Plateau, Tian Shan, and other western ranges) include mountainous terrain that is directly relevant to any harsh-environment field-validation programme, both because mountains host mining and infrastructure sites in their own right, and because ridge lines and valleys create some of the most severe non-thermal, non-EMI propagation challenges LoRa/LPWAN faces. This section sets out what the propagation-modeling and field-deployment literature says about the problem and the established mitigation options.

6.1 Diffraction, Fresnel-Zone Obstruction, and Shadow Zones

Radio signals do not travel in a geometric straight line but propagate through an ellipsoidal volume around the direct path known as the first Fresnel zone; engineering practice generally holds that at least 60% of this zone must remain unobstructed before diffraction losses become severe, and in mountainous terrain a ridge intruding into this zone can render a link unusable even where an optical line of sight technically exists ^[31]. Standard propagation models used to estimate this effect — knife-edge diffraction, the Bullington and Deygout methods, and the ITU-R P.526 recommendation — typically predict on the order of 15-25 dB of additional diffraction loss for the kind of grazing, near-tangent geometry common where a signal path just clears a ridge line ^[31,33,34]. Field studies in genuinely mountainous regions have documented multi-kilometre shadow zones behind ridges where no signal is receivable at all, and have shown that these shadow-zone distances vary enormously with local topography, underscoring that terrain-specific field survey — not a generic link-budget calculation — is necessary before committing to gateway locations in mountainous Kazakhstan or western China ^[34].

6.2 Gateway and Antenna Placement: The Highest-Value First Step

Before adding any repeater or additional infrastructure, raising the gateway antenna itself is consistently identified as the single highest-return intervention: classical path-loss models (Hata, Okumura) and field measurements agree that increasing antenna height from roughly 1.5 to 10 metres can improve received signal strength by on the order of 10-15 dB, and doubling the gateway height from roughly 12 to 30 metres can extend usable range by an estimated 40-50% — an effect that is essentially frequency-independent across the sub-GHz ISM bands relevant to both European-style 868 MHz and Chinese 470-510 MHz deployments ^[31,35]. In practical terms, this means ridge-top or elevated-mast gateway siting should be the starting point for any mountainous-terrain field trial design, evaluated before assuming that additional repeaters or gateways are required.

6.3 Repeaters, Standardized Relays, and Mesh Chains

Where elevating the gateway alone cannot close a shadow zone — for instance, a valley shielded from every plausible ridge-top gateway location — three complementary mitigation options exist. A dedicated proprietary repeater, typically mains-powered, is the simplest option for a confined, well-defined dead zone. A standards-based LoRaWAN relay, defined in the LoRa Alliance's TS011 specification, is battery-powered and interoperable across vendors, making it well suited to remote sensor clusters where running mains power is impractical — precisely the condition found at many remote Kazakhstan or high-altitude Chinese monitoring sites ^[31,32]. Where the coverage gap is structural rather than local — for example, covering a multi-kilometre valley from a single side is not feasible — an additional gateway with independent backhaul is the more reliable, if more costly, solution ^[31]. A repeater or relay placed just above a diffracting ridge edge can recover the great majority of the 15-25 dB diffraction loss described in Section 6.1, which is why ridge-line relay placement is identified in the field literature as the single highest-return intervention after gateway height itself ^[31].

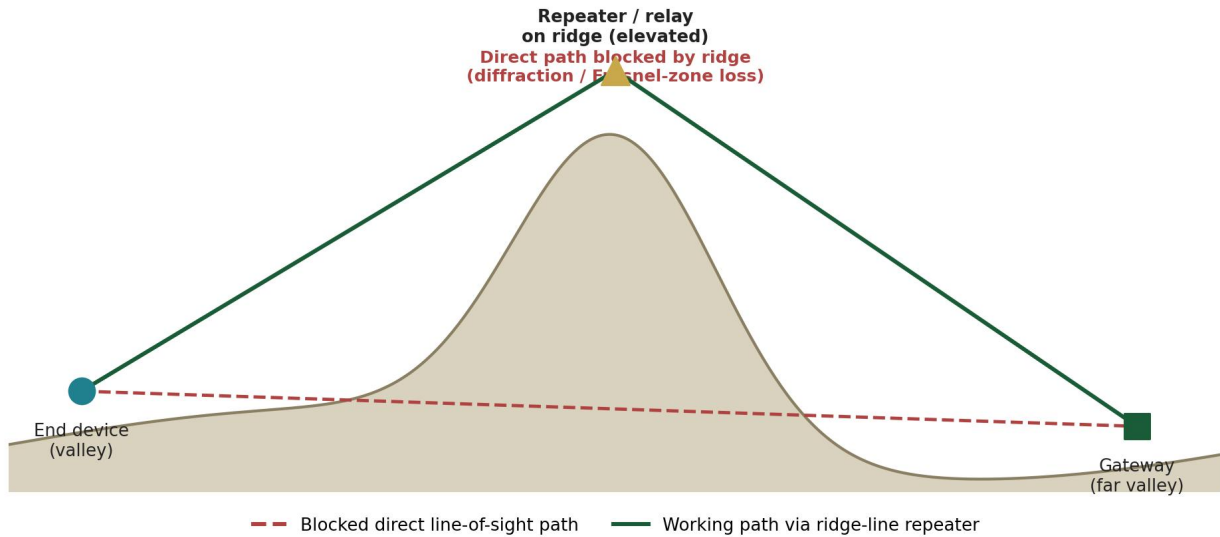
Figure 4. Mountainous Terrain: Diffraction Loss and Ridge-Line Repeater Placement

Figure 4. Illustrative mountainous-terrain scenario: a ridge line blocks the direct line-of-sight path between an end device and a distant gateway, but a repeater or relay placed on the ridge itself recovers a working path by avoiding the worst of the diffraction loss [31,33].

6.4 Aerial and Temporary Relay Options

For initial site surveys or temporary campaigns in terrain that is otherwise inaccessible, aerial relays — whether a temporary mast, a tethered or free-flying drone, or a solar-powered relay unit placed by helicopter or on foot at a summit — offer a way to characterize or bridge a difficult link before committing to permanent infrastructure. Comparative field measurements have found that a ground-level gateway in obstacle-heavy terrain can suffer extremely high packet loss (on the order of 70% or more) at ranges where an aerial relay at altitude achieves near-complete delivery with a substantially improved signal-to-noise ratio, illustrating how much of the mountainous-terrain problem is fundamentally a line-of-sight and elevation problem rather than a raw link-budget problem [31]. This makes aerial or temporary elevated relays a practical tool for the site-survey phase of any Kazakhstan or western-China mountainous field trial, ahead of finalizing permanent gateway and repeater locations.

7. Hazard and Environmental Monitoring Use Cases

The preceding sections establish that harsh-environment LoRa/LPWAN deployment is technically demanding even for routine operational monitoring. A distinct and, in several respects, more consequential category of use case is acute-hazard monitoring, where the communication system is not simply reporting operational status but functioning as part of a life-safety early-warning chain. This section surveys eight such use cases most relevant to Kazakhstan and China: toxic and explosive gas monitoring, fire and combustion detection, structural roof-collapse monitoring, seismic monitoring, snow-load/avalanche monitoring, general environmental monitoring, uranium mining radiological monitoring, and nuclear power facility monitoring.

7.1 Gas Monitoring: Methane, Carbon Monoxide, and Other Toxic Gases

Methane released during coal extraction can reach explosive concentrations rapidly and with little warning if ventilation and monitoring are inadequate, and continuous gas monitoring is accordingly treated as a foundational safety requirement in underground coal operations [22]. Documented safety-monitoring thresholds in the wireless-sensor-network literature include methane concentrations above roughly 1.0%, carbon monoxide above roughly 50 ppm, and elevated temperature and humidity as trigger conditions for automated alerts [23]. Beyond methane and carbon monoxide, comprehensive underground gas-monitoring systems typically also track oxygen, carbon dioxide, sulphur dioxide, and hydrogen sulphide, alongside airflow/ventilation measurements [24]. A wireless sensor layer for this purpose needs to prioritize reliability and low latency for alarm conditions over throughput, which aligns well with LoRa's long-range, low-power characteristics provided the underground propagation and backhaul architecture described in Section 5 is in place.

7.2 Fire and Spontaneous Combustion Detection

Coal mine fires can originate from spontaneous combustion within the coal seam itself (goaf combustion) as well as from equipment or electrical faults, and early detection is complicated by the fact that combustion gases can build up gradually in inaccessible voids before becoming apparent at the surface [25]. Specialized fibre-optic distributed sensing systems have been developed specifically to provide continuous, full-range methane and combustion-gas monitoring without the recalibration burden of conventional electrochemical sensors, and have been used to detect goaf combustion hazards at an early phase in field deployments [25]. A LoRa-based sensor layer would typically complement rather than replace such specialized fibre-optic systems, providing a lower-cost, easier-to-redeploy network of point-source gas and temperature sensors across a wider area of the mine, feeding into the same early-warning framework.

7.3 Roof and Structural Collapse Monitoring

Roof falls, rock bursts, and subsidence occur when accumulated stress in the surrounding rock mass exceeds the capacity of ground support, and these failures are frequently preceded by subtle, instrument-detectable movement that goes unnoticed without continuous monitoring [22]. The established geotechnical instrumentation toolkit for this purpose includes extensometers, load cells, tiltmeters, strain gauges, and piezometers, feeding data on deformation, stress, and rock-mass movement to a central monitoring system [21,22]. Seismic and geoacoustic sensors are also used specifically to detect the high-frequency vibration signals generated by internal fracturing of coal and rock ahead of a rock-burst event, and support-resistance monitoring on hydraulic roof supports provides a further, complementary signal of developing roof pressure [26]. Academic research specifically targeting wireless-sensor-network detection of gas accumulation and structural collapse in underground mines exists as a distinct research stream, indicating this is an active and still-developing area rather than a fully solved problem [27].

7.4 Seismic and Earthquake Monitoring

Both Kazakhstan (in its southern and southeastern mountainous zones, including the greater Almaty region) and China (across much of its western and southwestern territory) lie in areas of meaningful seismic hazard, in addition to the mining-induced micro-seismicity discussed above. A LoRa/LPWAN sensor network designed for structural or geotechnical monitoring can, in principle, incorporate the same class of vibration and tilt sensors used for rock-burst detection to provide a broader early-warning or post-event damage-assessment function for surface infrastructure, though this report does not identify published field research specifically validating LoRa/LPWAN networks for regional seismic early warning (as opposed to localized mine-seismicity monitoring), which Section 12 (Research Gaps) accordingly flags as an open area.

7.5 Snow Load and Avalanche Monitoring

Mountainous mining and infrastructure sites in Kazakhstan and China face avalanche risk in addition to the cold-climate stressors discussed in Section 4.1, and this is an area where LoRaWAN-based monitoring is already an established, field-tested practice rather than a purely theoretical option. Ski-resort and alpine deployments use LoRaWAN sensor networks to continuously measure snow depth, density, and temperature at multiple depths, alongside ground vibration and snow-cover movement, to assess avalanche risk and can automatically trigger alarms or evacuation procedures when monitored parameters cross risk thresholds ^[28]. A recent purpose-built sensor array developed specifically for continuous snowpack and avalanche-slope monitoring transmits temperature, humidity, position, and snowpack-movement data via LoRaWAN and cellular backhaul to a web platform, deployed directly onto avalanche-prone slopes by hand or drone ^[29]. Separately, large-scale wireless sensor network deployments for snowpack and mountain-hydrology monitoring — including a network of nearly a thousand environmental sensors across multiple basins reporting readings every 15 minutes — demonstrate that this class of network can be operated reliably at meaningful scale over multi-year periods ^[30]. Together, this body of work indicates that snow/avalanche monitoring is one of the more mature and directly transferable hazard-monitoring use cases available to a Kazakhstan or western-China mountainous field-validation programme, with a substantially shorter path from literature to field trial than the underground post-collapse survivability problem in Section 5.

7.6 General Environmental Monitoring: Air, Water, and Ecological Parameters

Beyond the acute-hazard use cases above, LoRaWAN is already one of the most widely deployed technologies for routine environmental monitoring globally, covering air quality (CO₂, NO₂, and particulate matter), water quality (pH, dissolved oxygen, turbidity, and contaminant detection), noise pollution, and carbon-footprint tracking for industrial facilities ^[36,37]. Purpose-built LoRaWAN environmental networks have also been demonstrated in remote, hard-to-access ecological settings — forests, rivers, and wetlands — where the technology's long range and low power make it possible to detect pollution, drought stress, or wildfire risk without wired infrastructure ^[37]. Field research on gateway mobility has further shown that a single mobile LoRaWAN gateway can be used to periodically service multiple remote environmental-monitoring sites in pristine or protected areas, reducing the fixed-infrastructure cost of covering a large or ecologically sensitive territory ^[39]. This general environmental-monitoring use case is a natural extension of EESEF's existing environmental research mandate, and would sit alongside — and could share field infrastructure and university partnerships with — the more acute hazard-monitoring use cases described above.

7.7 Uranium Mining: Radiological and Radon Monitoring

Kazakhstan is the world's largest producer of uranium, accounting for over 40% of global output, with national production of 25,839 tonnes of uranium (tU) in 2025 [48]. This gives Kazakhstan a uranium-mining monitoring use case of direct national significance, distinct from the general mining-sector applications discussed in Sections 5 and 8. Published environmental studies conducted specifically in Kazakhstan's uranium-mining regions provide a strong, country-specific evidence base for this use case. Research in the Shu-Sarysu uranium province of southern Kazakhstan recorded elevated outdoor ambient gamma dose rates of 0.5-1.2 microsieverts per hour near a preserved self-flowing well beyond the mining buffer zone, along with radionuclide concentrations in soil exceeding regional background levels [40]. Separately, a radon concentration survey across former uranium-mining settlements in northern Kazakhstan (Aqsu, Saumalkol, and Arykbalyk) found severe indoor radon contamination, with mean equivalent equilibrium volume activity reaching several hundred becquerels per cubic metre and maximum readings up to several thousand becquerels per cubic metre in the most affected settlement, alongside gamma dose rates as high as 0.56 microsieverts per hour attributable to abandoned mining areas [41].

Both of these Kazakhstan-specific studies explicitly call for extended, continuous monitoring rather than one-off screening surveys to properly characterize exposure risk to nearby populations [41] — which is precisely the gap a distributed LoRa/LPWAN sensor network is well suited to close. Underground uranium mining introduces a further, historically distinct monitoring requirement: radon and its short-lived decay progeny must be measured essentially continuously, since progeny concentrations change on a timescale of minutes and cannot be reconstructed from an infrequent spot check [42]. IoT-connected radon monitoring platforms already exist for indoor and occupational settings, typically augmenting a low-cost radon sensor with a wireless connectivity layer for remote, real-time reporting [43], and this general architecture — a long-life radiological or radon sensor paired with a long-range, low-power radio link — maps directly onto LoRa/LPWAN's core strengths. A field-validation programme covering both an active uranium-mining site and the radon-affected settlements identified in existing Kazakhstan research would combine an under-served national environmental-health priority with a genuinely differentiated technical contribution, since continuous, network-based radiological monitoring of this kind goes beyond the periodic survey methodology used in the published Kazakhstan studies to date.

7.8 Nuclear Power Facility Monitoring

Safety qualification: LoRa/LPWAN monitoring discussed here is a research and supplementary telemetry option. It must not be used as a standalone substitute for certified mine-safety alarms, emergency communications, nuclear safety-classified instrumentation, or other legally required protective systems. Any safety-related deployment requires a hazard analysis, verified end-to-end alarm latency and availability, redundant communications and power where appropriate, cybersecurity review, and approval by the competent operator and regulator.

Despite its position as the world's leading uranium producer, Kazakhstan has not generated nuclear electricity domestically since its Soviet-era BN-350 fast-neutron reactor at Aktau was shut down in 1999. Kazakhstan is now pursuing new nuclear power capacity. On May 28, 2026, Kazakhstan and Russia signed an intergovernmental agreement covering two proposed VVER-1200 units for the Balkhash nuclear power plant near Ulken. On September 3, 2026, Kazakhstan Nuclear Power Plants LLP and Rosatom signed an EPC contract; site investigations and regulatory approvals remain necessary before construction. A second nuclear power plant is planned, with China National Nuclear Corporation (CNNC) identified as a prospective technology partner, and Kazakhstan has outlined a longer-term multi-plant nuclear strategy. Commissioning schedules remain indicative and subject to project and regulatory progress [48,49]. This gives a Kazakhstan-China harsh-environment communications research programme a distinctive and directly relevant forward-looking use case: wireless environmental and structural monitoring in and around nuclear power infrastructure, an area with an established but still-developing research literature and, notably, direct precedent involving China's nuclear industry.

Wireless sensor networks have been deployed for radiation monitoring at operating nuclear facilities in several countries, historically using ZigBee or other short-range protocols — documented examples include a 17-node radiation-monitoring network at the Kalpakkam nuclear complex in India, a solar-powered portable gamma dose-rate monitor at the Paks nuclear power plant in Hungary, and experimental wireless sensor deployments at the Comanche Peak and Arkansas Nuclear One nuclear power stations in the United States ^[45,79].

Directly relevant to the Kazakhstan-China angle of this report, a wireless structural crack-monitoring system using 30 wireless sensor nodes was deployed on the surface of a reactor containment building at the Daya Bay Nuclear Power Station in China during an in-service pressure test, demonstrating that Chinese nuclear operators already have direct experience with wireless structural-health monitoring on reactor containment structures ^[46]. Separately, a low-power wireless sensor system for continuous acoustic and ultrasonic monitoring of isolated pipe systems has been developed and tested specifically to reduce the need for personnel to enter radiation-exposed areas of a nuclear power plant for routine inspection, a safety and labour-reduction rationale that would apply equally to a newly built Kazakhstan facility ^[47]. Most directly relevant of all, published research has explicitly combined LoRa wireless communications with a distributed network of radiation detectors — the Internet of Radiation Sensor System (IoRSS) — to provide wide-area radiological search, monitoring, and source-localization capability, confirming that LoRa/LPWAN is not merely a theoretical fit for this domain but has already been demonstrated in the radiological-detection research literature ^[44].

Any future EEESEF-supported activity in this space would need to be scoped conservatively and consistent with the non-profit, non-commercial framework set out in Section 13: work inside the security perimeter, physical protection systems, or safety-classified instrumentation of an operating or under-construction nuclear facility falls under strict national and IAEA-aligned regulatory control and is well outside EEESEF's mandate and competence. A realistic and appropriate role for EEESEF would instead be environmental and structural research monitoring in the vicinity of such facilities during construction and operation — for example, independent ambient radiation and environmental baseline monitoring in communities near the planned Ulken site, of the same kind already published for Kazakhstan's uranium-mining regions in Section 7.7 — rather than any function inside the regulated facility itself.

8. Kazakhstan Deployment Context

8.1 Climatic Profile

Kazakhstan has a sharply continental climate across most of its territory: long, severe winters with sustained sub-zero temperatures across the northern and central steppe, large diurnal and seasonal temperature swings, and hot, arid summers in the south. This range of conditions — often within the operating envelope of a single unattended sensor network over a full annual cycle — makes Kazakhstan a demanding but realistic testbed for cold-climate and thermal-cycling performance of the kind documented in northern-Sweden and Arctic/Antarctic LoRa field studies [8,9]. Unlike laboratory cold-chamber testing, a Kazakhstan field deployment would expose hardware to the freeze-thaw cycling, wind loading, and extended unattended operation that are difficult to replicate synthetically.

8.2 Industrial and Infrastructure Base

Kazakhstan's economy has a substantial base of mining, metallurgy, and oil and gas operations, many of them in remote locations with limited fixed communications infrastructure. These are exactly the conditions the mining-sector IoT literature identifies as best suited to LPWAN deployment: large sites where traditional wired telemetry is costly to install, and where LPWAN's long range and low infrastructure requirements are most valuable for monitoring equipment condition, environmental parameters, and personnel or asset location [12,13,14,15]. At the same time, these sites generate exactly the kind of industrial electromagnetic interference — heavy machinery, generators, and processing equipment — that the interference literature identifies as a key performance risk [1]. This combination of remoteness and industrial EMI makes Kazakhstan's mining and industrial sector a genuinely representative, rather than artificial, harsh-environment test case. Within this industrial base, uranium mining is a distinct and nationally significant sub-sector — Kazakhstan is the world's largest uranium producer, accounting for over 40% of global output — and, as Section 7.7 details, already has a published Kazakhstan-specific research base identifying a need for more continuous environmental radiological monitoring than current periodic survey methods provide [48]. Kazakhstan's newly agreed civil nuclear power programme (Section 7.8) adds a further, forward-looking dimension to the country's industrial monitoring landscape.

8.3 Candidate Test Environments

Based on the stressor categories identified in Section 4, the following Kazakhstan environments would offer distinct and complementary field-validation value:

- Open-pit and underground mining sites — industrial EMI, structural shielding, safety-critical monitoring requirements, and terrain-driven coverage gaps.
- Remote steppe and rural infrastructure corridors (pipelines, transmission lines, agricultural monitoring) — long-range, sparse-infrastructure conditions and extreme winter cold.
- Oil and gas field installations — combined thermal extremes, EMI from processing equipment, and remote/unattended operation requirements.
- Urban and peri-urban smart-city pilots (e.g., environmental or utility monitoring) — a lower-stress comparison baseline against which harsh-environment results can be benchmarked.

8.4 Regulatory and Spectrum Considerations

Any field deployment must operate within Kazakhstan's national radio-frequency spectrum allocations and import/certification requirements for radio equipment. These requirements are a matter of public regulatory record rather than technical research, and would need to be confirmed directly with the relevant Kazakhstani telecommunications authority before any physical field trial — this is noted here as a planning dependency rather than a technical finding of this report.

8.5 Complementarity with Existing EEESEF and Regional Research Activity

A Kazakhstan-based harsh-environment LoRa field-validation programme would sit naturally alongside EEESEF's existing academic and institutional relationships in the country. EEESEF's ongoing engagement with Kazakhstani research universities already spans environmental and industrial research themes, and the existing role of such a university partner as a Full Research Partner in EEESEF's waste-oil regeneration consortium demonstrates institutional readiness to take on an equivalent engineering-validation role for a harsh-environment communications field trial. Similarly, EEESEF's broader positioning as a UK-registered, internationally operating non-profit — rather than a Kazakhstan-domiciled entity — is directly relevant here, since it allows EEESEF to convene Kazakhstani, Canadian, and Chinese academic partners around a shared research question without any one national institution needing to act as the lead convening body. This positioning, already established through EEESEF's other academic partnership work, reduces the institutional set-up cost of adding a harsh-environment communications research stream alongside EEESEF's existing environmental and ESG-focused programme.

9. China Deployment Context

9.1 Climatic and Geographic Diversity

China's territory spans an unusually wide range of harsh-environment conditions relevant to LPWAN validation: severe winter cold across the northeast (Heilongjiang, Inner Mongolia) comparable to the sub-arctic conditions studied in the northern-Sweden LoRaWAN literature [9]; high-altitude, low-oxygen, and large diurnal temperature-swing conditions on the Tibetan Plateau and western regions; and extensive arid or semi-arid desert terrain across Xinjiang and Gansu, which combines long-range propagation requirements with sparse infrastructure. This breadth means China can, in principle, supply test conditions that complement rather than duplicate the Kazakhstan steppe and mining environment — for example, higher-altitude and desert-specific propagation data that Kazakhstan's terrain does not offer in the same form.

9.2 Industrial IoT Adoption and Manufacturing Ecosystem

China has one of the most developed LPWAN industrial ecosystems globally, with strong domestic adoption of LoRaWAN alongside cellular IoT standards (NB-IoT, LTE-M) and a large domestic manufacturing base for LoRa chipsets, modules, and gateways [3]. Industry commentary from recent trade events highlights continued momentum in industrial equipment monitoring, predictive maintenance, and edge-AI-assisted sensing built on LoRa platforms [6]. This manufacturing depth is directly relevant to any future harsh-environment system: China-based component and module sourcing, ruggedized enclosure manufacturing, and battery technology suited to cold or high-altitude operation are all more readily available domestically than in Kazakhstan, making a China-Kazakhstan combination potentially stronger than either country alone — Kazakhstan supplying distinctive test conditions and in-country field access, China supplying manufacturing and component depth.

9.3 Candidate Test Environments

Drawing the same distinctions as in Section 8.3, candidate Chinese environments of research interest include:

- Northeastern industrial and agricultural regions — deep winter cold comparable to the documented subarctic LoRaWAN case studies.
- Western desert and high-altitude regions (Xinjiang, Gansu, Tibetan Plateau) — long-range propagation over difficult, sparsely populated terrain, and thermal cycling driven by large diurnal swings.
- Established industrial and mining regions — mature IIoT deployment context against which harsh-environment-specific results can be benchmarked.

As with Kazakhstan, any physical field activity in China would need to be confirmed against national radio-spectrum and equipment-certification requirements before deployment; this report does not make any claim about current regulatory status.

9.4 Academic Research Linkages

China-side academic cooperation would logically build on EEESEF's existing research-partnership channels rather than starting from a blank page. EEESEF's established academic research relationships in China, including its existing ESG-focused cooperation agreements, provide a plausible starting point for identifying Chinese university or research-institute partners interested in the engineering and manufacturing side of a harsh-environment field-validation programme, complementing the in-country field access that a Kazakhstani university partner would provide. As with the Kazakhstan side, EEESEF's contribution here would remain limited to convening, academic dissemination, and publication, consistent with its non-profit purpose.

10. Comparative Analysis: A Combined Kazakhstan-China Testbed

Considered together, Kazakhstan and China offer a genuinely complementary rather than redundant set of harsh-environment conditions, industrial contexts, and supporting ecosystems. The table below summarizes this complementarity at a high level.

Dimension	Kazakhstan	China
Cold-climate exposure	Severe continental winter across steppe and north	Comparable severity in northeast; added high-altitude cold on the Tibetan Plateau
Arid / desert terrain	Southern semi-arid regions	Extensive desert terrain, Xinjiang and Gansu
Industrial EMI sources	Mining, metallurgy, oil & gas	Broad-based heavy industry plus mature IIoT deployment base
Manufacturing / component supply	Limited domestic base	Deep domestic LoRa chipset, module, and ruggedized-hardware manufacturing
Terrain-driven coverage challenges	Open steppe, remote infrastructure corridors	Mountainous west, high-altitude plateau
Regulatory environment	National spectrum authority approval required	National spectrum authority approval required

Table 2. Complementary harsh-environment and industrial characteristics of Kazakhstan and China relevant to LoRa field validation.

Illustrative Harsh-Environment Stressor Profile by Candidate Region

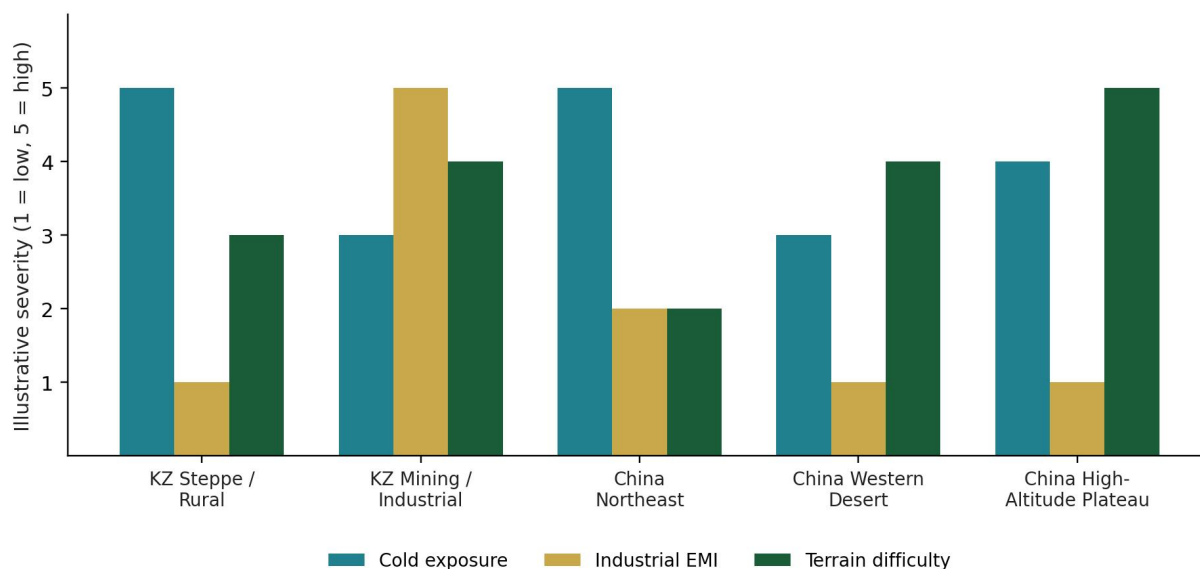


Figure 3. Illustrative harsh-environment stressor profile by candidate region, synthesized from the analysis in Sections 4-6. Ratings are a qualitative index (1-5) for comparison purposes, not measured field data.

This complementarity is the technical rationale for pursuing a joint, rather than single-country, field-validation research programme: a system validated only in one setting risks having its cold-climate, EMI, or terrain findings mistaken for general robustness when they may in fact be specific to the one environment tested.

A structured multi-country field programme, documented and published under independent academic or non-profit auspices, would produce a materially stronger and more credible evidence base than single-site testing — a point directly relevant to any future prospective industrial or institutional adopter evaluating the technology.

11. Priority Use Cases for Field Validation

Based on the stressor analysis in Section 4, the underground, mountainous, and hazard-specific considerations in Sections 5-7, and the country-specific contexts in Sections 8 and 9, the following use cases represent the strongest candidates for structured field-validation research, ranked by the clarity of the technical case for harsh-environment testing [11,12,13,14,15]:

Use Case	Primary Stressor(s)	Relevance
Underground gas monitoring (methane, CO, and other toxic gases)	Rock attenuation, need for survivable backhaul	Life-safety priority; strong existing WSN literature base [22,23,24]
Roof-collapse and rock-burst geotechnical monitoring	Structural failure risk, post-event survivability	Directly addresses the most severe underground hazard scenario [21,22,26]
Uranium mining radiological/radon monitoring	Long-term continuous measurement, remote settlements	Direct Kazakhstan-specific evidence base; national uranium-production significance [40,41,42]
Nuclear power facility environmental/structural monitoring (vicinity only)	Regulatory constraints, long-term structural integrity	Forward-looking; direct China precedent (Daya Bay) and Kazakhstan's new-build programme [46,48]
Snow load and avalanche monitoring (mountainous mining/infrastructure)	Extreme cold, terrain, established LoRaWAN precedent	Most field-mature hazard use case; direct literature precedent [28,29,30]
Mountainous-terrain relay/repeater validation (ridge-line siting)	Diffraction, Fresnel-zone obstruction, shadow zones	Directly testable against established propagation models [31,33,34]
General environmental monitoring (air/water quality, ecological)	Remote/ecologically sensitive sites, low infrastructure	Broad, low-risk extension of EESEF's existing environmental mandate [36,37,39]
Remote pipeline / transmission-corridor monitoring	Cold, long range, sparse infrastructure	Directly relevant to Kazakhstan oil & gas and cross-border energy infrastructure
Open-pit / underground mine condition monitoring	EMI, structural shielding, terrain	High industrial demand in both countries; strong literature base on mining IoT
Winter steppe / agricultural environmental monitoring	Extreme cold, battery performance, long unattended operation	Matches documented subarctic case-study conditions closely
High-altitude / desert infrastructure monitoring	Thermal cycling, terrain, low infrastructure density	Distinctive China-specific contribution (western regions)
Industrial predictive maintenance (equipment vibration/health)	EMI, high-density interference environment	Aligns with current China IIoT deployment trends

Table 3. Priority use cases for harsh-environment LoRa field validation, ranked by strength of technical rationale, including the underground, mountainous, and acute-hazard scenarios introduced in Sections 5-7.

12. Research Gaps and Opportunities

The published literature reviewed for this report leaves several specific gaps that a structured Kazakhstan-China field-validation programme could credibly address:

- Multi-season, multi-site cold-climate field data: most published cold-climate LoRa/LoRaWAN field studies cover a single deployment region (e.g., northern Sweden, Antarctic research stations) [8,9]. Comparable, published field data specifically from Central Asian steppe conditions is limited.
- Combined-stressor field data: most existing studies isolate a single stressor (temperature, or industrial interference, or terrain) rather than measuring their combined effect in a single real deployment, which is the condition most harsh-environment industrial sites actually present [4,10].
- Mesh-topology performance in extreme cold and industrial EMI simultaneously: while LoRa-mesh research is emerging, published field validation combining mesh architecture with both extreme cold and industrial interference is limited [4].
- Battery and hardware longevity data under real multi-year, multi-season harsh-environment operation, as distinct from laboratory-rated specifications.
- Integrated underground gas/structural sensor layers riding on LoRa/LPWAN specifically (as opposed to ZigBee or proprietary protocols): most of the underground gas and roof-collapse monitoring literature reviewed in Section 7 uses ZigBee, fibre-optic, or proprietary wireless protocols rather than LoRa/LPWAN, leaving the LoRa-specific underground integration question comparatively under-studied [20,25,27].
- Combined mesh-relay and post-collapse survivability field validation: Section 5 identifies mesh re-routing and through-the-earth LF/MF systems as complementary concepts, but published field data combining a LoRa-mesh relay chain with a real (not simulated) roof-collapse or structural-failure event is not identified in the literature reviewed here.
- LoRa/LPWAN-specific validation for regional seismic early warning: as noted in Section 7.4, the literature reviewed supports LoRa/LPWAN for mine-seismicity and structural monitoring, but not specifically for broader regional earthquake early warning, which remains an open question for a Kazakhstan or western-China field programme.
- Continuous, network-based radiological monitoring specifically in Kazakhstan's uranium-mining regions: the existing Kazakhstan studies reviewed in Section 7.7 are periodic surveys rather than continuous sensor networks, and while LoRa-based radiation-sensing research exists elsewhere in the literature, no published field deployment combining the two in a Kazakhstan uranium-mining context was identified in this review.

These gaps define a legitimate, publishable academic research agenda — independent of any single commercial technology — that would be a natural fit for university-led field validation with in-country support from a body such as EESEF.

13. Proposed Non-Profit Cooperation Framework

Consistent with EEESEF's non-profit purpose, any future cooperation arising from this report would be structured strictly as research support and academic dissemination, with no commercial, equity, royalty, or intellectual-property interest of any kind accruing to EEESEF. The following elements outline how such cooperation could be structured:

13.1 EEESEF's Role

- Identifying and facilitating access to candidate Kazakhstan field-test environments described in Section 8.3;
- Introducing and coordinating with regional university research partners capable of providing engineering validation and academic rigor;
- Co-authoring or publishing field-validation findings under the EEESEF working paper / technical report series, in the same format as this document;
- Supporting academic dissemination and, where relevant, connecting research findings to broader Central Asian ESG, environmental-monitoring, and industrial-modernization themes already within EEESEF's mandate.

13.2 What EEESEF Would Not Do

- EEESEF would not hold, license, or claim any equity or intellectual-property interest in any commercial LoRa/LPWAN system;
- EEESEF would not receive royalties, revenue share, or commercial consideration tied to any resulting product;
- EEESEF would not represent itself, in any document, as a commercialization partner, manufacturer, or distributor of any specific technology.

13.3 Suggested Sequencing

A practical path forward, consistent with EEESEF's existing model of building academic credibility before formalizing agreements, would be to: (1) circulate this technical report to relevant academic contacts as a shared, citable reference; (2) convene an exploratory discussion with a candidate Kazakhstan university partner (drawing on EEESEF's existing academic relationships in the country) to assess interest in a field-validation research role; and (3) allow any subsequent formal research-cooperation instrument — including a possible principal-investigator-level academic memorandum of understanding — to be scoped separately and later, once the shape of a concrete field-validation programme is clearer.

14. Recommended Field-Trial Methodology

If a field-validation programme proceeds along the lines outlined in Section 13, the credibility of its results — both academically and for prospective industrial adopters — will depend heavily on methodological discipline. This section sets out general methodological recommendations drawn from the structure of the studies reviewed in this report, without prescribing a specific technical system or test plan.

14.1 Multi-Season Design

Several of the strongest findings in the literature reviewed here — particularly the northern-Sweden LoRaWAN case study — come from deployments left in place across a full annual cycle rather than short test windows. A credible Kazakhstan or China field trial should be designed from the outset to run across at least one full winter-to-summer cycle, since single-season testing risks capturing only one operating regime (e.g., cold-weather SNR improvement) while missing others (e.g., warm-weather adaptive data-rate behavior, or battery degradation patterns that only appear after repeated freeze-thaw cycling).

14.2 Isolating and Combining Stressors

Section 12 noted that most published research isolates a single stressor. A stronger field-trial design would deliberately include both single-stressor test sites (e.g., a remote steppe site with cold but minimal EMI) and combined-stressor sites (e.g., a mining site with both cold and heavy industrial interference), allowing researchers to distinguish the individual contribution of each stressor from their combined effect — which is closer to the real operating condition end users actually face.

14.3 Independent Measurement and Publication

For results to carry weight with prospective institutional or industrial adopters, measurement and reporting should follow recognized field metrics — RSSI, SNR, packet error rate, and spreading-factor/data-rate behavior under Adaptive Data Rate — reported transparently, including negative or inconclusive results, and published through an academic or independent non-profit channel rather than solely through a commercial vendor's own marketing materials. This is consistent with EEESEF's existing publication model and would be one of its primary contributions to any future cooperation.

14.4 University Partner Role

A Kazakhstan-based university partner would be well positioned to provide engineering validation, instrumentation, and independent data analysis, mirroring the Full Research Partner role a university partner already occupies in EEESEF's waste-oil research consortium. This keeps the technical validation function inside an academic institution rather than inside EEESEF itself, consistent with EEESEF's role as a research facilitator and publisher rather than a technical laboratory.

15. Conclusion

Harsh-environment performance is one of the genuine open technical challenges in LoRa/LPWAN deployment, and the published literature — while informative — remains geographically limited, particularly for Central Asian steppe conditions and for combined-stressor (cold plus industrial EMI plus difficult terrain) field data. Kazakhstan and China together offer a distinctive and complementary set of real-world test conditions: severe continental cold, industrial EMI from mining and heavy industry, difficult desert and high-altitude terrain, and, in China's case, deep domestic manufacturing capacity for the hardware itself.

This combination positions the region as a credible, high-value location for structured academic field-validation research into harsh-environment LoRa systems — work that EEEEESEF, in its non-profit capacity, is well placed to support through research facilitation, university partnership, and academic publication, without engaging in or claiming any interest in the underlying commercial technology.

16. References

- [1] Bouras, C. et al. Performance Evaluation of LoRa Communications in Harsh Industrial Environments. *Journal of Sensor and Actuator Networks / MDPI*.
- [2] MOKOSmart. What is LoRa Technology? Ultimate 2026 Guide to Long-Range IoT.
- [3] MOKOSmart. Beyond Connectivity: 12 Impactful LoRaWAN Use Cases in 2026.
- [4] Tang, M. et al. Data-Driven Energy-Saving Methods Based on LoRa-Mesh Hierarchical Network. *Sensors (Basel)*, 2026.
- [5] Semtech Corporation. CES 2026: Semtech Showcases Next-Generation IoT Innovation with LoRa and Edge AI Solutions.
- [6] Survey on Scalable LoRaWAN for Massive IoT: Recent Advances, Potentials, and Challenges. *arXiv preprint*.
- [7] A Harsh Environment Wireless Pressure Sensing Solution Utilizing High Temperature Electronics. *PMC / NCBI*.
- [8] LoRa Based Transceiver for Arctic Region. Research study on polar LPWAN deployment.
- [9] Temperature Impact in LoRaWAN: A Case Study in Northern Sweden. *PMC / NCBI*.
- [10] Application and Performance of a Low Power Wide Area Sensor Network for Distributed Remote Hydrological Measurements. *PMC / NCBI*.
- [11] GAO Tek. Applications of LoRaWAN & LPWAN in the Cold Chain Monitoring Industry.
- [12] Meshed Pty Ltd. IoT in Mining: Automation and Asset Management.
- [13] Full article: On the Impact of Industrial Internet of Things (IIoT) — Mining Sector Perspectives. *Mining Technology journal*.
- [14] Appinventiv. IoT in Mining: A Guide to Safer, Faster Operations.
- [15] Open Automation Software. IoT in Mining: Safety, Tracking, and Smarter Operations.
- [16] MCA Solutions. Underground Wireless Communications Support Mining Operations (helical antenna vs. leaky feeder comparison).
- [17] Carroll Technologies Group. Leaky Feeder Wi-Fi Communication Systems in Mines.
- [18] Underground Radio Communications and Personnel Tracking System (patent). LF/MF through-the-earth attenuation and post-disaster survivability data.
- [19] Leaky Feeder Light Emitting Diode Lighting System (patent). Background reference to the U.S. 2006 MINER Act post-accident communication requirement.
- [20] Advances in Autonomous Navigation for Underground Mining Operations: Driven by Camera, LiDAR, and Radar-Based SLAM. *ScienceDirect*.
- [21] Encardio Rite. Smart Safety Measures for Coal Mines.
- [22] Preventing Coal Mine Disasters Through Smart Monitoring and Safety Measures. *smemonitoring.co.za*.
- [23] A Wireless Sensor Network for Coal Mine Safety Powered by Modified Localization Algorithm. *ScienceDirect*.
- [24] Research on Intelligent Monitoring and Protection Equipment of Vital Signs of Underground Personnel in Coal Mines: Review. *PMC / NCBI*.
- [25] Fibre Optic Sensors for Coal Mine Hazard Detection. *ScienceDirect*.
- [26] Intelligent Monitoring and Early-Warning Device and Method for Rock Burst Based on Multi-Field and Multi-Source Information Fusion (patent).

- [27] On IoT Based Underground Mine Environment Monitoring Systems. Proceedings of the 26th International Conference on Distributed Computing and Networking (ACM).
- [28] Teleproject. LoRaWAN for Ski Resorts: IoT Solutions for Smart Mountain Management.
- [29] Continuous Snow-Cover Monitoring and Avalanche Detection with a Novel Sensor Array Box. Sensors (Basel) / MDPI, 2026.
- [30] Long-Term Monitoring of the Sierra Nevada Snowpack Using Wireless Sensor Networks. IEEE Journals & Magazine.
- [31] LoRaWAN Repeater Placement in Complex Terrain: A Field-Tested Strategy Guide. Move Solutions.
- [32] Semtech Corporation. LoRaWAN® Relay: A Battery-Powered Network Extender (White Paper).
- [33] A Critical Review of the Propagation Models Employed in LoRa Systems. PMC / MDPI.
- [34] Diffraction Loss Prediction of Multiple Edges Using Bullington Method with Neural Network in Mountainous Areas. ResearchGate.
- [35] Smartmakers. LoRaWAN Range Explained, Part 2: Range and Coverage of LoRaWAN in Practice.
- [36] GAO Tek. Applications of LoRaWAN & LPWAN in the Environmental Monitoring.
- [37] GAO Tek. Environmental Monitoring Using LoRaWAN Technologies (air, water, carbon, and radiation/hazardous-gas monitoring).
- [38] Semtech Corporation. IoT Applications for Smart Environment with LoRa Technology.
- [39] Mobility of LoRaWAN Gateways for Efficient Environmental Monitoring in Pristine Sites. PMC / NCBI.
- [40] Environmental Monitoring in Uranium Deposit and Indoor Radon Survey in Settlements Located near Uranium Mining Area, South Kazakhstan. Atmosphere / MDPI, 2025.
- [41] Radon Concentration Survey in Settlements Located in Uranium Mining Territory in Northern Kazakhstan. International Journal of Environmental Research and Public Health, 2025.
- [42] Monitoring of Radon and Its Progeny in Underground Uranium Mines. ResearchGate.
- [43] An IoT System for Monitoring Indoor Radon Gas Exposure. ResearchGate.
- [44] An Internet of Radiation Sensor System (IoRSS) to Detect Radioactive Sources Out of Regulatory Control. Scientific Reports / Nature.
- [45] Wireless in Nuclear, Report 2018:513. Energiforsk Nuclear Safety.
- [46] A Wireless Monitoring System for Cracks on the Surface of Reactor Containment Buildings. PMC / NCBI (Daya Bay Nuclear Power Station, China).
- [48] World Nuclear Association. Uranium and Nuclear Power in Kazakhstan (updated 23 October 2026); <https://world-nuclear.org/information-library/country-profiles/countries-g-n/kazakhstan>. 2025 production cross-checked against Kazatomprom 2025 full-year results: https://www.kazatomprom.kz/en/media/view/announces_2025_full_year_financial_results_.
- [49] World Nuclear Association. Kazakhstan — World Nuclear Outlook Report (updated 16 October 2026); <https://world-nuclear.org/our-association/publications/world-nuclear-outlook-report/kazakhstan---world-nuclear-outlook-report>. See also Rosatom, 3 September 2026 EPC contract announcement: <https://atommedia.online/en/press-releases/-rosatom-i-agentstvo-respubliki-kazakhstan-po-atomnoy-energii-podpisali-kontrakt-na-sooruzhenie-aes-/>
- [49] Nuclear Power in Kazakhstan. Wikipedia.

Note: bracketed numbers throughout this report (e.g. [1] or [4,9]) refer to the numbered sources above. Sources were originally compiled in July 2026; selected factual and regulatory references were updated and checked for the October 25, 2026 publication. This report paraphrases and synthesizes publicly available research and industry commentary; no proprietary or confidential technical data is included.

Appendix A: Glossary of Terms

Term	Definition
LoRa	Proprietary chirp spread spectrum (CSS) radio modulation technique used for long-range, low-power wireless communication.
LoRaWAN	Open MAC-layer and network architecture protocol built on top of LoRa, standardized by the LoRa Alliance.
LPWAN	Low-Power Wide-Area Network; a class of wireless technologies designed for long range and low energy consumption at low data rates.
ISM Band	Industrial, Scientific, and Medical radio frequency band, generally unlicensed but regulated by national authorities.
Spreading Factor (SF)	A LoRa configuration parameter controlling the tradeoff between range/robustness and data rate/airtime.
ADR	Adaptive Data Rate; a LoRaWAN mechanism that adjusts spreading factor and transmit power based on link conditions.
RSSI	Received Signal Strength Indicator; a measure of the power level of a received radio signal.
SNR	Signal-to-Noise Ratio; the ratio of desired signal power to background noise power.
PER	Packet Error Rate; the proportion of transmitted data packets that fail to arrive correctly.
FEC	Forward Error Correction; a coding technique that allows a receiver to correct certain transmission errors without retransmission.
EMI	Electromagnetic Interference; disruption of a wireless signal caused by other electrical or electronic sources.
IIoT	Industrial Internet of Things; the application of IoT technologies within industrial and manufacturing settings.
Mesh Topology	A network architecture in which nodes can relay data for one another, as opposed to communicating only with a central hub.
Leaky Feeder	A coaxial cable, run throughout a tunnel or mine, that intentionally radiates and receives radio signal along its entire length, acting as a continuous distributed antenna.
LF/MF Through-the-Earth Communication	Low-frequency or medium-frequency radio systems that couple to a mine's natural rock and coal-seam structure as a waveguide, rather than relying on an installed cable, used mainly for post-disaster survivability.
Fresnel Zone	An ellipsoidal volume of space around the direct line between a transmitter and receiver that must be substantially free of obstructions to avoid diffraction-related signal loss.
Diffraction Loss	Signal loss that occurs when a radio wave bends around an obstruction, such as a ridge line, rather than traveling along a clear line of sight.
TS011 Relay	A LoRa Alliance specification for a standardized, battery-powered LoRaWAN relay device that extends network coverage without requiring mains power or a full gateway installation.
Rock Burst	A sudden, violent failure of stressed rock in an underground mine, often preceded by detectable micro-seismic activity.

Term	Definition
Geotechnical Monitoring	The use of instruments such as extensometers, tiltmeters, and strain gauges to track deformation, stress, and movement in rock or soil, used to anticipate structural failures.
Radon	A naturally occurring radioactive noble gas, produced in the decay chain of uranium, that can accumulate in enclosed spaces such as underground mines or buildings.
Becquerel (Bq)	The standard unit of radioactivity, equal to one radioactive decay event per second; radon concentrations are often expressed in becquerels per cubic metre (Bq/m ³).
Sievert (Sv)	The standard unit for the health effect of ionizing radiation dose; ambient dose rates are commonly expressed in microsieverts per hour (μSv/h).
Radon Progeny	The short-lived radioactive decay products of radon, which contribute most of the radiation dose associated with radon exposure and must be measured on a timescale of minutes rather than as a one-off reading.

Appendix B: Indicative Candidate Site Longlist

The following longlist expands on Table 3 and is intended as a working reference for future site-selection discussions. It describes site types rather than specific named facilities, consistent with the exploratory, pre-agreement stage of this cooperation.

Country	Site Type	Key Stressor Profile	Notes
Kazakhstan	Open-pit mining site	EMI, terrain shielding, moderate-to-severe cold	Strong alignment with existing mining-sector IoT literature
Kazakhstan	Underground mine drift/shaft (gas & structural monitoring)	Rock attenuation, EMI, roof-collapse risk	Requires layered backhaul design per Section 5; strong life-safety rationale
Kazakhstan	Uranium mining region / affected settlements (e.g., Shu-Sarysu, northern KZ)	Long-term radon/gamma monitoring need	Direct evidence base from existing Kazakhstan studies; national significance
Kazakhstan	Vicinity of planned Ulken nuclear power plant site	Long-term environmental/structural baseline monitoring	Forward-looking; construction-phase baseline data has lasting reference value
Kazakhstan	Mountainous ridge/valley site (Tian Shan or Altai foothills)	Diffraction, shadow zones, avalanche risk	Directly tests ridge-line repeater placement from Section 6
Kazakhstan	Remote steppe / agricultural monitoring station	Extreme cold, long range, minimal infrastructure	Closest analogue to published subarctic case studies
Kazakhstan	Oil & gas field installation	Combined thermal extremes, processing-equipment EMI	Requires site-operator cooperation and safety clearance
Kazakhstan	Urban / peri-urban pilot (e.g., Almaty region)	Low-to-moderate stressor baseline	Useful as a control comparison against harsh-site results
China	Northeastern industrial or agricultural site	Severe winter cold	Direct comparison point with Kazakhstan steppe results
China	Western desert site (Xinjiang / Gansu)	Long-range propagation, large diurnal thermal swing	Distinctive contribution not available from Kazakhstan alone
China	High-altitude plateau or avalanche-prone slope	Low oxygen/pressure effects on hardware, cold, terrain, avalanche risk	Requires specialized logistics and safety planning; strong precedent in avalanche literature
China	Underground coal mine (gas & fire monitoring)	Rock attenuation, methane/CO risk, combustion risk	Deep literature base on gas monitoring; requires local operator partnership
China	Established industrial / manufacturing region	Mature IIoT deployment baseline	Benchmark against existing commercial deployments

Table 4. Indicative candidate site longlist for future scoping discussions (illustrative; not a commitment to any specific location).

This independent technical report is provided for scientific, educational and research-planning purposes. It synthesizes published literature and identifies potential LoRa/LPWAN field-validation methods; it does not certify any equipment, network, measurement system or deployment for a particular application.

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Sign-Off and Closing Block

APPROVAL FOR PUBLICATION

This technical report has been reviewed and approved for publication by the Euro-Eurasia Environmental Science & Education Foundation (EEEESEF).

Gelu Negreanu

Founder & Chairman

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