Beyond Access: Rethinking Mobile Application Use Under Variable Connectivity Through a Multi-Layer Framework*

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Abstract

Mobile applications have become essential tools in everyday and professional life, yet how effectively they can be used in rural and Arctic environments remains poorly understood. While research on the digital divide has focused primarily on infrastructure availability and coverage, less attention has been given to how connectivity variability, environmental conditions, device limitations, and application design interact to shape mobile application use in practice. This study examines these conditions in Northern Finland, drawing on survey data collected from 148 respondents across Finnish Lapland and adjacent cross-border areas. The findings reveal that the ability to use mobile applications is shaped by multiple interacting factors rather than connectivity alone. Severe cold, unstable signal quality, seasonal network congestion, device constraints, and limited engagement with service terms and conditions all contribute to variable application performance. Based on these findings, the study proposes a multi-layer framework that integrates infrastructural, environmental, device-level, application-level, and governance-related dimensions. The framework extends IS and digital inclusion perspectives by positioning reliability, variability, and governance accountability as central determinants of mobile application use in infrastructure-sensitive environments.

Keywords

mobile application use, rural connectivity, Arctic environments, digital inclusion, connectivity variability, multi-layer framework, digital inequalities

1. Introduction

Mobile applications and digital services have become deeply embedded in everyday life, supporting communication, navigation, commerce, and entertainment. The performance of these services depends heavily on stable and high-quality network connectivity, as many rely on continuous data exchange and real-time interaction. Consequently, the quality of the underlying communication infrastructure shapes how digital applications are experienced in practice.

While network coverage has expanded considerably in recent years, connectivity conditions remain uneven across geographic regions. In rural and sparsely populated areas, users frequently encounter challenges related to infrastructure limitations, lower network density, and environmental constraints [1, 2, 3]. Studies focusing on northern Europe highlight persistent connectivity gaps in Arctic and rural regions, despite broader advances in digital infrastructure. These challenges are particularly pronounced in northern environments, where long distances, harsh climatic conditions, and dispersed settlements create challenging conditions for communication networks [4]. In such settings, connectivity is not simply a matter of access, but equally a matter of reliability and stability. Variations in signal quality, capacity limitations, and environmental factors can produce fluctuating network performance that directly shapes how digital services are experienced, especially for applications that depend on continuous connectivity [5].

Despite growing infrastructure investment, the ability to use mobile applications effectively in rural environments remains uneven. Existing approaches to the digital divide have largely concentrated on

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infrastructure availability, coverage, and nominal performance indicators such as connection speed [1, 2]. While these metrics offer valuable insight into connectivity provision, they do not fully capture how network conditions are experienced in practice. In many rural and Arctic contexts, connectivity is characterized by variability rather than outright absence. Users may nominally have access to network services yet still encounter unstable signal quality, intermittent connectivity, and performance fluctuations that directly affect the operation of mobile applications, particularly those that rely on real-time interaction or cloud-based processing [5]. Work on rural connectivity has primarily addressed infrastructure deployment and broadband availability [1, 3], while research on distributed systems and edge computing has examined technical challenges such as latency, bandwidth limitations, and adaptive system behavior [6, 7, 8], yet neither strand adequately addresses how infrastructural conditions, environmental variability, device-level constraints, and application design interact to shape lived user experience in rural contexts. Within information systems research, the digital divide has been examined across topics including technology adoption, digital skills, access, use, and social inclusion [9, 10, 11]. However, the specific question of how variable connectivity conditions shape the practical use of mobile applications in rural settings remains underdeveloped in this literature.

This study aims to address that gap by examining how connectivity conditions influence the ability to use mobile applications effectively in rural and infrastructure-constrained environments. Drawing on survey data collected from users in Northern Finland, the study investigates how variations in network performance, environmental conditions, device limitations, and application design features shape how mobile services are experienced in practice. The main contribution is a multi-layer framework for mobile application use in rural Arctic environments that integrates infrastructural, environmental, device-level, application-level, and governance-related factors. In this study, use refers broadly to the ability to use mobile applications effectively, encompassing the conditions that enable or constrain that ability in rural Arctic environments. Derived from empirical findings, the framework provides a structured basis for understanding how different layers interact under variable connectivity conditions. Beyond this conceptual contribution, the study offers empirical insights into user experiences in Arctic and rural contexts, advancing a more nuanced understanding of mobile application use that moves beyond access-based perspectives.

2. Background

Research on rural and remote connectivity has consistently documented disparities in infrastructure deployment, coverage, and service quality between urban and sparsely populated regions [1, 2, 3]. These disparities are attributed to structural factors, including low population density, high deployment costs, and limited commercial incentives for network expansion. In northern and Arctic regions, geographic and environmental conditions intensify these challenges further, as terrain characteristics, long distances between settlements, and extreme weather increase both the technical complexity and cost of providing reliable connectivity [1, 3, 4]. The digital divide in these contexts therefore extends beyond a simple distinction between connected and unconnected populations. It reflects a combination of infrastructural, geographic, and contextual factors that shape both how connectivity is deployed and how it affects the practical use of digital services in everyday life. Despite significant infrastructure investment and the broadening availability of digital services in many rural regions, these structural conditions persist and continue to shape digital experience in ways that aggregate coverage statistics do not adequately capture. IS research has similarly argued that the digital divide in technologically advanced settings is no longer primarily a question of access but of the conditions that shape effective use and use outcomes [9, 12]. Understanding rural connectivity therefore requires attention not only to whether infrastructure exists, but to the conditions under which it operates and the reliability with which it supports the services that users depend on.

A central limitation of access-based perspectives is their reliance on nominal metrics such as coverage availability and advertised broadband speed. Recent research has highlighted that these indicators do not adequately reflect the quality of connectivity as experienced by users under real-world conditions

[5, 13]. Empirical network measurement studies demonstrate that broadband performance varies significantly across users, locations, and time, with substantial differences in throughput, latency, and sensitivity to congestion [13]. In rural and sparsely populated regions, lower infrastructure density and capacity constraints make these fluctuations more pronounced. From a user perspective, even when nominal connectivity is present, instability and performance variability can significantly affect the use of digital services, particularly those that depend on continuous data exchange or real-time interaction. This distinction between nominal access and experienced reliability is significant for how digital inclusion is assessed and addressed, and has been recognized within IS research as a fundamental limitation of access-focused approaches to universal connectivity [11]. Policies and infrastructure strategies oriented around coverage targets may overestimate the quality of digital service use in rural areas, while the everyday experience of users remains shaped by variability that such targets do not measure. Reliability and consistency, rather than coverage alone, are therefore the more meaningful dimensions of connectivity for understanding digital inclusion in rural and Arctic contexts.

These performance characteristics have direct consequences for the technical systems through which digital services are delivered. Modern applications increasingly rely on distributed computing architectures that integrate cloud and edge resources to support data processing, storage, and real-time interaction [14, 15]. In environments where connectivity cannot be assumed to be stable or continuous, intermittent bandwidth and variable latency affect task execution, data synchronization, and system responsiveness [6, 7]. Distributed systems incorporate adaptive mechanisms such as task offloading, local edge processing, and dynamic resource allocation to maintain service continuity under such conditions. However, these mechanisms mitigate but do not eliminate the impact of intermittent connectivity, particularly for coordination and synchronization tasks [6, 8]. This body of work establishes infrastructure conditions as a fundamental constraint in the design and deployment of distributed digital services, though its focus remains primarily on system optimization rather than on the user experience consequences of operating under constrained and variable network conditions.

The use of digital services is shaped not only by technical and infrastructural factors but also by how users interact with applications and interpret system behavior. In environments where connectivity is variable, challenges in using digital services effectively may arise not only from performance degradation but also from how service limitations are communicated and understood. Prior research has shown that users rarely engage meaningfully with formal documentation such as terms and conditions, which are frequently lengthy, legally complex, and poorly suited to everyday comprehension [16, 17]. More recent work has identified broader transparency gaps in connected digital environments, where data practices and system behavior are insufficiently communicated to users [18]. In rural and Arctic contexts these issues carry particular weight, as service performance depends on multiple interacting components including network conditions, device capabilities, and backend infrastructure, yet users may have limited visibility into the causes of disruptions or how responsibility is distributed within service agreements. IS research has called for empirical work that moves beyond access toward understanding digital participation and use outcomes in practice [10, 19]. Yet what remains insufficiently explored is how infrastructural conditions, environmental variability, device-level constraints, and application design interact to shape lived user experience in rural contexts, and how governance mechanisms mediate user understanding of those limitations.

3. Methodology

The study focuses on Northern Finland, particularly Finnish Lapland, along with adjacent cross-border areas including parts of northern Sweden. The region is characterized by long distances between settlements, low population density, and strong reliance on mobile and wireless networks for everyday activities including communication, work, education, and access to services. Key municipalities include Inari, Sodankylä, Kittilä, and Salla, where local livelihoods such as tourism and reindeer herding depend significantly on stable digital connectivity. The Arctic setting introduces additional constraints relevant to this study: harsh climatic conditions, pronounced seasonal variation, and dispersed settlement

structures that make the provision of reliable connectivity both technically demanding and economically challenging. These features make the region a well-suited context for examining how environmental, infrastructure, and spatial factors interact to shape the use of mobile applications. The geographic distribution of survey respondents across the study region is illustrated in Table 1.

Region	Respondents
Northern Lapland (Sodankylä, Inari or Utsjoki)	34.5%
Rovaniemi region (Rovaniemi or Ranua)	14.9%
Fell Lapland (Kittilä, Kolari, Muonio or Enontekiö)	13.5%
Eastern Lapland (Pelkosenniemi, Kemijärvi, Posio, Salla or Savukoski)	10.8%
Kemi–Tornio (Tornio, Tervola, Keminmaa, Kemi or Simo)	8.1%
Northern Sweden	7.4%
Torne Valley (Pello or Ylitornio)	2.7%
Outside primary study area[a]	8.1%

[a]Combines respondents from other Finnish regions (4.7%) and locations outside the primary study region (3.4%).

Table 1
Geographic distribution of survey respondents by region.

Data were collected through an online survey designed to examine connectivity-related experiences and mobile application use in rural environments. The questionnaire comprised 45 items covering everyday and professional use of digital services, including usage patterns, perceived challenges, and expectations related to connectivity. Structured items used single-choice, multiple-choice, and scaled response formats to enable quantitative and categorical analysis, while open-ended questions allowed respondents to elaborate on their experiences beyond the structured responses. The survey was administered over a six-month period between December 2023 and June 2024 using the Webropol platform and was available in both Finnish and English. Distribution was carried out through direct email invitations via a Finnish business information service, outreach through a national reindeer herders' association, publication on partner university websites, and promotion through social media. Participation was voluntary and anonymous. A total of 148 responses were collected, with respondents distributed across Northern Lapland (34.5%), the Rovaniemi region (14.9%), Fell Lapland (13.5%), Eastern Lapland (10.8%), and Northern Sweden (7.4%). The sample was primarily composed of working-age individuals, with the largest age cohorts being 55 to 64 years (29.1%), 45 to 54 years (26.3%), and 35 to 44 years (22.3%). In terms of employment, 51.4% identified as entrepreneurs and 39.9% as employed, representing sectors including tourism (20%), education (19%), and reindeer husbandry (9%).

The analysis combined quantitative and qualitative approaches [20]. Quantitative data from structured items were analyzed using descriptive statistics, including frequency distributions and percentage values, to identify general patterns in mobile application use and user experiences. Qualitative data from open-ended responses were analyzed through systematic thematic grouping [21], with responses reviewed iteratively and organized into categories based on recurring patterns in content and meaning. The qualitative findings were used to contextualize and extend the quantitative results, enabling a more complete understanding of how users experience mobile applications under variable connectivity conditions.

The multi-layer framework presented in the discussion was developed inductively from the thematic findings. Recurring patterns across the five themes were synthesized to identify structural layers and their interrelationships, following an approach to framework construction grounded in empirical data [22]. This process aimed to ensure that the framework reflects the empirical findings rather than imposing a predetermined theoretical structure.

4. Findings

The survey findings are organized around five themes: mobile application use and user requirements, local environmental conditions, user-suggested improvements to mobile application use, engagement with terms and conditions, and cybersecurity experiences. Together they provide a multi-layered

picture of how users in rural and Arctic environments experience mobile applications under variable connectivity conditions.

4.1. Mobile Application Use and User Requirements

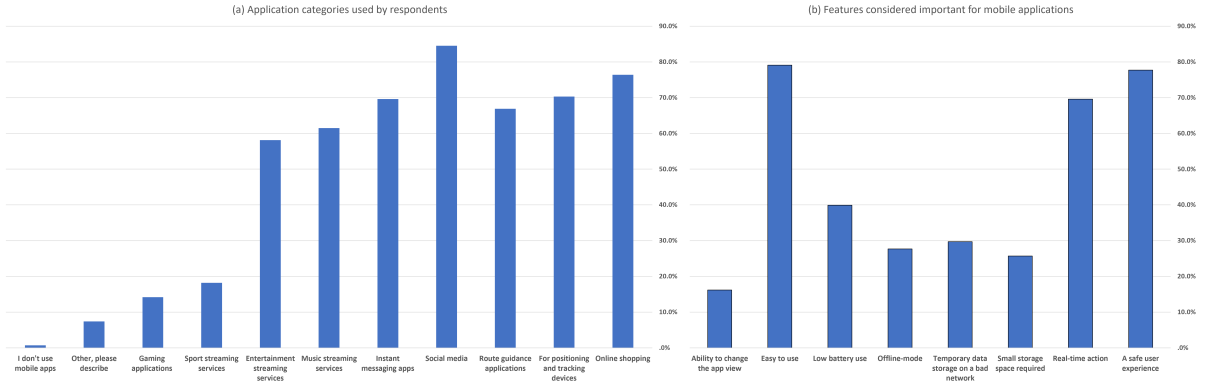


Figure 1: Mobile application usage and user requirements: (a) application categories used by respondents, (b) features considered important for mobile applications. Percentages indicate the proportion of respondents selecting each option.

Respondents reported broad and frequent use of mobile applications across multiple categories (Figure 1a). Social media was the most commonly used category (84.5%), followed by online shopping (76.4%), positioning and tracking applications (70.3%), instant messaging (69.6%), and route guidance (66.9%). Music streaming was reported by 61.5% and entertainment streaming by 58.1% of respondents, while sport streaming (18.2%) and gaming (14.2%) were less common. Only one respondent (0.7%) reported not using mobile applications at all, indicating near-universal adoption across the sample.

Regarding important application characteristics (Figure 1b), ease of use was the most frequently selected feature (79.1%), followed by a safe user experience (77.7%) and real-time functionality (69.6%). Features supporting operation under constrained conditions were also valued: low battery consumption was considered important by 39.9% of respondents, temporary data storage during poor network conditions by 29.7%, and offline mode by 27.7%. Small storage requirements (25.7%) and the ability to customize the visual layout (16.2%) were selected less frequently. These results indicate that respondents prioritize applications that are intuitive, secure, and real-time capable, while a substantial proportion also value features that support functionality under limited connectivity or battery constraints.

4.2. Local Conditions Affecting Application Use

As shown in Figure 2, severe cold was by far the most frequently reported condition hindering mobile application use (56.8%), reflecting the Arctic character of the study region. Other conditions included loud wind or background noise (20.9%), humidity (19.6%), sun glare (13.5%), and darkness (4.1%). A total of 17.6% indicated that local conditions do not hinder their application use. Among the 15.5% who selected other and provided open-ended responses, four main categories emerged. The most frequent concerned poor network connectivity and infrastructure, including weak or unstable signal quality, lack of coverage, insufficient base station density, and recurring local network malfunctions. A second category related to geographic and terrain-related barriers, where landscape features such as elevation differences and uneven terrain were reported to obstruct signal reception. A third category concerned weather-related challenges beyond severe cold, including heavy snowfall and snowstorms that can further disrupt network stability. The fourth category involved network congestion linked to tourism and seasonal peaks in user density, where respondents reported reduced connection quality in areas near tourist destinations during high-demand periods. A small number of responses also referenced structural constraints such as proximity to national borders and lack of electricity access. These findings suggest that environmental conditions and infrastructural limitations are closely intertwined in the

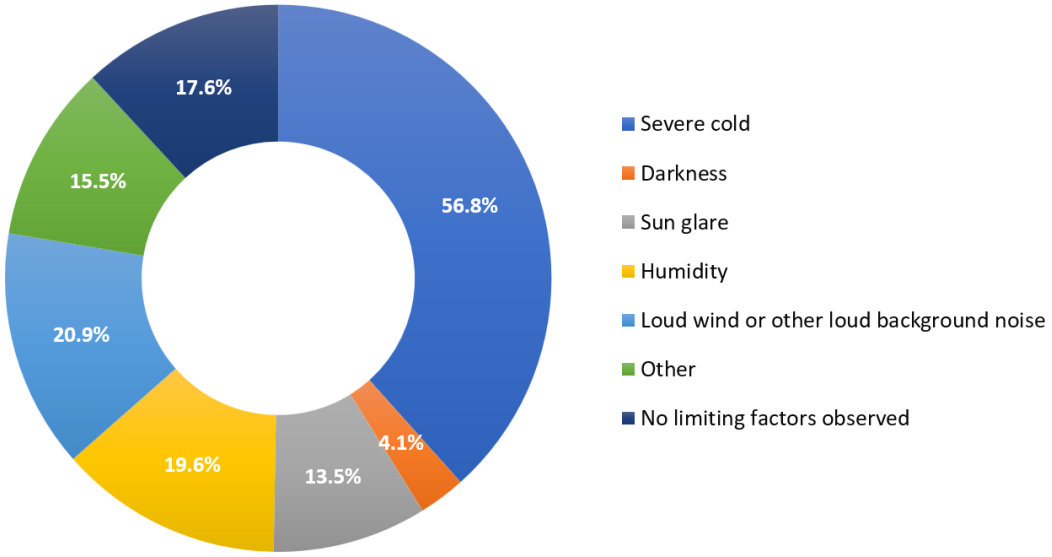


Figure 2: Environmental conditions affecting mobile application use.

Arctic context, and that the challenges users face extend well beyond physical exposure to harsh weather.

4.3. User-Suggested Improvements to Mobile Application Use

Thematic analysis of open-ended responses identified four categories of suggested improvement. The most frequently expressed suggestions concerned network infrastructure. Respondents emphasized that problems with mobile application use are fundamentally linked to weak or unstable connectivity, and proposed increasing bandwidth, adding base stations and antennas, reducing distances to masts, and expanding fiber-optic networks. As one respondent stated: ”To start with, phones and Internet should work throughout the country. I now live on the outskirts of the city center and even here my phone doesn’t always have reception.” These responses indicate that users view reliable basic connectivity as the primary prerequisite for improved mobile application use.

A second theme concerned connectivity stability during adverse weather, with respondents noting that network instability increases during weather events, suggesting that existing infrastructure lacks sufficient resilience to environmental stress and seasonal variation. A third theme related to device hardware performance in cold climates, where low temperatures reduce battery life and device functionality; respondents proposed enhanced battery management, frost resistance, and battery heating solutions. The fourth theme focused on application-level design adaptations, including offline functionality, improved battery efficiency, customizable contrast settings for bright sunlight conditions, and voice control to reduce manual input in cold conditions. As one respondent noted: ”Voice control, so you don’t have to freeze your hands in the cold.”

Across all themes, infrastructure-level improvements were most consistently emphasized as the foundational requirement.

4.4. Terms and Conditions and User Engagement

Respondents were asked whether terms and conditions clearly address problems caused by connectivity issues. Only 17.0% considered them clear, while 28.6% stated they are not clear. A large proportion reported limited engagement: 24.5% use applications without reading the terms and conditions, and 29.9% do not remember their content. Thematic analysis identified six recurring barriers. The most prominent was excessive document length, with essential information difficult to locate within large volumes of text. A second barrier concerned linguistically complex and legally inaccessible language. A third related to lack of time or motivation to engage with lengthy documents. A fourth involved

interface and accessibility issues, including small font sizes, cognitive challenges such as dyslexia, and slow-loading documents. A fifth concerned lack of trust, with terms perceived as instruments that shift responsibility to the user rather than providing neutral information. Finally, a smaller group indicated limited awareness of what terms and conditions are meant to regulate, suggesting that formal disclosure mechanisms may not fulfil their intended informational function in practice.

4.5. Cybersecurity Experiences

A total of 41.5% of respondents reported having encountered cybersecurity-related issues, while 58.5% reported no such experiences. Qualitative responses were limited, with only two detailed accounts provided, covering impersonation and scam attempts via messaging applications and a general call for greater digital literacy in rural areas where access to support may be limited. Given the limited qualitative data, broader conclusions cannot be drawn. Nevertheless, the proportion of security-related experiences points to a relevant dimension of digital service use in this context that warrants further investigation.

Across the five themes, mobile applications emerge as deeply embedded in everyday and professional life, yet the ability to use them effectively is consistently shaped by the interplay of infrastructural, environmental, device-level, and design-related factors. Severe cold and network infrastructure limitations stand out as the most prominent constraints, while limited engagement with terms and conditions points to a governance dimension that sits alongside the technical challenges. These patterns collectively motivate the multi-layer framework developed in the following section.

5. Discussion

The findings of this study reveal that the ability to use mobile applications in rural and Arctic environments is shaped by a combination of structural, environmental, device-level, application-level, and governance-related factors rather than any single constraint. Although mobile applications are deeply embedded in everyday and professional life across communication, navigation, commerce, and entertainment, the conditions under which these services are experienced vary considerably. Infrastructural limitations emerge as the primary constraint, yet their effects are amplified by environmental exposure and mediated by the capabilities of devices and applications. Limited engagement with terms and conditions further indicates that formal transparency mechanisms do not adequately support user awareness of service limitations. Together, these findings motivate a shift from access-based interpretations of digital inclusion toward a layered understanding of mobile application use that better reflects the realities of infrastructure-sensitive rural environments.

5.1. A Multi-Layer Framework for Mobile Application Use in Rural Arctic Environments

The empirical findings suggest that the ability to use mobile applications in rural contexts is shaped by interacting structural layers rather than a single overriding constraint. Based on these findings, this study proposes a multi-layer framework in which each layer contributes distinct capabilities and constraints, and in which lower layers set the conditions under which upper layers can operate effectively. Figure 3 illustrates the five layers and their dependency structure.

At the foundation lies the infrastructure layer, encompassing network coverage, bandwidth capacity, base station density, and network stability. Respondents consistently identified weak signal strength, insufficient masts, seasonal congestion during tourism peaks, and limited fiber infrastructure as the primary determinants of mobile application use, positioning infrastructure reliability as the fundamental condition that enables or constrains all other layers.

Above this sits the environmental layer, comprising severe cold, snowfall, wind, terrain differences, and seasonal variability. With 56.8% of respondents identifying severe cold as a primary hindrance, and open-ended responses highlighting snowstorms, terrain obstructions, and tourism-related demand

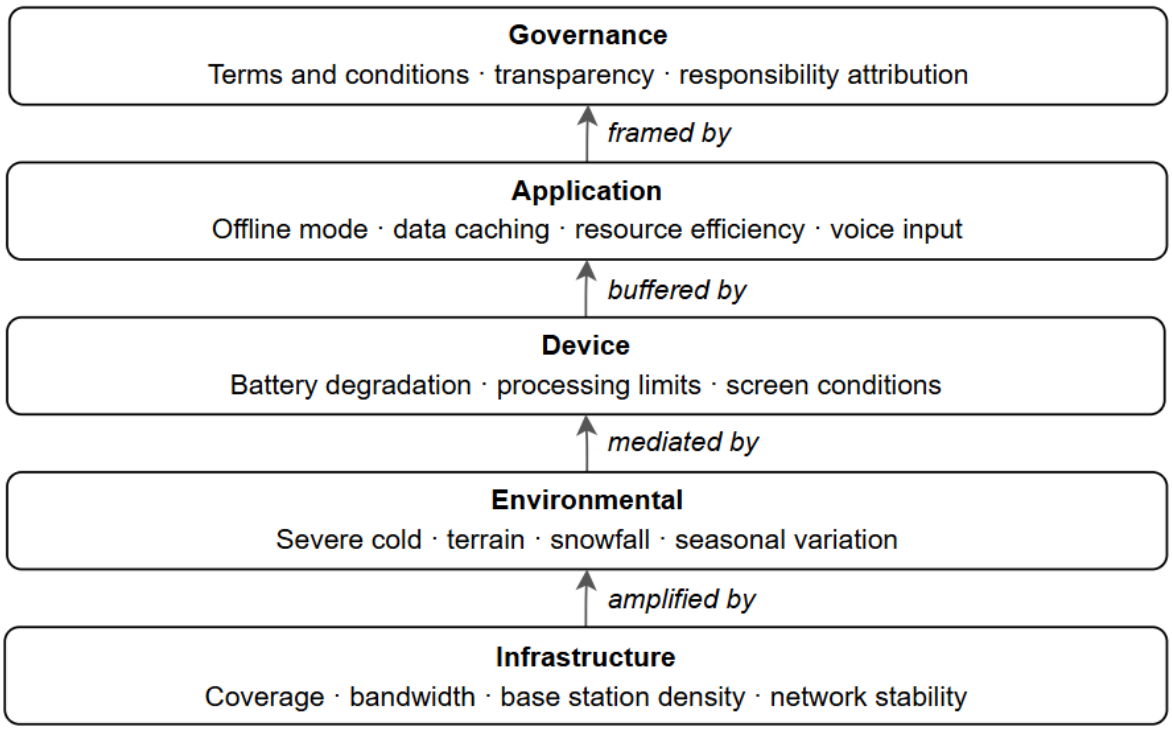


Figure 3: Multi-layer framework for mobile application use in rural Arctic environments, ordered by structural dependency

surges, environmental conditions emerge as an amplifier of infrastructural constraints. Cold temperatures degrade battery performance and reduce device responsiveness, while terrain and precipitation disrupt signal propagation.

The device layer captures the technical capabilities and physical limitations of user hardware. Battery degradation in cold conditions and slower device operation at low temperatures were recurring themes, with 39.9% rating low battery consumption as an important application feature. Device limitations mediate how environmental and infrastructural conditions translate into the user-facing experience.

The application layer encompasses design features such as offline functionality, data caching, resource efficiency, and alternative interaction methods. Respondents proposed voice control for cold-weather use, customizable contrast settings for Arctic light conditions, and offline modes to maintain continuity under unstable connectivity. These features can partially buffer the effects of lower-layer constraints, though application-level adaptations cannot fully compensate when underlying infrastructure remains unreliable.

The outermost layer is governance, encompassing transparency mechanisms, responsibility allocation, and user awareness of service conditions. Only 17.0% of respondents considered terms and conditions clear, while 24.5% reported using applications without reading them and 29.9% did not recall their content. Governance functions not as a technical determinant of mobile application use but as an interpretive frame shaping how service failures are understood and attributed.

These layers do not operate independently. Infrastructure instability cascades upward, amplifying the consequences of environmental stress and constraining what application design can achieve. Application features can absorb some of this pressure but remain bound by the infrastructure beneath them. Governance mechanisms shape whether users can anticipate and make sense of the disruptions they encounter. Table 2 summarizes the key dimensions, empirical evidence, implications for mobile application use, and design and policy responses associated with each layer, presented in order from the foundational infrastructure layer upward.

Table 2
Multi-dimensional analysis of layers shaping mobile application use in rural Arctic environments

Layer	Key dimensions	Empirical evidence	Implications for mobile application use	Design and policy response
Infrastructure *Foundation*	Coverage; bandwidth; base station density; fiber; network stability; congestion	Weak signals and sparse masts cited as primary barrier; Seasonal congestion near tourist areas; Largest respondent share from low-density coverage areas	Determines baseline availability; Variability propagates to all upper layers; Nominal coverage does not ensure reliable performance	Targeted base station investment; fiber extension; seasonal capacity planning; reliability metrics beyond advertised speed
Environmental *Amplifies infrastructure*	Temperature; precipitation; wind; terrain; seasonal variation	Severe cold is most frequently reported hindrance; Snowstorms and terrain obstructions raised in open responses	Reduces signal stability and coverage; Seasonal peaks strain network and device capacity simultaneously	Weatherproof infrastructure; terrain-aware antenna placement; seasonal capacity modelling
Device *Mediates impact*	Battery capacity; cold-weather degradation; processing speed; screen visibility	Battery degradation and slower operation in cold widely reported; Low battery consumption rated a priority application feature	Mediates how lower-layer constraints reach the interface; Device failure in cold compounds connectivity problems	Cold-resistant hardware; battery management optimization; adaptive power modes; screen adjustment for Arctic light
Application *Partial buffer*	Offline mode; caching; resource efficiency; adaptive UI; voice input; real-time dependency	Ease of use and real-time functionality rated most important; Offline mode and temporary storage valued under poor connectivity; Voice control proposed for cold conditions	Partial compensation via graceful degradation and local processing; Effectiveness bounded by infrastructure stability	Offline-first design; local caching; voice interfaces; bandwidth-efficient protocols; adaptive UI for light and device states
Governance *Interpretive frame*	Terms and conditions clarity; transparency; responsibility allocation; digital literacy	Majority found terms unclear or did not engage with them; Barriers: length, legal language, distrust	Shapes how failures are interpreted and attributed; Low transparency widens gap between system behavior and user expectations	Plain-language summaries; context-specific disclosures; clearer responsibility attribution; rural digital literacy investment

5.2. Theoretical Implications

The five layers and their interactions have implications for how rural digital inclusion and mobile application use are theorized and studied. The multi-layer framework extends access-based perspectives on the digital divide by conceptualizing mobile application use as the outcome of interacting structural conditions rather than a function of coverage or speed alone. While prior research has documented persistent infrastructure disparities between urban and rural regions [1, 2, 3], these accounts tend to treat access as the primary analytical category. The present findings demonstrate that access, even when nominally present, does not guarantee consistent or reliable digital service use. This aligns with

the IS argument that universal access initiatives focus on physical connectivity but cannot ensure meaningful use [11]. The framework extends IS research on digital inequalities by examining how infrastructural, environmental, and governance conditions interact to shape use outcomes in a rural Arctic context [9, 10]. This positions reliability and stability as the conceptually central dimensions of connectivity in rural and Arctic contexts, consistent with recent calls to look beyond broadband speed as the dominant metric [5, 13].

The framework also contributes to research on distributed and mobile computing by grounding infrastructure-level constraints within a user experience perspective. Prior work has examined how latency, bandwidth limitations, and intermittent connectivity affect system responsiveness [6, 7, 8], primarily from a system optimization standpoint. The present study connects these technical dimensions to lived user experience in infrastructure-constrained environments, demonstrating that the consequences of connectivity variability are shaped not only by network architecture but also by environmental exposure, device limitations, and application design.

The governance layer contributes further theoretical insight by situating transparency and responsibility allocation within the broader system shaping mobile application use. Existing research has documented low engagement with digital agreements [16, 17] and identified transparency gaps in connected environments [18]. This study extends that literature by showing that governance failures carry particular consequences where service variability is frequent, widening the gap between formal service definitions and user experience. Governance is thus theorized not as peripheral to mobile application use but as an integral layer shaping how the system is interpreted by users.

5.3. Practical Implications

For application and system design, the results indicate that variable connectivity should be treated as a baseline condition rather than an exception. Applications should incorporate offline functionality, local data caching, and efficient synchronization capable of maintaining effective use when network conditions fluctuate. Resource efficiency is important given the interplay between cold temperatures and battery performance. Voice-based interaction represents a relevant design consideration given respondents' suggestions to reduce manual input demands under cold exposure. These adaptations are necessary but bounded: application design should account for the likelihood that minimum infrastructure thresholds will be breached, making graceful degradation and local processing structural requirements rather than optional enhancements.

For infrastructure planning, the findings point toward a shift in emphasis from nominal coverage to reliability and consistency. Respondents were less constrained by the absence of connectivity than by its variability, including fluctuating signal quality, capacity limitations during seasonal demand peaks, and terrain-related coverage gaps. Effective infrastructure strategies require capacity modelling that accounts for seasonal tourism-driven demand, terrain-aware antenna placement, and weatherproofing suited to Arctic conditions. The repeated references to insufficient mast density suggest that network topology is a critical determinant of service quality that uniform coverage targets alone do not address.

For policy and digital inclusion, the study supports reorienting evaluation frameworks away from binary access indicators. Coverage availability and advertised connection speeds inadequately capture operational user experience in environments where connectivity is variable rather than absent, reflecting a broader pattern in which access metrics fail to account for the tangible conditions that shape everyday digital participation [12]. Policymakers should consider supplementing these metrics with reliability indicators and application-level functionality assessments under real-world conditions. The findings on governance engagement indicate that formal transparency mechanisms do not effectively communicate service limitations to users. More accessible, plain-language disclosure of how network variability affects performance, combined with digital literacy investment in rural communities, would better support informed digital participation.

5.4. Limitations and Future Research

The study has several limitations. The survey was conducted in a specific regional context, Northern Finland and adjacent cross-border areas, which limits the direct generalizability of findings to other rural or Arctic environments. The sample, though occupationally diverse, was self-selected and composed primarily of working-age adults, which may underrepresent populations with lower levels of digital service engagement. Reliance on self-reported data means that perceptions of mobile application use reflect subjective experience rather than objectively measured network performance, and the cross-sectional design cannot capture how connectivity variability shifts across seasons.

Future research should pursue longitudinal and measurement-based studies that document real-world network performance variation over time and across locations, complementing self-reported perceptions with objective connectivity data. Empirical validation of the multi-layer framework in other rural, remote, or environmentally exposed contexts would assess its broader applicability. Research on the deployment of AI-enabled and edge computing applications in rural settings is a priority area, as these services depend on data exchange patterns that are acutely sensitive to the kinds of infrastructure variability documented here. More broadly, future research could examine how rural communities and digital infrastructures maintain functioning under persistently constrained connectivity conditions, addressing questions of sociotechnical resilience that the present study points toward but does not fully explore. Finally, the governance layer merits further investigation. Research on alternative transparency approaches, such as contextual disclosure and plain-language service status communication, would inform both the theoretical development of the framework and the design of more effective governance in variable-connectivity environments.

6. Conclusion

This study examined how connectivity conditions, environmental factors, device limitations, and application design jointly shape the ability to use mobile applications effectively in rural and Arctic environments. The findings demonstrate that access alone does not adequately explain how digital services are experienced in practice. Even where connectivity is nominally available, signal variability, seasonal congestion, cold-related device constraints, and limited application adaptability combine to reduce effective mobile application use in ways that access-based metrics do not capture. The study proposed a multi-layer framework that conceptualizes mobile application use as the outcome of interactions between infrastructure, environmental conditions, device capabilities, application design, and governance. The framework extends existing digital inclusion perspectives by positioning reliability, variability, and governance accountability as central dimensions of rural digital service experience. As digital services become more deeply embedded in everyday and professional life in remote regions, and as advanced applications increasingly depend on continuous data exchange, understanding the layered conditions under which these services operate becomes more rather than less important. The framework offers a structured basis for that understanding, with implications for the design, deployment, and governance of digital services in infrastructure-sensitive environments.

Declaration on Generative AI

During the preparation of this manuscript, the first author used Claude Sonnet 4.6 (Anthropic) to correct grammar, refine language, and adjust the academic tone. The first author reviewed and edited all AI-assisted content and takes full responsibility for the final version of the manuscript.

References

[1] E. A. Mack, S. Loveridge, T. Keene, J. Mann, A review of the literature about broadband internet connections and rural development (1995-2022), International Regional Science Review 47 (2024)

231–292.
[2] S. Dempsey, A. Hoy, Exacerbating the divide? Investigating rural inequalities in high speed broadband availability, Telecommunications Policy 48 (2024) 102819.
[3] A. Marshall, A new rural digital divide? Taking stock of geographical digital inclusion in Australia, Media International Australia 190 (2024) 68–84.
[4] P. Karppinen, S. Bandaranayake, L. Haukipuro, Y. Elmistikawy, H. Saarnisaari, Gaps in value-driven connectivity: A case study on connectivity challenges in Northern Europe, in: 2024 IEEE 35th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), IEEE, 2024, pp. 1–6.
[5] K. L. Rush, C. L. Seaton, A.-I. Louloudi, E. P. Li, K. Hasan, Looking beyond digital broadband speeds: Rural British Columbian's experiences with internet connectivity as a basic necessity, PLoS One 20 (2025) e0330347.
[6] T. Deng, Z. Yu, D. Yuan, Task offloading optimization in mobile edge computing under uncertain processing cycles and intermittent communications, Computer Networks 245 (2024) 110359.
[7] X. Xu, S. Zang, M. Bilal, X. Xu, W. Dou, Intelligent architecture and platforms for private edge cloud systems: A review, Future Generation Computer Systems 160 (2024) 457–471.
[8] A. Carvalho, D. Riordan, J. Walsh, A novel edge platform streamlining connectivity between modern edge devices and the cloud, Future Internet 16 (2024) 111.
[9] P. Vassilakopoulou, E. Hustad, Bridging digital divides: A literature review and research agenda for information systems research, Information Systems Frontiers 25 (2023) 955–969.
[10] I. N. Tanyel, J. B. Windeler, T. Syn, A. Ramaprasad, Social inclusion/exclusion in information systems: A review and roadmap for research, Information Systems Journal 35 (2025) 1311–1343.
[11] P. Racherla, M. Mandviwalla, Moving from access to use of the information infrastructure: A multilevel sociotechnical framework, Information Systems Research 24 (2013) 709–730.
[12] E. Helsper, The Digital Disconnect: The Social Causes and Consequences of Digital Inequalities, SAGE Publications, 2021.
[13] D. P. Reed, J. Schnitzer, D. Sekar, Benchmarking Internet Progress: Analysis of FCC's Broadband Performance Data, Technical Report, 2025.
[14] M. Ergen, B. Saoud, I. Shayea, A. A. El-Saleh, O. Ergen, F. Inan, M. F. Tuysuz, Edge computing in future wireless networks: A comprehensive evaluation and vision for 6G and beyond, ICT Express 10 (2024) 1151–1173.
[15] F. Golpayegani, N. Chen, N. Afraz, E. Gyamfi, A. Malekjafarian, D. Schäfer, C. Krupitzer, Adaptation in edge computing: a review on design principles and research challenges, ACM Transactions on Autonomous and Adaptive Systems 19 (2024) 1–43.
[16] J. A. Obar, A. Oeldorf-Hirsch, The biggest lie on the internet: Ignoring the privacy policies and terms of service policies of social networking services, Information, Communication & Society 23 (2020) 128–147.
[17] Y. Javed, A. Sajid, A systematic review of privacy policy literature, ACM Computing Surveys 57 (2024) 1–43.
[18] A. I. Hudig, A. M. Mandalari, C. Norval, H. Haddadi, R. Binns, J. Singh, Rights out of sight: Data practices and transparency gaps in smart consumer IoT ecosystems, in: Proceedings of the 2025 ACM Conference on Fairness, Accountability, and Transparency, 2025, pp. 2260–2273.
[19] S. Park, J. Freeman, C. Middleton, M. Allen, R. Eckermann, R. Everson, The multi-layers of digital exclusion in rural Australia, in: 2015 48th Hawaii International Conference on System Sciences, IEEE, 2015, pp. 3631–3640.
[20] J. W. Creswell, J. D. Creswell, Research Design: Qualitative, Quantitative, and Mixed Methods Approaches, 5th ed., SAGE, 2018.
[21] V. Braun, V. Clarke, Using thematic analysis in psychology, Qualitative Research in Psychology 3 (2006) 77–101.
[22] S. M. Ravitch, M. Riggan, Reason & Rigor: How Conceptual Frameworks Guide Research, 2nd ed., SAGE, 2016.