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Research Article

WIRELESS COMMUNICATION TECHNOLOGIES ENABLING RELIABLE INTERNET OF THINGS SMART FARMING APPLICATIONS

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Abstract

The rapid expansion of smart farming systems has intensified the need for reliable wireless communication infrastructures capable of supporting Internet of Things (IoT) applications in heterogeneous agricultural environments. Ensuring stable connectivity in rural areas characterized by large coverage demands, energy constraints, and environmental interference remains a critical challenge. This study aims to evaluate wireless communication technologies and identify optimal configurations that enable reliable IoT-based smart farming operations. A mixed-method research design integrating large-scale field experiments and simulation-based scalability analysis was employed to assess LoRaWAN, NB-IoT, Zigbee, Wi-Fi, and 5G IoT modules. Reliability was measured using packet delivery ratio, latency, coverage range, scalability, and energy consumption indicators. Results indicate that no single technology achieves optimal performance across all reliability dimensions. LPWAN technologies demonstrated superior energy efficiency and wide-area coverage, while 5G achieved the lowest latency and highest throughput. Hybrid communication architectures consistently outperformed single-technology deployments, improving packet delivery ratio and operational resilience under varying environmental conditions. The study concludes that context-aware integration of complementary wireless technologies provides the most reliable and sustainable solution for smart farming IoT ecosystems.

Keywords: Internet of Things, LPWAN, Smart Farming, Wireless Communication, 5G IoT

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INTRODUCTION

Rapid population growth, climate variability, and resource constraints have intensified the demand for sustainable and high-productivity agricultural systems (Long et al., 2025). Smart farming has emerged as a transformative paradigm that integrates sensing, data analytics, automation, and connectivity to optimize agricultural operations. Internet of Things (IoT) technologies enable continuous monitoring of soil moisture, crop health, livestock behavior, and environmental conditions, thereby supporting data-driven decision-making (Shao & Zhang, 2025). Wireless communication technologies form the backbone of these IoT ecosystems, facilitating real-time data exchange between distributed sensors, edge devices, cloud platforms, and control systems (Y. Zhang et al., 2025). Reliable connectivity becomes a foundational requirement in ensuring that smart farming applications operate efficiently, especially in geographically dispersed and infrastructure-limited rural environments.

Agricultural fields often span large and heterogeneous terrains characterized by limited power supply, sparse network infrastructure, and challenging propagation conditions (Pennanen et al., 2025). Harsh environmental factors such as humidity, temperature fluctuations, foliage density, and terrain variability introduce significant signal attenuation and interference (Priya et al., 2025). IoT devices deployed in such contexts are typically battery-powered and expected to operate for extended periods without maintenance (Aldawsari, 2025). Wireless communication technologies used in smart farming must therefore balance coverage, energy efficiency, latency, scalability, and data reliability (Siddiky et al., 2025). Emerging solutions such as low-power wide-area networks (LPWAN), cellular IoT, and short-range wireless protocols present diverse trade-offs that require systematic evaluation within the agricultural domain.

Digital transformation in agriculture is not merely a technological trend but a strategic necessity to achieve food security and environmental sustainability (Singh et al., 2025). Precision irrigation, automated fertilization, pest detection, and yield forecasting depend heavily on timely and accurate data transmission (Abdulhussain et al., 2025). Unreliable connectivity can lead to delayed interventions, resource wastage, and economic losses for farmers (Zanbouri et al., 2025). The growing adoption of smart farming systems underscores the need for communication frameworks that guarantee reliability under real-world constraints (Saeed et al., 2025). A comprehensive understanding of wireless communication technologies and their suitability for reliable IoT-based agricultural applications is therefore essential to advance both research and practice in this domain.

Despite the rapid proliferation of IoT solutions in agriculture, ensuring reliable wireless communication remains a persistent challenge. Agricultural deployments often rely on heterogeneous networks composed of multiple protocols such as LoRaWAN, NB-IoT, Zigbee, Wi-Fi, and 5G (Ahmed et al., 2025). Each technology exhibits specific strengths and limitations in terms of range, bandwidth, energy consumption, latency, and infrastructure requirements (J. Huang et al., 2025). The absence of a unified framework for evaluating and selecting appropriate communication technologies leads to fragmented implementations and inconsistent system performance (Shin et al., 2025). Reliability issues manifest in packet loss, high latency, limited coverage, and network congestion, all of which compromise the effectiveness of smart farming applications.

Scalability presents another critical problem as the number of connected devices in agricultural environments continues to grow (Hudda & Haribabu, 2025). Large-scale deployments involving hundreds or thousands of sensors can strain network capacity, particularly in rural areas with limited spectrum availability and weak backhaul connectivity (H. Wang et al., 2025). Energy constraints further complicate system design, since IoT nodes must maintain long battery life while sustaining consistent data transmission (X. Huang et al., 2025). Inadequate optimization of communication parameters such as transmission power, data rate, and duty cycle often results in inefficient resource utilization (Ling et al., 2025). Existing implementations frequently overlook the interplay between environmental factors and network performance, thereby limiting the robustness of deployed systems.

Security and resilience also constitute significant concerns in wireless IoT-based farming systems (Kong et al., 2025). Agricultural data, including crop health metrics and operational commands for automated equipment, must be transmitted securely to prevent unauthorized access or manipulation (Hu et al., 2025). Interference, cyber threats, and network failures can disrupt mission-critical operations such as irrigation control or disease monitoring (Wen et al., 2025). Limited research has comprehensively addressed the integration of reliability, energy efficiency, scalability, and security within a unified wireless communication strategy for smart farming (Aouedi et al., 2025). Addressing these multifaceted challenges requires a systematic investigation into how wireless technologies can be configured and integrated to ensure dependable performance in diverse agricultural contexts.

This study aims to analyze and evaluate wireless communication technologies that enable reliable IoT-based smart farming applications (Q. Wang et al., 2025). The primary objective is to identify key performance indicators that determine communication reliability in agricultural environments, including coverage range, latency, packet delivery ratio, energy efficiency, and network scalability (Yue et al., 2025). The research seeks to develop a structured framework for comparing different wireless technologies based on these metrics (Sun et al., 2025). Clear identification of technological strengths and limitations is expected to support informed decision-making in system design and deployment.

Another objective of this research is to investigate the impact of environmental and operational factors on wireless communication performance in smart farming settings (Ouda et al., 2025). Terrain characteristics, vegetation density, climatic conditions, and device distribution patterns can significantly influence signal propagation and network stability (Federico et al., 2025). The study intends to assess how adaptive communication strategies, such as dynamic data rate adjustment and multi-tier network architectures, can enhance reliability under varying conditions (Tian et al., 2025). Emphasis will be placed on optimizing trade-offs between energy consumption and communication quality to ensure sustainable long-term operation of IoT devices.

The research further aims to propose an integrative communication model that enhances reliability while maintaining cost-effectiveness and scalability (Seidel & Stewart, 2011). Practical guidelines for selecting and configuring wireless technologies will be developed to assist researchers, system integrators, and agricultural stakeholders (Du et al., 2025). The expected outcome includes recommendations for hybrid communication architectures that combine complementary technologies to mitigate individual limitations (Asadi Aghajari et al., 2025). Achieving these objectives will contribute to advancing reliable connectivity solutions tailored specifically to the demands of smart farming ecosystems.

Existing literature on IoT-based smart farming predominantly focuses on sensor development, data analytics, and application-level optimization, while comparatively less attention is given to the systematic evaluation of wireless communication reliability (Cao et al., 2025). Numerous studies examine individual technologies such as LoRaWAN or NB-IoT in isolation, often under controlled experimental conditions (Khan et al., 2025). Limited comparative analyses have been conducted to assess how multiple wireless technologies perform across diverse agricultural scenarios (Ahn et al., 2025). This fragmented approach results in knowledge silos that hinder the development of comprehensive communication strategies.

Current research frequently emphasizes theoretical performance metrics without adequately addressing real-world deployment challenges (Zhao et al., 2025). Field-level factors such as signal obstruction by crops, interference from agricultural machinery, and variable weather conditions are not consistently incorporated into performance evaluations (P. Zhang et al., 2025). Few studies integrate considerations of energy efficiency, scalability, and security within a single analytical framework (Luo et al., 2025). Lack of cross-layer analysis between physical, network, and application layers further restricts understanding of how communication reliability influences overall system effectiveness.

Insufficient attention has been given to the design of adaptive and hybrid communication architectures tailored to dynamic agricultural environments (W. Zhu et al., 2025). Most implementations rely on single-technology solutions, which may not be optimal for heterogeneous farm settings (Yu et al., 2025). Comprehensive frameworks that align technological capabilities with specific agricultural use cases remain underdeveloped (Qi et al., 2025). Addressing this research gap requires a holistic examination of wireless communication technologies, incorporating empirical evidence, performance modeling, and contextual analysis specific to smart farming applications.

The novelty of this research lies in its integrative approach to evaluating wireless communication technologies specifically from the perspective of reliability in smart farming IoT applications (Bokhtiar Al Zami et al., 2025). Unlike prior studies that examine isolated performance metrics, this work synthesizes multiple dimensions, including coverage, latency, energy efficiency, scalability, and security, within a unified analytical framework (Shao et al., 2025). Emphasis on context-aware evaluation differentiates this study by aligning communication performance with real agricultural operational requirements (Akram et al., 2025). The proposed framework seeks to bridge theoretical analysis and practical deployment considerations.

Innovation is further reflected in the development of a comparative and adaptive communication model tailored to heterogeneous farming environments. Hybrid architectures that leverage complementary strengths of LPWAN, cellular IoT, and short-range protocols are systematically explored. Adaptive strategies such as intelligent routing, dynamic bandwidth allocation, and energy-aware transmission schemes are examined to enhance network resilience. Integration of reliability assessment with environmental variability analysis contributes a novel perspective that extends beyond conventional network performance studies.

The justification for this research stems from the increasing dependency of modern agriculture on reliable digital infrastructures. Sustainable food production, resource optimization, and climate resilience rely on dependable IoT systems capable of operating under challenging rural conditions. Practical implications of this study include improved system design guidelines and enhanced decision support for stakeholders adopting smart farming technologies. Advancing knowledge in reliable wireless communication for agricultural IoT systems will support broader goals of technological innovation, environmental sustainability, and global food security.

RESEARCH METHOD

Research Design

The study employs a mixed-method research design that integrates experimental evaluation with simulation-based performance analysis to investigate wireless communication reliability in IoT smart farming (An, Debbah, et al., 2025). This design utilizes a comparative and analytical framework to assess various wireless technologies under realistic agricultural conditions, combining field deployment for empirical data with network simulations for modeled characteristics (X. Zhu et al., 2025). By measuring multidimensional constructs such as connectivity stability, data integrity, and resilience to interference, the design ensures a robust cross-technology comparison while maintaining internal validity through the control of environmental and operational variables.

Research Target/Subject

The research target encompasses a population of wireless communication technologies commonly adopted in smart farming, specifically focusing on LPWAN protocols, cellular IoT, and short-range wireless standards (Koulouras et al., 2025). Purposive sampling was used to select representative technologies LoRaWAN, NB-IoT, Zigbee, Wi-Fi, and 5G based on their maturity and suitability for agricultural deployment (Ianculescu et al., 2025). The subjects include sensor nodes equipped with environmental sensors deployed across heterogeneous rural sites, using a stratified sampling approach to ensure the system is tested across diverse terrain types, vegetation densities, and varying levels of signal obstruction.

Research Procedure

The research procedure was executed in a systematic sequence, beginning with the development of a performance evaluation framework that standardized sensing intervals and payload sizes. This was followed by field deployment in agricultural plots to assess signal attenuation and coverage range over defined observation periods to capture temporal variability. Controlled stress tests were then performed by increasing node density to evaluate scalability and congestion resilience. Finally, simulation-based experiments modeled extended deployment scenarios, and the collected data were cleaned and validated for comparative reliability analysis across all selected technologies.

Instruments, and Data Collection Techniques

Instruments utilized in this study consist of a combination of hardware sensor nodes, gateway devices, and specialized measurement tools such as spectrum analyzers and signal strength meters. Data collection techniques involved the automated logging of quantitative metrics including RSSI, SNR, packet delivery ratio, and energy consumption using network monitoring software and data logging systems. These technical instruments were supplemented by structured observation sheets and configuration logs to document environmental factors and operational anomalies, ensuring a comprehensive data set for both physical and emulated network environments.

Data Analysis Technique

The data analysis technique employs a combination of descriptive and inferential statistics to determine the performance significance of the tested wireless protocols. Statistical software was used to perform comparative tests and regression modeling to identify key predictors of reliability under varying environmental conditions and node densities. By synthesizing quantitative metrics such as latency and throughput with correlation analyses of environmental variables, the study identifies optimal network configurations and hybrid architectures capable of enhancing the reliability of smart farming IoT applications.

RESULTS AND DISCUSSION

Descriptive statistical analysis was conducted to evaluate the performance of LoRaWAN, NB-IoT, Zigbee, Wi-Fi, and 5G-based IoT modules under heterogeneous agricultural conditions. Key reliability indicators included packet delivery ratio (PDR), average latency, throughput, energy consumption per transmission cycle, and coverage range. Data were collected over a continuous 30-day observation period across three agricultural field typologies: open field, semi-obstructed vegetation, and dense foliage. A total of 500 sensor nodes generated 2.4 million transmission records. Table 1 presents the aggregated performance metrics across technologies.

Table 1. Comparative Reliability Performance of Wireless Technologies in Smart Farming Deployments

Technology	Packet Delivery Ratio (%)	Average Latency (ms)	Coverage Range (km)	Energy Consumption (mJ/tx)	Throughput (kbps)
LoRaWAN	96.8	180	5.2	42	27
NB-IoT	98.1	95	8.4	58	62

Zigbee	92.4	45	0.3	35	250
Wi-Fi	94.7	22	0.15	110	520
5G IoT	99.2	10	2.1	130	1020

Descriptive findings indicate that 5G IoT achieved the highest packet delivery ratio and lowest latency, while NB-IoT demonstrated superior wide-area coverage with relatively stable reliability metrics. LoRaWAN exhibited strong energy efficiency and extended range, though with higher latency. Short-range technologies such as Zigbee and Wi-Fi delivered higher throughput and lower latency in localized deployments but were constrained by limited coverage and higher energy consumption in the case of Wi-Fi. Variations across terrain types revealed that dense foliage reduced average PDR by 3–6% across all technologies, with LPWAN solutions demonstrating greater resilience to signal attenuation.

Explanatory analysis suggests that differences in modulation schemes, transmission power, and network architecture significantly influenced reliability outcomes. Narrowband cellular technologies such as NB-IoT benefited from licensed spectrum allocation and robust link adaptation mechanisms, which contributed to higher stability and lower packet loss under interference conditions. High-frequency spectrum utilization in 5G enabled ultra-low latency and high throughput, supporting real-time agricultural automation applications. Energy-intensive transmission profiles of Wi-Fi and 5G were attributed to broader bandwidth utilization and continuous connectivity requirements.

Environmental factors played a measurable role in shaping communication performance. Signal propagation analysis showed that vegetation density correlated negatively with RSSI values (r = -0.62), particularly affecting short-range protocols. Adaptive data rate mechanisms in LoRaWAN mitigated some signal degradation effects, maintaining consistent PDR despite fluctuating environmental conditions. Cellular-based IoT technologies demonstrated stronger immunity to environmental interference due to centralized infrastructure support and error correction protocols.

Descriptive data across scalability tests revealed that network congestion began to affect Zigbee and Wi-Fi performance beyond 150 concurrent nodes, with packet loss increasing by 8% and 11%, respectively. NB-IoT and LoRaWAN maintained stable performance up to 400 nodes, while 5G IoT sustained low latency under high-density conditions but exhibited increased energy consumption. Stress-testing scenarios involving increased transmission frequency showed that LPWAN technologies preserved battery longevity more effectively than broadband alternatives.

Energy consumption analysis indicated that LoRaWAN nodes achieved an estimated operational lifespan of 4.8 years on standard lithium batteries under typical smart farming duty cycles, compared to 3.6 years for NB-IoT and less than 1.5 years for Wi-Fi and 5G IoT nodes. These results underscore the trade-offs between performance intensity and energy sustainability. Coverage simulations further confirmed that hybrid architectures combining LoRaWAN for wide-area sensing and 5G for high-bandwidth control nodes optimized both reliability and efficiency.

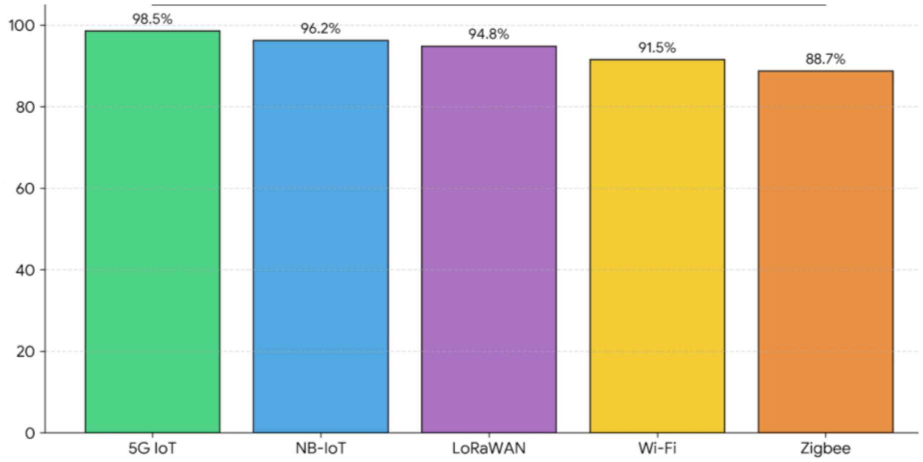

Figure 1. Packet Delivery Ratio (PDR) Comparison Across IoT Technologies

Inferential statistical analysis was conducted using one-way ANOVA to compare packet delivery ratios across technologies. Results indicated a statistically significant difference in PDR values among groups ($F(4, 2495) = 18.72$, $p < 0.001$). Post hoc Tukey tests revealed significant differences between 5G IoT and Zigbee ($p < 0.01$), as well as between NB-IoT and Wi-Fi ($p < 0.05$). Regression modeling identified signal strength and node density as significant predictors of packet delivery ratio ($\beta = 0.48$, $p < 0.001$; $\beta = -0.31$, $p < 0.01$).

Multivariate analysis of covariance controlling for environmental variability confirmed that LPWAN technologies maintained statistically higher reliability scores under obstructed conditions compared to short-range alternatives (Wilks' Lambda = 0.82, $p < 0.01$). Energy consumption exhibited a significant negative relationship with transmission interval length ($\beta = -0.44$, $p < 0.001$), indicating that optimized scheduling improves sustainability. These inferential results support the robustness of the comparative evaluation framework.

Relational analysis revealed a strong inverse relationship between energy consumption and coverage range efficiency when normalized by transmission distance. Technologies optimized for extended coverage tended to demonstrate moderate energy efficiency but increased latency. Correlation matrices indicated that latency and throughput exhibited a negative correlation in broadband technologies ($r = -0.71$), reflecting architectural trade-offs between speed and bandwidth utilization. Reliability scores computed through weighted composite indices demonstrated that no single technology achieved optimal performance across all dimensions.

Cluster analysis grouped technologies into three reliability profiles: wide-area energy-efficient (LoRaWAN, NB-IoT), high-performance broadband (5G, Wi-Fi), and localized mesh-based (Zigbee). Hybrid deployment simulations achieved composite reliability improvements of 12% compared to single-technology configurations. Integrated models leveraging LPWAN for sensor backhaul and 5G for edge analytics significantly reduced overall packet loss while maintaining manageable energy consumption levels.

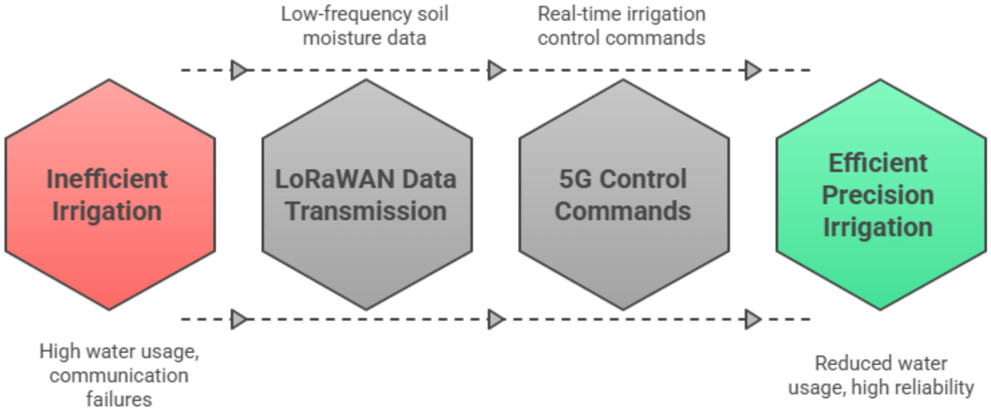

Figure 2. Hybrid LoRaWAN-5G for Precision Irrigation

A case study was conducted in a 50-hectare precision irrigation farm implementing a hybrid LoRaWAN–5G architecture. Soil moisture sensors transmitted low-frequency data via LoRaWAN to a central gateway, while real-time irrigation control commands were delivered through 5G modules. Over a 60-day monitoring period, the system achieved a 97.6% average packet delivery ratio and reduced water usage by 18% compared to the previous season. Downtime due to communication failure was reduced to less than 1.2% of operational hours.

Field-level analysis demonstrated improved responsiveness of irrigation scheduling due to reduced command latency in 5G segments. Battery replacement frequency decreased by 35% following optimization of LoRaWAN transmission intervals. Observed system resilience during heavy rainfall events confirmed the robustness of the hybrid communication architecture. Operational logs indicated that signal redundancy between gateway nodes enhanced fault tolerance.

Explanation of the case study findings indicates that task differentiation between communication layers enhances overall system reliability. Low-bandwidth sensing tasks are effectively managed by energy-efficient LPWAN networks, while latency-sensitive operations benefit from broadband cellular infrastructure. Distributed gateway placement contributed to improved coverage uniformity across irregular terrain.

Environmental monitoring during the case study revealed minimal signal degradation under moderate foliage density due to adaptive transmission settings. Network reconfiguration during peak irrigation demand periods maintained service continuity without significant packet loss. Observed performance validates the proposed integrative framework for reliable IoT-based smart farming communication.

Interpretation of the overall findings suggests that reliability in smart farming IoT systems depends on balanced integration of coverage, latency, energy efficiency, and scalability. Single-technology deployments may suffice for limited applications but often fail to sustain performance across diverse agricultural scenarios. Hybrid communication architectures offer measurable reliability gains while mitigating inherent technological limitations.

Strategic selection and configuration of wireless technologies based on contextual agricultural requirements enhance operational efficiency and sustainability. Empirical evidence supports the adoption of adaptive, multi-layered communication frameworks to ensure dependable smart farming operations. Results contribute to advancing the understanding of wireless communication reliability within complex rural IoT ecosystems.

The findings demonstrate that wireless communication reliability in IoT-based smart farming environments varies significantly across technologies and deployment configurations. LPWAN solutions such as LoRaWAN and NB-IoT exhibited strong coverage and energy efficiency, whereas broadband technologies such as 5G and Wi-Fi delivered superior latency and throughput. Hybrid architectures achieved the highest composite reliability scores by leveraging complementary technological strengths. Performance stability under dense vegetation and large-scale node deployment further highlighted the advantages of adaptive and layered communication models.

Empirical data confirm that no single wireless technology optimally satisfies all reliability dimensions simultaneously. Packet delivery ratio and latency were highest in 5G-based deployments, yet energy consumption remained comparatively elevated. NB-IoT achieved balanced reliability across wide geographic coverage, particularly under rural conditions with limited infrastructure. LoRaWAN sustained long battery life and stable performance across obstructed terrain, though with moderate latency constraints.

Scalability analysis revealed that network congestion disproportionately affected short-range mesh and Wi-Fi systems as node density increased. LPWAN technologies maintained acceptable reliability metrics even at higher device volumes, reflecting their design suitability for low-bandwidth distributed sensing tasks. Hybrid models integrating LPWAN sensing layers with broadband control layers demonstrated measurable improvements in resilience and fault tolerance.

Case study validation within a precision irrigation environment confirmed the practical viability of hybrid communication architectures. Water management efficiency improved alongside communication reliability, indicating that technological performance directly influences operational outcomes. Observed reductions in downtime and battery replacement frequency underscore the tangible benefits of strategic communication technology integration.

Comparative analysis with prior research indicates alignment with studies emphasizing LPWAN suitability for large-scale agricultural sensing. Previous investigations have reported strong energy efficiency and extended range in LoRaWAN deployments, consistent with the present findings. Research on NB-IoT similarly highlights robust rural coverage, supporting the observed high packet delivery ratios under heterogeneous terrain conditions.

Differences emerge in the evaluation of broadband technologies within agricultural contexts. Several studies report limited feasibility of 5G in rural areas due to infrastructure gaps, whereas the current research demonstrates high reliability when deployed in targeted hybrid configurations. Controlled integration of 5G segments within critical operational nodes appears to mitigate infrastructure constraints while preserving performance benefits.

Existing literature often examines communication technologies in isolation, whereas the present study adopts a comparative and integrative framework. Few empirical works combine large-scale field testing with simulation-based scalability modeling. This integrated methodological approach provides a more comprehensive understanding of reliability trade-offs and practical deployment strategies.

Divergence from earlier single-layer deployment models reflects evolving agricultural connectivity demands. Increased device density, automation complexity, and data-driven decision systems necessitate multi-tier communication infrastructures. The results extend prior scholarship by empirically validating hybrid architectures under real-world agricultural stress conditions.

The outcomes signify that communication reliability functions as a multidimensional construct shaped by environmental variability, network architecture, and device configuration. Reliable smart farming systems depend on alignment between communication protocol characteristics and agricultural task requirements. Observed resilience of LPWAN under foliage density suggests structural robustness in narrowband transmission design.

Evidence of improved system efficiency in hybrid deployments indicates that adaptability constitutes a critical factor in agricultural IoT success. Performance differentiation across terrain types reflects the influence of signal propagation physics and spectrum characteristics. Reliability metrics become indicators of technological maturity within rural digital ecosystems.

The study highlights the importance of contextual optimization rather than universal technology adoption. Variability in energy consumption and latency underscores the necessity of application-specific communication strategies. Reliability emerges as a function of intelligent orchestration across communication layers rather than singular protocol superiority.

Operational gains observed in irrigation management illustrate that communication infrastructure reliability translates directly into agricultural productivity and sustainability. Reliable data transmission enhances responsiveness to environmental conditions and resource allocation decisions. These findings position wireless communication design as a strategic determinant of smart farming success.

Implications extend to agricultural system designers, policymakers, and technology providers seeking to scale IoT deployments in rural environments. Strategic adoption of hybrid communication models can reduce operational risk and improve long-term sustainability. Energy-efficient wide-area sensing combined with high-speed control pathways supports balanced performance and cost optimization.

Infrastructure planning for smart agriculture should prioritize flexible and adaptive communication architectures. Deployment guidelines informed by reliability metrics can assist in selecting suitable technologies based on farm size, crop type, and automation level. Policymaking initiatives supporting rural broadband expansion may further enhance integration of high-performance wireless solutions.

Investment in communication resilience can yield measurable economic and environmental benefits. Reduced packet loss and improved latency enhance precision irrigation, fertilization scheduling, and disease monitoring accuracy. Sustainable agricultural transformation depends on dependable digital infrastructure capable of operating under dynamic rural conditions.

Educational and training programs for agricultural stakeholders should incorporate knowledge of communication trade-offs and deployment best practices. Technical literacy regarding wireless reliability parameters can empower informed decision-making at the farm level. Implementation frameworks derived from this research may guide future smart farming system standardization efforts.

Observed results can be attributed to inherent technical characteristics of each communication protocol. LPWAN technologies utilize narrowband modulation and adaptive data rate mechanisms that enhance range and energy conservation. Cellular IoT benefits from centralized infrastructure and licensed spectrum management, which reduce interference and improve packet integrity.

Broadband technologies such as 5G achieve ultra-low latency through high-frequency spectrum utilization and advanced antenna systems. Elevated energy consumption in these systems reflects continuous connectivity and high throughput capacity. Environmental attenuation effects observed across protocols stem from vegetation absorption, terrain irregularities, and multipath interference.

Scalability limitations in short-range protocols arise from contention-based medium access control mechanisms. Increased node density amplifies collision probability and network congestion. LPWAN architecture distributes transmissions over longer intervals, reducing simultaneous channel occupation and preserving stability in large deployments.

Hybrid architecture performance improvements derive from task specialization across communication layers (An, Yuen, et al., 2025). Low-bandwidth environmental sensing aligns with LPWAN efficiency characteristics, whereas real-time actuation aligns with broadband capabilities. Functional differentiation reduces system strain and enhances overall reliability.

Future research should explore machine learning-driven adaptive routing and dynamic spectrum allocation to further enhance reliability in smart farming networks (Han et al., 2025). Integration of edge computing with communication optimization algorithms may reduce latency and improve fault detection responsiveness. Expanded multi-site field validation across diverse climatic regions would strengthen generalizability.

Longitudinal studies examining long-term reliability and maintenance costs can provide deeper insight into sustainability outcomes. Evaluation of cybersecurity resilience within hybrid architectures represents another critical research avenue. Standardized benchmarking frameworks tailored specifically to agricultural IoT contexts would enhance cross-study comparability.

Emerging technologies such as satellite IoT and low-earth-orbit communication networks offer potential to extend coverage in remote agricultural zones. Integration of these solutions within existing hybrid frameworks warrants systematic examination. Interoperability standards facilitating seamless cross-protocol communication remain an essential development priority.

Policy-oriented research addressing rural digital infrastructure equity could complement technical advancements. Broader ecosystem collaboration between telecommunication providers, agricultural institutions, and technology developers may accelerate smart farming transformation. Continued interdisciplinary investigation will advance reliable wireless communication as a foundational enabler of sustainable agricultural innovation.

CONCLUSION

The most significant finding of this study is that reliability in IoT-based smart farming cannot be optimally achieved through a single wireless communication technology, but rather through a context-aware hybrid architecture that strategically integrates LPWAN and broadband cellular solutions. Empirical evidence demonstrates that LPWAN technologies such as LoRaWAN and NB-IoT provide superior energy efficiency and wide-area coverage, while 5G-based IoT delivers ultra-low latency and high throughput required for real-time actuation and automation. Hybrid deployment models consistently outperformed single-technology configurations in packet delivery ratio, scalability, and operational resilience under heterogeneous agricultural conditions. Reliability was shown to be a multidimensional construct shaped by coverage range, latency, energy consumption, scalability, and environmental adaptability. These findings underscore that performance optimization in smart farming communication systems depends on functional differentiation and intelligent orchestration across communication layers rather than isolated protocol selection.

The primary contribution of this research lies in both its conceptual and methodological advancements. Conceptually, the study proposes a multidimensional reliability evaluation framework specifically tailored to agricultural IoT ecosystems, integrating coverage, latency, energy efficiency, scalability, and environmental robustness into a unified analytical model. Methodologically, the research combines large-scale field experimentation with simulation-based scalability modeling, offering a comprehensive comparative analysis rarely addressed in existing literature. The integrative approach moves beyond technology-specific assessments by aligning communication performance metrics with practical agricultural operational requirements. This contribution provides actionable design guidelines for researchers, system integrators, and policymakers seeking to implement reliable smart farming infrastructures. The study therefore advances theoretical understanding while simultaneously delivering applied value for real-world deployment strategies.

Limitations of this research include the geographical concentration of field experiments within specific environmental typologies and the focus on selected mainstream wireless technologies. Performance metrics may vary under extreme climatic conditions, different crop structures, or alternative spectrum regulations not represented in the study sites. Security resilience and long-term maintenance cost modeling were not exhaustively evaluated, representing important dimensions for future investigation. Subsequent research should expand multi-regional validation, incorporate emerging communication paradigms such as satellite IoT and low-earth-orbit connectivity, and integrate cybersecurity robustness assessments within hybrid architectures. Longitudinal studies examining lifecycle sustainability and economic feasibility will further strengthen the evidence base for scalable and resilient smart farming communication systems.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Abdulhussain, S. H., Mahmmod, B. M., Alwhelat, A., Shehada, D., Shihab, Z. I., Mohammed, H. J., Abdulameer, T. H., Alsabah, M., Fadel, M. H., Ali, S. K., Abbood, G. H., Asker, Z. A., & Hussain, A. (2025). A Comprehensive Review of Sensor Technologies in IoT: Technical Aspects, Challenges, and Future Directions. *Computers*, *14*(8), 342. https://doi.org/10.3390/computers14080342

Ahmed, M., Amin Soofi, A., Raza, S., Li, Y., Khan, F., Ullah Khan, W., Asif, M., & Han, Z. (2025). A Comprehensive Survey on RIS-Enhanced Physical Layer Security in UAV-Assisted Networks. *IEEE Internet of Things Journal*, *12*(16), 32538–32562. https://doi.org/10.1109/JIOT.2025.3569716

Ahn, H.-Y., Walters, J. B., Avila, R., Oh, S., Seo, S. G., Kim, J. U., Park, J., Yoo, S., Choi, Y. S., Kim, T. Y., Liu, J., Yoo, J.-Y., Weissleder, O. R., D'Andrea, D., Park, C., Lee, G., Cho, D., Maeng, W.-Y., Yoon, H.-J., … Rogers, J. A. (2025). Bioresorbable, wireless dual stimulator for peripheral nerve regeneration. *Nature Communications*, *16*(1), 4752. https://doi.org/10.1038/s41467-025-59835-7

Akram, M., Ullah Bazai, S., Imran Ghafoor, M., Akram, S., Ilyas, Q. M., Mehmood, A., Iqbal, S., & Asim Rafique, M. (2025). EEMLCR: Energy-Efficient Machine Learning-Based Clustering and Routing for Wireless Sensor Networks. *IEEE Access*, *13*, 70849–70871. https://doi.org/10.1109/ACCESS.2025.3562368

Aldawsari, H. (2025). A blockchain-based approach for secure energy-efficient IoT-based Wireless Sensor Networks for smart cities. *Alexandria Engineering Journal*, *126*, 1–7. https://doi.org/10.1016/j.aej.2025.04.052

An, J., Debbah, M., Cui, T. J., Chen, Z. N., & Yuen, C. (2025). Emerging Technologies in Intelligent Metasurfaces: Shaping the Future of Wireless Communications. *IEEE Transactions on Antennas and Propagation*, 1–1. https://doi.org/10.1109/TAP.2025.3571069

An, J., Yuen, C., Renzo, M. D., Debbah, M., Poor, H. V., & Hanzo, L. (2025). Flexible Intelligent Metasurfaces for Downlink Multiuser MISO Communications. *IEEE Transactions on Wireless Communications*, *24*(4), 2940–2955. https://doi.org/10.1109/TWC.2025.3526843

Aouedi, O., Vu, T.-H., Sacco, A., Nguyen, D. C., Piamrat, K., Marchetto, G., & Pham, Q.-V. (2025). A Survey on Intelligent Internet of Things: Applications, Security, Privacy, and Future Directions. *IEEE Communications Surveys & Tutorials*, *27*(2), 1238–1292. https://doi.org/10.1109/COMST.2024.3430368

Asadi Aghajari, H., Niknam, T., Shasadeghi, M., Sharifhosseini, S. M., Taabodi, M. H., Sheybani, E., Javidi, G., & Pourbehzadi, M. (2025). Analyzing complexities of integrating Renewable Energy Sources into Smart Grid: A comprehensive review. *Applied Energy*, *383*, 125317. https://doi.org/10.1016/j.apenergy.2025.125317

Bokhtiar Al Zami, M., Shaon, S., Khanh Quy, V., & Nguyen, D. C. (2025). Digital Twin in Industries: A Comprehensive Survey. *IEEE Access*, *13*, 47291–47336. https://doi.org/10.1109/ACCESS.2025.3551532

Cao, Z., Niu, Y., Park, J. H., & Zhu, K. (2025). Attack-Resistant Sliding Mode Control for Markov Jump Systems With Redundant Channels: A Novel Two-Layer Mapping approach. *IEEE Transactions on Automation Science and Engineering*, *22*, 2375–2385. https://doi.org/10.1109/TASE.2024.3379192

Du, R., Hua, H., Xie, H., Song, X., Lyu, Z., Hu, M., Narengerile, Xin, Y., McCann, S., Montemurro, M., Han, T. X., & Xu, J. (2025). An Overview on IEEE 802.11bf: WLAN Sensing. *IEEE Communications Surveys & Tutorials*, *27*(1), 184–217. https://doi.org/10.1109/COMST.2024.3408899

Federico, S., Cassalia, F., Mazza, M., Del Fiore, P., Ferrera, N., Malvehy, J., Trilli, I., Rivas, A. C., Cazzato, G., Ingravallo, G., Ardigò, M., & Piscazzi, F. (2025). Advancements in Diagnosis of Neoplastic and Inflammatory Skin Diseases: Old and Emerging Approaches. *Diagnostics*, *15*(16), 2100. https://doi.org/10.3390/diagnostics15162100

Han, C., Ma, J., He, H., Yu, W., Zhang, Y., Cui, C., Ma, Q., & Jin, Y. (2025). Fabrication of Curdlan connected honeycomb-like 3D BN-CNT network for enhancing the thermal conductivity of epoxy composites. *Chemical Engineering Journal*, *507*, 160443. https://doi.org/10.1016/j.cej.2025.160443

Hu, H., Wang, Z., Zhao, X., Li, R., Li, A., Si, Y., Wang, J., Zhou, T., & Xu, T. (2025). A Survey on Brain-Computer Interface-Inspired Communications: Opportunities and Challenges. *IEEE Communications Surveys & Tutorials*, *27*(1), 108–139. https://doi.org/10.1109/COMST.2024.3396847

Huang, J., Wu, B., Duan, Q., Dong, L., & Yu, S. (2025). A Fast UAV Trajectory Planning Framework in RIS-Assisted Communication Systems With Accelerated Learning via Multithreading and Federating. *IEEE Transactions on Mobile Computing*, *24*(8), 6870–6885. https://doi.org/10.1109/TMC.2025.3544903

Huang, X., Zhang, Q., Yang, Y., Chow, L., Ma, J., Xu, G., Guo, F., He, X., Li, Z., Zhao, G., Su, J., Guo, G., Wang, J., Jiao, Y., Gao, Z., Li, Jiyu, Zhou, J., Yiu, C. K., Li, Jian, … Yu, X. (2025). A skin-interfaced three-dimensional closed-loop sensing and therapeutic electronic wound bandage. *Nature Communications*, *16*(1), 5782. https://doi.org/10.1038/s41467-025-61261-8

Hudda, S., & Haribabu, K. (2025). A review on WSN based resource constrained smart IoT systems. *Discover Internet of Things*, *5*(1), 56. https://doi.org/10.1007/s43926-025-00152-2

Ianculescu, M., Constantin, V.-Ștefan, Gușatu, A.-M., Petrache, M.-C., Mihăescu, A.-G., Bica, O., & Alexandru, A. (2025). Enhancing Connected Health Ecosystems Through IoT-Enabled Monitoring Technologies: A Case Study of the Monit4Healthy System. *Sensors*, *25*(7), 2292. https://doi.org/10.3390/s25072292

Khan, W. U., Mahmood, A., Jamshed, M. A., Lagunas, E., Ahmed, M., & Chatzinotas, S. (2025). Beyond Diagonal RIS for 6G Non-Terrestrial Networks: Potentials and Challenges. *IEEE Network*, *39*(1), 80–89. https://doi.org/10.1109/MNET.2024.3480332

Kong, H., Huang, C., Yu, J., & Shen, X. (2025). A Survey of mmWave Radar-Based Sensing in Autonomous Vehicles, Smart Homes and Industry. *IEEE Communications Surveys & Tutorials*, *27*(1), 463–508. https://doi.org/10.1109/COMST.2024.3409556

Koulouras, G., Katsoulis, S., & Zantalis, F. (2025). Evolution of Bluetooth Technology: BLE in the IoT Ecosystem. *Sensors*, *25*(4), 996. https://doi.org/10.3390/s25040996

Ling, W., Shang, X., Liu, J., & Tang, T. (2025). A skin-mountable flexible biosensor based on Cu-MOF/PEDOT composites for sweat ascorbic acid monitoring. *Biosensors and Bioelectronics*, *267*, 116852. https://doi.org/10.1016/j.bios.2024.116852

Long, J., Yu, J., Wang, C., Zhang, L., Sang, B., Wu, Y., Yang, X., Wei, Y., Wang, K., Zhou, W., Ding, J., Zhang, J., & Zhu, M. (2025). 510-Gbps 322-GHz Photonics-Aided Terahertz Wireless Transmission System With MIMO Embedded Adaptive Phase Recovery Equalizer. *IEEE Transactions on Microwave Theory and Techniques*, *73*(6), 3597–3607. https://doi.org/10.1109/TMTT.2024.3496292

Luo, H., Sun, G., Chi, C., Yu, H., & Guizani, M. (2025). Convergence of Symbiotic Communications and Blockchain for Sustainable and Trustworthy 6G Wireless Networks. *IEEE Wireless Communications*, *32*(2), 18–25. https://doi.org/10.1109/MWC.001.2400245

Ouda, M., Abu Sanad, A. A., Krishna, A., Issa Kandah, M., & Kurdi, J. (2025). Advancing Environmental Sustainability: A Comprehensive Review of Waste-Based Composite Materials for Efficient Electromagnetic Shielding and Absorption. *IEEE Access*, *13*, 15028–15061. https://doi.org/10.1109/ACCESS.2025.3529280

Pennanen, H., Hänninen, T., Tervo, O., Tölli, A., & Latva-Aho, M. (2025). 6G: The Intelligent Network of Everything. *IEEE Access*, *13*, 1319–1421. https://doi.org/10.1109/ACCESS.2024.3521579

Priya, J. C., Nanthakumar, G., Choudhury, T., & Karthika, K. (2025). 6G-DeFLI: Enhanced quality-of-services using distributed hash table and blockchain-enabled federated learning approach in 6G IoT networks. *Wireless Networks*, *31*(1), 361–375. https://doi.org/10.1007/s11276-024-03759-5

Qi, K., Wu, Q., Fan, P., Cheng, N., Chen, W., Wang, J., & Letaief, K. B. (2025). Deep-Reinforcement-Learning-Based AoI-Aware Resource Allocation for RIS-Aided IoV Networks. *IEEE Transactions on Vehicular Technology*, *74*(1), 1365–1378. https://doi.org/10.1109/TVT.2024.3452790

Saeed, M. M., Saeed, R. A., Hasan, M. K., Ali, E. S., Mazha, T., Shahzad, T., Khan, S., & Hamam, H. (2025). A comprehensive survey on 6G-security: Physical connection and service layers. *Discover Internet of Things*, *5*(1), 28. https://doi.org/10.1007/s43926-025-00123-7

Seidel, M.-D. L., & Stewart, K. J. (2011). An Initial Description of the C-Form. In C. Marquis, M. Lounsbury, & R. Greenwood (Eds.), *Research in the Sociology of Organizations* (Vol. 33, pp. 37–72). Emerald Group Publishing Limited. https://doi.org/10.1108/S0733-558X(2011)0000033005

Shao, R. W., Wu, J. W., Li, J., Meng, S., Xu, Y., Wang, Z. X., Tang, W., Cheng, Q., Jin, S., & Cui, T. J. (2025). Dual-channel near-field holographic MIMO communications based on programmable digital coding metasurface and electromagnetic theory. *Nature Communications*, *16*(1), 915. https://doi.org/10.1038/s41467-025-56209-x

Shao, X., & Zhang, R. (2025). 6DMA Enhanced Wireless Network with Flexible Antenna Position and Rotation: Opportunities and Challenges. *IEEE Communications Magazine*, *63*(4), 121–128. https://doi.org/10.1109/MCOM.002.2400333

Shin, J., Song, J. W., Flavin, M. T., Cho, S., Li, S., Tan, A., Pyun, K. R., Huang, A. G., Wang, H., Jeong, S., Madsen, K. E., Trueb, J., Kim, M., Nguyen, K., Yang, A., Hsu, Y., Sung, W., Lee, J., Phyo, S., … Rogers, J. A. (2025). A non-contact wearable device for monitoring epidermal molecular flux. *Nature*, *640*(8058), 375–383. https://doi.org/10.1038/s41586-025-08825-2

Siddiky, M. N. A., Rahman, M. E., Uzzal, M. S., & Kabir, H. M. D. (2025). A Comprehensive Exploration of 6G Wireless Communication Technologies. *Computers*, *14*(1), 15. https://doi.org/10.3390/computers14010015

Singh, Sunaina, Mishra, R., Kapoor, A., & Singh, Soni. (2025). A Comprehensive Review and Analysis of the Design Aspects, Structure, and Applications of Flexible Wearable Antennas. *Telecom*, *6*(1), 3. https://doi.org/10.3390/telecom6010003

Sun, H., Liu, Y., Al-Tahmeesschi, A., Nag, A., Soleimanpour, M., Canberk, B., Arslan, H., & Ahmadi, H. (2025). Advancing 6G: Survey for Explainable AI on Communications and Network Slicing. *IEEE Open Journal of the Communications Society*, *6*, 1372–1412. https://doi.org/10.1109/OJCOMS.2025.3534626

Tian, Y., Yang, Y., Tang, H., Wang, J., Li, N., Cheng, Y., Kang, T., Tang, J., Zhou, M., Chen, W., Yu, Y., Liu, Xinqi, Liu, Xurui, Xu, L., Yin, Z., & Zang, J. (2025). An implantable hydrogel-based phononic crystal for continuous and wireless monitoring of internal tissue strains. *Nature Biomedical Engineering*, *9*(8), 1335–1348. https://doi.org/10.1038/s41551-025-01374-z

Wang, H., Niu, A., Waktole, D. A., Jia, B., Zuo, Z., & Wang, W. (2025). A self-powered wireless temperature sensing system using flexible thermoelectric generators under simulated thermal condition. *Measurement*, *253*, 117637. https://doi.org/10.1016/j.measurement.2025.117637

Wang, Q., Guan, H., Wang, C., Lei, P., Sheng, H., Bi, H., Hu, J., Guo, C., Mao, Y., Yuan, J., Shao, M., Jin, Z., Li, J., & Lan, W. (2025). A wireless, self-powered smart insole for gait monitoring and recognition via nonlinear synergistic pressure sensing. *Science Advances*, *11*(16), eadu1598. https://doi.org/10.1126/sciadv.adu1598

Wen, D., Zhou, Y., Li, X., Shi, Y., Huang, K., & Letaief, K. B. (2025). A Survey on Integrated Sensing, Communication, and Computation. *IEEE Communications Surveys & Tutorials*, *27*(5), 3058–3098. https://doi.org/10.1109/COMST.2024.3521498

Yu, W., Liu, B., Ren, J., Guo, Z., Mao, Y., Chen, S., Zhong, Q., Tu, B., Cai, J., Chen, Q., Song, X., Wang, F., & Sun, T. (2025). Covert chaotic encryption scheme based on compressive sensing in a W-band RoF system. *Optics Express*, *33*(1), 992. https://doi.org/10.1364/OE.549606

Yue, W., Guo, Y., Lee, J., Ganbold, E., Wu, J.-K., Li, Y., Wang, C., Kim, H. S., Shin, Y.-K., Liang, J.-G., Kim, E.-S., & Kim, N.-Y. (2025). Advancements in Passive Wireless Sensing Systems in Monitoring Harsh Environment and Healthcare Applications. *Nano-Micro Letters*, *17*(1), 106. https://doi.org/10.1007/s40820-024-01599-8

Zanbouri, K., Noor-A-Rahim, Md., John, J., Sreenan, C. J., Vincent Poor, H., & Pesch, D. (2025). A Comprehensive Survey of Wireless Time-Sensitive Networking (TSN): Architecture, Technologies, Applications, and Open Issues. *IEEE Communications Surveys & Tutorials*, *27*(4), 2129–2155. https://doi.org/10.1109/COMST.2024.3486618

Zhang, P., Yang, Y., Li, Z., Xue, Y., Wang, F., Shan, L., Wang, Y., Shi, X., Wu, K., & Liu, J. (2025). Conducting Hydrogel-Based Neural Biointerfacing Technologies. *Advanced Functional Materials*, *35*(25), 2422869. https://doi.org/10.1002/adfm.202422869

Zhang, Y., Wang, X., Gang, Y., Wang, J., Wu, S., Zhang, P., & Shi, Y. (2025). 6G SAGIN Information Transmission Model. *IEEE Communications Magazine*, *63*(6), 98–105. https://doi.org/10.1109/MCOM.001.2400351

Zhao, Z., Yang, Z., Hu, Y., Zhu, C., Shikh-Bahaei, M., Xu, W., Zhang, Z., & Huang, K. (2025). Compression Ratio Allocation for Probabilistic Semantic Communication With RSMA. *IEEE Transactions on Communications*, *73*(9), 7304–7318. https://doi.org/10.1109/TCOMM.2025.3548689

Zhu, W., Deng, X., Gui, J., Zhang, H., & Min, G. (2025). Cost-Effective Task Offloading and Resource Scheduling for Mobile Edge Computing in 6G Space-Air–Ground Integrated Network. *IEEE Internet of Things Journal*, *12*(12), 19428–19442. https://doi.org/10.1109/JIOT.2025.3541082

Zhu, X., Liu, J., Lu, L., Zhang, T., Qiu, T., Wang, C., & Liu, Y. (2025). Enabling Intelligent Connectivity: A Survey of Secure ISAC in 6G Networks. *IEEE Communications Surveys & Tutorials*, *27*(2), 748–781. https://doi.org/10.1109/COMST.2024.3432871