



APPLICATION OF WIRELESS COMMUNICATION TECHNOLOGIES IN ROBOTICS

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Abstract: *The integration of wireless communication technologies into robotic systems represents one of the most transformative developments in contemporary engineering. This paper provides a comprehensive review of the wireless standards currently employed in robotics — including Wi-Fi, Bluetooth, Zigbee, LoRa, 5G, and Ultra-Wideband (UWB) — examining their technical characteristics, latency profiles, energy efficiency, and deployment contexts. Through comparative analysis of seven major wireless standards, evaluation of real-world robotic deployments, and statistical data from the global robotics market (2018–2028), this study demonstrates that 5G and Wi-Fi 6 are emerging as the dominant platforms for high-performance robot communication. The paper also identifies critical challenges such as interference, cybersecurity vulnerabilities, and energy constraints, and proposes engineering solutions including cognitive radio, edge computing, and semantic communication. Findings indicate a projected global wireless robotics market exceeding USD 140 billion by 2028. Future directions including 6G, Terahertz links, and quantum key distribution are discussed.*

Keywords: *wireless communication, robotics, 5G, IoT, robot operating systems, autonomous systems, edge computing, sensor networks*

INTRODUCTION

The modern era of robotics is fundamentally defined by connectivity. As robotic systems transition from isolated, pre-programmed machines to intelligent, context-aware agents operating in complex environments, the role of wireless communication has become central to their functionality [1]. Whether it is a surgical robot receiving haptic feedback over a 5G link, a swarm of agricultural drones coordinating through LoRa mesh networks, or warehouse automation guided by Ultra-Wideband (UWB) positioning — the quality, reliability, and speed of the wireless link directly determines operational capability.

Wireless communication in robotics is not a single technology but an ecosystem of complementary standards, each optimized for different trade-offs between range, data rate, power consumption, and latency [2]. Understanding which technology fits which application domain is therefore a critical engineering decision. Incorrect technology selection can result in mission failure, energy waste, or security vulnerabilities.

This paper investigates the full spectrum of wireless technologies applicable to robotics, from short-range personal area networks (Bluetooth, Zigbee) to wide-area cellular networks (4G LTE, 5G NR), and from conventional radio frequency (RF) systems to emerging approaches such as Visible Light Communication (VLC) and Terahertz (THz) links [3]. The analysis is grounded in current market statistics, real-world case studies, and performance benchmarks drawn from peer-reviewed literature. According to the



International Federation of Robotics (IFR), the global installed base of industrial robots exceeded 3.5 million units in 2023, with wireless-enabled systems representing approximately 74% of all new deployments — a figure that underscores the urgency of this topic [4].

The structure of this paper is as follows: Section 2 reviews the wireless technologies landscape; Section 3 presents comparative analysis and statistical data; Section 4 discusses real-world deployments; Section 5 addresses challenges and solutions; Section 6 examines future directions; and Section 7 concludes the paper.

2. WIRELESS COMMUNICATION TECHNOLOGIES IN ROBOTICS

2.1 Overview and Classification

Wireless communication technologies used in robotics can be broadly classified along three axes: (i) range — short, medium, or long; (ii) data rate — from kilobits per second (kbps) for sensor data to gigabits per second (Gbps) for video streaming; and (iii) power profile — from ultra-low power (μ W-scale for Zigbee sleep modes) to high power (W-scale for 5G mmWave). Table 1 provides a consolidated comparison of the seven most widely deployed wireless standards in robotics as of 2024 [5][6].

Table 1: Comparative Overview of Wireless Communication Technologies Used in Robotics

Technology	Frequency Band	Range	Data Rate	Power Usage	Typical Application
Wi-Fi (802.11ac)	5 GHz	-50 m	Up to 3.5 Gbps	High	Indoor localization
Bluetooth 5.0	2.4 GHz	-240 m	2 Mbps	Low	Short-range comms
Zigbee	2.4 GHz	-100 m	250 kbps	Very Low	Sensor networks
Z-Wave	868/915 MHz	-100 m	100 kbps	Low	Mesh robotics
LoRa / LoRaWAN	433/868/915 MHz	Up to 15 km	0.3–50 kbps	Very Low	Agricultural robots
5G NR	Sub-6 / mmWave	-1 km (Sub-6)	Up to 20 Gbps	High	Industrial automation
UWB	3.1–10.6 GHz	-10 m	480 Mbps	Medium	Precise positioning

Source: IEEE 802 Standards Committee; 3GPP Release 17; LoRa Alliance Technical Committee [5][6][7]

2.2 Short-Range Technologies

2.2.1 Bluetooth 5.0 and Bluetooth Low Energy (BLE)

Bluetooth 5.0, standardized in IEEE 802.15.1, provides a peak data rate of 2 Mbps with an extended range of up to 240 meters in open environments. Its most significant feature for robotics is the Bluetooth Low Energy (BLE) mode, which enables sensor beacons to operate for years on coin cell batteries. BLE is extensively used in wearable robotics and prosthetic limb interfaces [8]. Bluetooth Mesh, introduced in Bluetooth 5.0, allows star-to-



mesh topology conversion, enabling multi-robot communication without centralized access points.

9.3.1.2.2.2 Zigbee and Z-Wave

Zigbee (IEEE 802.15.4) and Z-Wave operate on the 2.4 GHz and sub-GHz bands respectively. They are designed for low-power, low-data-rate mesh networks ideal for distributed sensor arrays in robot environments. Zigbee's mesh architecture allows up to 65,000 nodes per network, making it suitable for large-scale agricultural or industrial sensor deployments [9]. Z-Wave's sub-GHz frequency provides superior wall penetration compared to 2.4 GHz alternatives, making it preferred for indoor robotic systems where obstacles are prevalent.

9.3.2 2.2.3 Ultra-Wideband (UWB)

UWB (IEEE 802.15.4z) operates across the 3.1–10.6 GHz spectrum with extremely short pulses (nanosecond scale), enabling centimeter-level ranging accuracy [10]. This property makes UWB the preferred technology for indoor robot localization where GPS is unavailable. Apple's AirTag and the positioning systems in Amazon's Kiva warehouse robots both leverage UWB for ±10 cm positioning accuracy. The technology also offers resistance to multipath interference, a critical advantage in cluttered indoor environments.

9.4 2.3 Medium-Range Technologies

9.4.12.3.1 Wi-Fi 6 (IEEE 802.11ax)

Wi-Fi 6 represents a paradigm shift from previous 802.11 standards, introducing Orthogonal Frequency Division Multiple Access (OFDMA), Multi-User MIMO, and Target Wake Time (TWT). For robotic applications, the most critical improvement is the four-fold increase in network efficiency in dense environments — a scenario common in factory floors with dozens of robots [11]. Wi-Fi 6E extends operation to the 6 GHz band, providing additional spectrum largely free from legacy device interference. Peak throughput exceeds 9.6 Gbps in theory, with real-world robot applications typically utilizing 500 Mbps–2 Gbps for HD video telemetry and sensor fusion data streams.

9.5 2.4 Long-Range Technologies

9.5.12.4.1 LoRa and LoRaWAN

LoRa (Long Range) is a physical layer modulation technique using Chirp Spread Spectrum (CSS) encoding, developed by Semtech. LoRaWAN is the MAC layer protocol built on top. Together they provide communication ranges of 2–15 km in suburban environments and up to 40 km line-of-sight, with data rates from 0.3 to 50 kbps [12]. These characteristics suit agricultural robots, environmental monitoring drones, and remote inspection vehicles where bandwidth requirements are low but coverage must be extensive. The LoRa Alliance reports over 200 million LoRaWAN-connected devices globally as of 2024.

9.5.2 2.4.2 5G New Radio (NR)

5G NR, defined in 3GPP Releases 15 through 17, introduces three distinct use-case categories: enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC), and Ultra-Reliable Low-Latency Communications (URLLC). For robotics, URLLC is transformative — it provides sub-1 ms latency with 99.9999% reliability, enabling true real-time robot control over wireless links [13]. Network slicing allows a



single 5G infrastructure to simultaneously support HD video telemetry (eMBB slice) and precision control commands (URLLC slice). The millimeter-wave (mmWave) band (24–100 GHz) offers peak rates exceeding 20 Gbps for high-density indoor robot deployments.

3. STATISTICAL ANALYSIS AND MARKET DATA

9.6 3.1 Global Robotics Market Growth

The global robotics market has experienced sustained double-digit growth driven by wireless connectivity advancements, labor cost pressures, and advances in AI. Table 2 presents market data from 2018 through 2024 with projections to 2028 [4][14].

Table 2: Global Robotics Market Size by Segment (USD Billions), 2018–2028

Year	Industrial Robots (USD B)	Service Robots (USD B)	Total Market (USD B)	YoY Growth (%)
2018	16.5	9.2	25.7	+12.3%
2019	17.8	11.1	28.9	+12.5%
2020	16.9	12.3	29.2	+1.0%
2021	20.7	14.8	35.5	+21.6%
2022	25.1	18.7	43.8	+23.4%
2023	30.4	23.9	54.3	+24.0%
2024*	37.1	30.2	67.3	+23.9%
2028 (Proj.)	72.0	68.0	140.0	-20%/yr

Source: International Federation of Robotics (IFR) World Robotics Report 2024; MarketsandMarkets Analysis [4][14]. *Preliminary estimate.

The compound annual growth rate (CAGR) from 2020 to 2024 stands at approximately 23.2%. Service robotics — including medical, logistics, and agricultural robots — has outpaced industrial robotics growth since 2021, reflecting the expanding role of wireless communication in consumer-facing robot deployments. Analysts project the total market will reach USD 140 billion by 2028, representing a 2.6× increase from 2023 levels [14].

9.7 3.2 Wireless Technology Adoption in Robotic Systems

Figure 1 presents a statistical visualization of wireless technology adoption rates among commercially deployed wireless-enabled robots as surveyed in 2024. The data was compiled from IFR industry reports, IEEE publications, and vendor deployment statistics [15].

Figure 1: Wireless Technology Adoption Rates in Commercial Robot Deployments (2024)

Metric	Adoption Rate Among Wireless-Enabled Robots (2024)	Value
5G		68%



Wi-Fi 6		82%
Bluetooth 5		75%
Zigbee / Z-Wave		45%
LoRa / LPWAN		38%
UWB		29%

Source: IFR Annual Survey 2024; IEEE Spectrum Wireless Robotics Report [4][15].
 Note: Percentages sum >100% as systems often use multiple wireless technologies simultaneously.

Wi-Fi 6 leads adoption at 82%, followed by Bluetooth 5 at 75% and 5G at 68%. The high co-deployment rate reflects a general trend toward multi-radio architectures: a typical industrial robot may use 5G for primary cloud connectivity, Wi-Fi 6 for local area coordination, UWB for indoor positioning, and BLE for sensor node communication [15].

3.3 Latency and Reliability Benchmarks

Table 3 summarizes latency and reliability benchmarks for the primary wireless standards used in robotic control systems. Reliability is defined as the percentage of packets delivered within twice the nominal latency threshold [16].

Table 3: Latency and Reliability Benchmarks for Wireless Technologies in Robotic Applications

Wireless Standard	Typical Latency	Reliability (%)	Deployment Cost	Robot Suitability
5G (Ultra-Reliable)	< 1 ms	99.9999%	High	Excellent
Wi-Fi 6 (802.11ax)	2–5 ms	99.99%	Medium	Very Good
4G LTE	10–50 ms	99.9%	Low	Good
Bluetooth LE	3–6 ms	99.5%	Low	Limited
Zigbee	15–30 ms	99.2%	Very Low	Moderate
LoRaWAN	100+ ms	98.5%	Very Low	Low

Source: 3GPP TR 22.261; IEEE 802.11ax Standard; ETSI TS 101 867 [7][11][16]

4. SYSTEM ARCHITECTURE AND REAL-WORLD DEPLOYMENTS

4.1 Three-Layer Wireless Robotics Architecture

Modern wirelessly-connected robotic systems typically adhere to a three-layer communication architecture: the Robot Layer (onboard embedded systems), the Communication Layer (wireless infrastructure), and the Cloud/Control Layer (remote computation and human interfaces). Figure 2 illustrates this architecture.

Figure 2: Three-Layer Architecture for Wireless Robotic Communication Systems





<ul style="list-style-type: none"> ● Wireless Transceiver ● ROS / Middleware 	<ul style="list-style-type: none"> ● Wi-Fi Access Points ● Mesh Network Nodes ● Edge Computing Units 	<ul style="list-style-type: none"> ● Cloud AI / ML Models ● Fleet Management ● Telemetry Database ● Human Operator UI
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Source: Author's illustration based on frameworks from [1][3][13]

The Robot Layer contains the physical actuators, sensors, onboard processing units (typically ARM Cortex-M/A series or NVIDIA Jetson platforms), and wireless transceivers. The Communication Layer encompasses the wireless infrastructure — 5G base stations, Wi-Fi access points, LoRa gateways, or mesh nodes — along with edge computing servers that pre-process data before forwarding to the cloud. The Cloud/Control Layer provides fleet-level AI inference, mission planning, historical data storage, and the human-machine interface.

Edge computing within the Communication Layer is increasingly critical: by processing latency-sensitive data (obstacle avoidance, collision detection) at the edge rather than the cloud, end-to-end response times can be reduced from 50–100 ms (cloud round-trip) to under 5 ms [17].

4.2 Real-World Deployment Case Studies

Table 4 summarizes eight representative robotic systems from across application domains, highlighting the wireless technologies employed and measurable outcomes.

Table 4: Wireless Communication Technologies in Real-World Robotic Deployments

Application Domain	Wireless Tech Used	Key Benefit	Representative System
Manufacturing	5G / Wi-Fi 6	Ultra-low latency control	ABB YuMi collaborative robot
Medical Surgery	5G / UWB	High-precision teleoperation	da Vinci Surgical System
Agriculture	LoRa / Zigbee	Wide-area field coverage	Blue River LettuceBot
Search & Rescue	Wi-Fi / Mesh RF	GPS-denied navigation	DARPA Subterranean robots
Logistics & Warehousing	Wi-Fi 6 / UWB	Real-time fleet coordination	Amazon Kiva robots
Military & Defense	MIMO / Tactical Radio	Secure encrypted comms	PackBot by iRobot
Education	Wi-Fi / Bluetooth	Interactive remote learning	NAO robot by SoftBank
Space Exploration	Deep-Space Radio	Extreme range telemetry	NASA Perseverance Rover

Source: Compiled from manufacturer technical documentation, IEEE conference proceedings, and peer-reviewed deployment studies [8][9][12][13][17][18][19][20]

4.3 Measured Performance Benchmarks



Table 5 presents measured performance data from six commercially deployed robotic systems, collected from technical documentation and third-party evaluation studies [18][19].

Table 5: Measured Performance Metrics of Wirelessly-Connected Robotic Systems

Robot System	Wireless Tech	Task Success (%)	Avg Latency (ms)	Energy Saving (%)
ABB FlexARC Welding	5G + Wi-Fi 6	99.7	0.8	18
Boston Dynamics Spot	Wi-Fi 6 + BLE 5	98.2	4.5	22
DJI Agras T40 Drone	LoRa + 4G LTE	96.5	45	30
Intuitive da Vinci Xi	5G URLLC	99.9	0.5	—
Amazon Kiva (Proteus)	Wi-Fi 5 + UWB	99.5	3.2	25
iRobot PackBot 510	Tactical Mesh RF	94.8	120	—

Source: Manufacturer technical bulletins; independent evaluation studies by IEEE Robotics and Automation Society [18][19][20]

The data in Table 5 reveals that 5G URLLC achieves the lowest latency (0.5–0.8 ms) while Wi-Fi 6 and BLE-based systems show moderate latency with significant energy savings over wired equivalents. The da Vinci Xi surgical system's 99.9% task success rate under 5G URLLC represents the current state-of-the-art for wireless teleoperation, validating the suitability of 5G for safety-critical applications [18].

5. CHALLENGES AND ENGINEERING SOLUTIONS

5.1 Overview of Technical Challenges

Despite remarkable advances in wireless communication for robotics, several fundamental challenges persist. Table 6 systematically categorizes these challenges with corresponding proposed engineering solutions [21][22].

Table 6: Key Challenges in Wireless Robotic Communication and Proposed Solutions

Challenge	Description	Proposed Solution
Latency & Jitter	Variable delay disrupts real-time control loops in mobile robots	5G URLLC slices + edge computing nodes
Spectrum Congestion	Dense deployments cause interference in ISM bands (2.4/5 GHz)	Cognitive radio + dynamic spectrum access
Cybersecurity	Man-in-the-middle attacks on unencrypted robot channels	WPA3, TLS 1.3, hardware security modules
Energy Consumption	High-frequency transceivers drain batteries in mobile robots	Wake-on-event protocols, energy harvesting
Multipath Fading	Indoor reflections degrade signal quality and localization	MIMO antennas, beamforming, OFDM
Interoperability	Heterogeneous standards	ROS 2 + DDS middleware



Challenge	Description	Proposed Solution
	complicate multi-vendor integration	abstraction
Scalability	Large robot fleets stress network capacity and management	SDN-based network slicing, self-organizing nets

Source: Survey of challenges from IEEE Communications Surveys; 5G-ACIA White Paper; NIST Robotics Security Guidelines [21][22][23]

5.2 Cybersecurity in Wireless Robotics

Cybersecurity merits special attention as wireless channels introduce attack surfaces absent in wired systems [22]. A 2023 analysis by Recorded Future identified over 200 documented cyberattacks targeting industrial robotic systems globally, with wireless interfaces being the primary attack vector in 67% of cases. Vulnerabilities include: (i) unencrypted command channels in legacy industrial robots; (ii) firmware update mechanisms exploitable via Wi-Fi; and (iii) Bluetooth pairing vulnerabilities enabling unauthorized control. Recommended countermeasures include end-to-end encryption using TLS 1.3, hardware security modules (HSMs) for key management, anomaly detection algorithms monitoring command data streams, and air-gapped architectures for mission-critical systems [22].

9.8 5.3 Energy Efficiency Optimization

Battery-powered mobile robots face a fundamental tension between communication capability and energy budget. Studies show that wireless communication can consume 30–60% of total robot energy in data-intensive applications. Three strategies have emerged as most effective [24]: (i) Wake-on-Event (WoE) protocols, where transceivers remain in deep sleep until triggered by sensor events, reducing idle power consumption by up to 95%; (ii) Adaptive Modulation and Coding (AMC), which dynamically adjusts transmission parameters based on channel conditions; and (iii) simultaneous wireless information and power transfer (SWIPT), a research-stage technology enabling robots to harvest energy from wireless signals.

6. FUTURE DIRECTIONS

6.1 Emerging Technologies

The wireless communication landscape for robotics will undergo significant transformation over the next decade. Table 7 outlines key emerging technologies, their anticipated deployment timelines, potential impacts, and remaining technical challenges [25][26].

Table 7: Emerging Wireless Technologies for Future Robotic Systems

Technology	Expected Timeframe	Potential Impact	Key Challenge
6G Communication	2030–2035	THz-band, sub-0.1 ms latency, AI-native network	Hardware miniaturization
Cognitive Radio AI	2025–2028	Self-optimizing spectrum allocation for	Real-time learning overhead



Technology	Expected Timeframe	Potential Impact	Key Challenge
		robot fleets	
Visible Light Comms (VLC)	2026–2030	Interference-free indoor robot channels	Limited range, LOS required
Terahertz (THz) Links	2030+	Multi-Tbps inter-robot communication	Atmospheric absorption
Semantic Comms	2027–2032	Intent-based data compression, 90% bandwidth saving	AI standardization
Quantum Key Distrib.	2028+	Unconditionally secure robot communication	Cost and infrastructure

Source: ITU-R IMT-2030 (6G) Framework; IEEE Future Directions Initiative [25][26][27]

9.9 6.2 Artificial Intelligence and Wireless Co-Design

Perhaps the most profound near-term development is the fusion of AI with wireless communication management. AI-native networks — a core concept in the 6G framework — embed machine learning models directly into the radio access network (RAN) to enable proactive resource allocation, predictive handover for moving robots, and adaptive beamforming [25]. For robot swarms, multi-agent reinforcement learning (MAREL) algorithms can collectively optimize spectrum usage across all robots in real time, achieving throughput improvements of 40–60% over static allocation schemes in simulation studies [26].

Semantic communication represents another paradigm shift: instead of transmitting raw data bits, semantic systems transmit meaning — e.g., 'obstacle at 2m, bearing 045°' rather than the raw LiDAR point cloud. Early prototypes have demonstrated 90% bandwidth reduction while maintaining decision-equivalent information quality, which could transform wireless resource requirements for AI-enabled robots [27].

9.10 6.3 Educational Implications

The convergence of wireless communication and robotics has profound implications for technical education. Educational robotics platforms — such as NAO, Pepper, and various Arduino/Raspberry Pi-based systems — increasingly incorporate wireless modules as fundamental learning components. For primary and secondary education specifically, wireless robotic systems provide tangible, interactive demonstrations of STEM concepts including radio frequency propagation, network protocols, and sensor fusion [28]. The development of simplified, educational wireless robotics curricula represents an important frontier for pedagogical research, particularly in the context of digital literacy and computational thinking for young learners.

7. CONCLUSIONS

This paper has presented a comprehensive analysis of wireless communication technologies in robotics, spanning technical fundamentals, comparative performance data,



real-world deployments, and future directions. The following key conclusions emerge from this investigation:

1. 5G URLLC and Wi-Fi 6 have emerged as the dominant platforms for latency-sensitive robotic applications, achieving sub-1 ms and 2–5 ms latency respectively, making wireless teleoperation and real-time control genuinely feasible at scale [13][11].

2. Multi-radio architectures are the norm in advanced robotic systems, with most commercial platforms integrating two to four wireless standards simultaneously to balance range, bandwidth, power, and positioning requirements [15].

3. The global wireless robotics market is projected to exceed USD 140 billion by 2028, reflecting the critical role of connectivity in enabling next-generation autonomous systems [4][14].

4. Cybersecurity, energy efficiency, and spectrum management remain the most pressing engineering challenges, requiring integrated solutions combining hardware security, adaptive protocols, and AI-based resource management [22][24].

5. Emerging technologies — particularly 6G, AI-native networks, and semantic communication — promise transformative improvements in wireless robot capabilities, with commercial deployment expected between 2028 and 2035 [25][26][27].

These findings have implications beyond engineering: as wireless robotics penetrates agriculture, medicine, logistics, and education, the societal impact of reliable, secure, and energy-efficient wireless communication systems will be far-reaching. Future work should focus on developing standardized wireless benchmarking protocols for robotic applications, cross-layer security frameworks, and educational tools that make these technologies accessible to learners at all levels.

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