Journal of Science Research and Reviews
PRINT ISSN: 1595-9074
E-ISSN: 1595-8329
DOI: https://doi.org/10.70882/josrar.2026.v3i3.271
Homepage: https://josrar.esrgngr.org
Review Article

Internet of Things-Based Smart Parking Systems: An Integrative Review of Architectures, Technologies and Deployment Challenges

[1]Babatunde Emmanuel Olagoke, *[2]Adewale Abayomi Alabi, [3]Akinwale Olusola Ojoawo, [1]Olasunkanmi Olaogun Ogundipe and [2]Bolarinwa Samson Adeleke

[1]Department of Civil Engineering, Adeseun Ogundoyin Polytechnic, Eruwa, Oyo State, Nigeria
[2]Department of Electrical Engineering, Adeseun Ogundoyin Polytechnic, Eruwa, Oyo State, Nigeria
[3]Department of Computer Science, Adeseun Ogundoyin Polytechnic, Eruwa, Oyo State
*Corresponding Author's email: adewalealabi01@gmail.com

KEYWORDS
Internet of Things,
Smart Parking,
Wireless Sensor Networks,
Edge Computing,
Intelligent Transportation Systems,
Cybersecurity.

ABSTRACT
Rapid urbanisation, increasing vehicle ownership and inefficient parking operations have intensified search traffic, congestion and underutilisation of parking resources. This paper presents an integrative review of Internet of Things (IoT)-based smart parking systems, with emphasis on architecture, enabling technologies, operational requirements and deployment in resource-constrained environments. A transparent search and thematic-synthesis procedure was applied to 28 sources comprising 24 peer-reviewed publications and four recognised technical standards. Evidence was extracted on sensing and identification, communication, edge-fog-cloud processing, application services, security, performance evaluation and implementation constraints. The synthesis shows that reliable smart parking is not produced by a sensor or mobile application alone; it depends on coordinated responsibilities across six layers: perception and identification, edge and gateway processing, communication, platform and data management, application services, and security and governance. Ultrasonic, magnetic, infrared, inductive and camera-based methods provide different trade-offs in accuracy, coverage, energy demand, privacy and lifecycle cost. Wi-Fi and ZigBee are suited to bound facilities, while LoRaWAN and NB-IoT support dispersed low-power deployments. Edge and fog processing improve responsiveness and continuity, whereas cloud services support historical analysis and multi-site management. The review identifies persistent weaknesses in short-term prototype evaluation, cybersecurity, interoperability, maintenance planning, cost reporting and evidence from African cities. A phased, context-sensitive deployment framework and a multidimensional evaluation set are proposed for campuses, hospitals, commercial facilities and municipal parking environments.

CITATION
Olagoke, B. E., Alabi, A. A., Ojoawo, A. O., Ogundipe, O. O., & Adeleke, B. S. (2026). Internet of Things-Based Smart Parking Systems: An Integrative Review of Architectures, Technologies and Deployment Challenges. *Journal of Science Research and Reviews*, *3*(3), 228-239. https://doi.org/10.70882/josrar.2026.v3i3.271

INTRODUCTION

Parking is a necessary component of urban mobility because most private-vehicle journeys begin and end with a parking event. When information about available spaces is incomplete, drivers enter full facilities, circulate through parking aisles or cruise on nearby roads while searching for a suitable space. This behaviour increases travel time, fuel consumption, local emissions and driver frustration, and it can obstruct access routes around hospitals, universities, markets, airports, worship centres, stadiums and government complexes (Al-Turjman & Malekloo, 2019; Biyik et al., 2021).

Conventional parking management commonly depends on attendants, barrier gates, paper tickets, periodic visual inspection and static signboards. These methods may be adequate in small facilities with stable demand, but they do not create a continuously updated digital representation of occupancy. An operator may know the nominal capacity of a car park without knowing which spaces are free, how long vehicles remain, where queues are forming or when demand is likely to exceed supply. Consequently, drivers make decisions with limited information, while managers lack reliable evidence for allocation, pricing, maintenance and enforcement.

The Internet of Things (IoT) provides a technical basis for closing this information gap by linking physical objects, sensors, embedded processors, communication networks and software services. In a smart parking service, a sensor observes the presence or absence of a vehicle; an edge device or gateway validates the reading; a network transports the event; a platform updates the state of the space; and an application presents information to a driver or operator. More advanced systems may support vehicle identification, reservation, digital payment, access control, prediction, incident detection and integration with intelligent transportation systems (Barriga et al., 2019; Fahim et al., 2021).

Smart parking should therefore be treated as a cyber-physical service rather than as the installation of a single sensor type or the development of a mobile application. Physical events and digital decisions influence one another: a sensor event can change a reservation, redirect a driver, activate a bay indicator, open a barrier or initiate payment. Accurate sensing is insufficient when communication is unstable, events are applied to the wrong space, reservations are duplicated or the platform cannot recover from failure. Dependable service requires consistent state management across devices, networks, software and institutional procedures.

Earlier studies established cloud middleware, sensor-based prototypes, camera analytics, resource allocation and wireless sensor networks, while later work introduced low-power wide-area communication, fog and edge computing, predictive analytics and reusable architectures (Amato et al., 2017; Geng & Cassandras, 2013; Ji et al., 2014; Kadusic et al., 2022). However, the evidence base remains fragmented. Many prototypes monitor few spaces for short periods, cost estimates omit civil works and maintenance, security is considered after design, and performance is frequently reduced to detection accuracy even though latency, packet delivery, availability, recovery time, reservation consistency and user adoption are also critical (Alam et al., 2023; Lee et al., 2022).

These limitations are particularly important in developing urban environments, where irregular power supply, uneven network coverage, constrained budgets and limited specialist maintenance capacity can determine whether a pilot becomes sustainable infrastructure. African smart-city research also stresses the need to align technology with institutional readiness, inclusion and local service priorities rather than importing high-cost models without adaptation (Echendu & Okafor, 2021). Accordingly, this paper reviews the architecture, technologies, operating workflow, implementation requirements, benefits and limitations of IoT-based smart parking. Its specific contribution is an evidence-informed six-layer reference architecture, a context-sensitive implementation framework and a multidimensional set of performance measures for real deployments.

MATERIALS AND METHODS

Review Design

An integrative review design was adopted to combine evidence from empirical prototypes, architecture studies, technical surveys and recognised IoT standards. This design was selected because smart parking research spans electrical and electronic engineering, computer science, civil and transportation engineering, information systems, cybersecurity and urban management. The purpose was not to calculate a pooled statistical effect, because the studies use heterogeneous technologies, settings and performance measures, but to identify recurring design responsibilities, compare technological trade-offs and derive an implementation-oriented reference framework.

Search Strategy and Eligibility

Source identification used targeted searches of Google Scholar, IEEE Xplore, ScienceDirect, SpringerLink and publisher platforms. The search was updated in July 2026. Search strings combined the terms “Internet of Things” OR IoT with “smart parking”, “parking occupancy detection”, “wireless sensor network”, RFID, LoRaWAN, NB-IoT, edge computing, fog computing, cloud parking, computer vision, parking prediction, reservation, digital payment, cybersecurity and intelligent transportation systems. Reference lists of relevant reviews and implementation papers were also examined to identify foundational and closely related studies.

Sources were eligible when they: (i) addressed parking as the principal application; (ii) described a sensing, identification, communication, computing, allocation, security or implementation method; (iii) reported an architecture, prototype, comparative evaluation, field deployment or substantial review; and (iv) were available in English with sufficient methodological or technical detail. Purely promotional descriptions, duplicate reports, brief papers without technical detail and publications that mentioned parking only as an incidental smart-city example were excluded. Recognised standards were retained where they directly informed communication security, IoT device capabilities or messaging.

Data Extraction and Synthesis

For each retained publication, information was extracted on publication year, deployment context, sensing or identification technology, communication method, processing location, user services, security considerations, reported evaluation measures and principal limitations. The extracted evidence was coded under eight themes: evidence characteristics; architecture; occupancy sensing and identification; communication and computing; platform and application services; implementation and lifecycle management; security, privacy and governance; and performance evaluation. Cross-study comparison was used to distinguish stable responsibilities from replaceable technologies, leading to the six-layer architecture presented in this paper.

The final evidence base comprised 28 sources: 24 peer-reviewed journal or conference publications and four recognised technical standards. The corpus included foundational work from 2013 onward and recent studies through 2025. The review does not claim exhaustive retrieval or meta-analytic generalisation; rather, it provides a transparent integrative synthesis of representative, technically detailed and implementation-relevant evidence. This limitation is considered when conclusions are drawn.

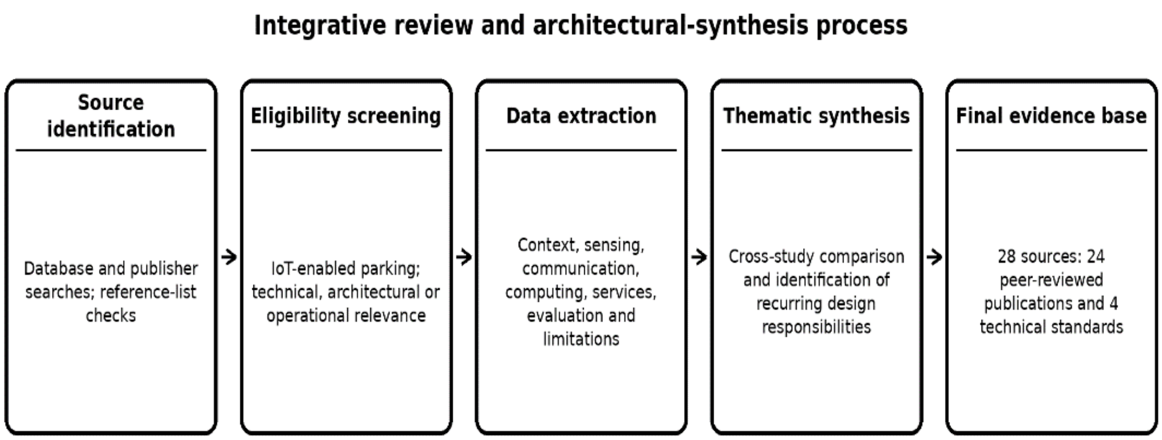

Figure 1: Integrative review and architectural-synthesis process

RESULTS AND DISCUSSION

Characteristics and Evolution of the Evidence Base

The reviewed literature shows a clear progression from isolated vacancy detection towards integrated parking services. Foundational work concentrated on cloud middleware, resource allocation and the feasibility of connecting field devices to a common platform (Geng & Cassandras, 2013; Ji et al., 2014). Subsequent studies compared sensor families and demonstrated decentralised camera analytics, while broad reviews consolidated sensing, networking, computation and application taxonomies (Amato et al., 2017; Barriga et al., 2019; Paidi et al., 2018).

From 2020 onward, the field increasingly addressed modular backend services, low-power wide-area communication, fog and edge processing, prediction and practical campus deployment. Barriga et al. (2020) combined LoRaWAN, MQTT and containerised services; Balfaqih et al. (2021) distributed processing through fog nodes; Kadusic et al. (2022) integrated NB-IoT with a core IoT platform; and Jabbar et al. (2024) examined long-range communication and energy-aware field sensing. Recent studies have expanded towards machine-learning prediction, number-plate recognition, reference architectures and practical fog-cloud comparison (Ala'anzy et al., 2025; Ditta et al., 2025; Enríquez et al., 2024; Ozkaya & Turunc, 2025).

Despite this development, the studies remain difficult to compare because they differ in scale, environment, duration and reported measures. Some report sensor accuracy, others focus on communication range, platform design, latency or user services, and only a limited number provide long-term maintenance or lifecycle-cost evidence. Table 1 therefore summarises the contribution and principal implication of selected studies without treating unlike evaluations as directly equivalent.

Table 1: Evidence Profile of Selected Smart Parking Studies

Study	Context or approach	Principal contribution	Limitation or implementation implication
Geng & Cassandras (2013)	Urban allocation and reservation model	Optimised assignment using driver cost, proximity and parking price	Strong allocation logic; depends on reliable real-time inventory and user compliance.
Ji et al. (2014)	Cloud middleware for smart cities	Separated field devices from reusable parking information services	Supports integration but increases dependence on connectivity and central services.
Amato et al. (2017)	Smart-camera occupancy detection	Compact CNN executed near the camera and evaluated across visual datasets	Wide coverage; performance remains sensitive to viewpoint, occlusion and environmental change.
Barriga et al. (2020)	LoRaWAN and Kubernetes architecture	Separated low-power sensing, messaging and scalable backend services	Modularity aids scaling, but operations require gateway, cluster and security expertise.
Jabbar et al. (2021)	Raspberry Pi smart-campus prototype	Combined ultrasonic sensing, camera support and mobile access	Useful feasibility evidence; small prototypes do not establish city-scale reliability.
Balfaqih et al. (2021)	Fog-enabled reservation system	Moved time-sensitive processing closer to the parking site	Reduces cloud dependence; fog-node availability and management become new requirements.
Kadusic et al. (2022)	NB-IoT platform integration	Used licensed LPWAN infrastructure for sensor connectivity and services	Managed coverage is attractive; recurring subscription and operator dependence must be budgeted.
Nasim et al. (2022)	University of Oulu pilot	Integrated sensors, application services and longitudinal occupancy analysis	Demonstrates institutional use; site-specific findings require cautious generalisation.
Enríquez et al. (2024)	Fog and occupancy prediction	Combined local processing with machine-learning forecasting	Prediction improves planning but requires representative data and drift monitoring.
Jabbar et al. (2024)	LoRaWAN outdoor deployment	Combined magnetic/ultrasonic sensing and solar-assisted power	Addresses range and energy; enclosure, gateway placement and field maintenance remain critical.
Ozkaya & Turunc (2025)	Reference-architecture study	Defined reusable responsibilities and components for parking management	Improves design consistency; reference models still require context-specific validation.
Ala'anzy et al. (2025)	Fog-cloud evaluation and campus case	Compared latency, cost, network use and energy across architectures	Supports multidimensional evaluation and local processing, but wider longitudinal evidence is needed.

Six-Layer Reference Architecture

A dependable smart parking system can be organised into six coordinated layers: perception and identification, edge and gateway processing, communication, platform and data management, application services, and security and governance. These layers describe responsibilities rather than mandatory products. A small facility may combine several responsibilities in one device, whereas a municipal deployment may distribute them across many devices, gateways and cloud services. The layered structure separates relatively stable functions from replaceable technologies, thereby supporting scalability, interoperability and staged procurement (Barriga et al., 2020; Ozkaya & Turunc, 2025).

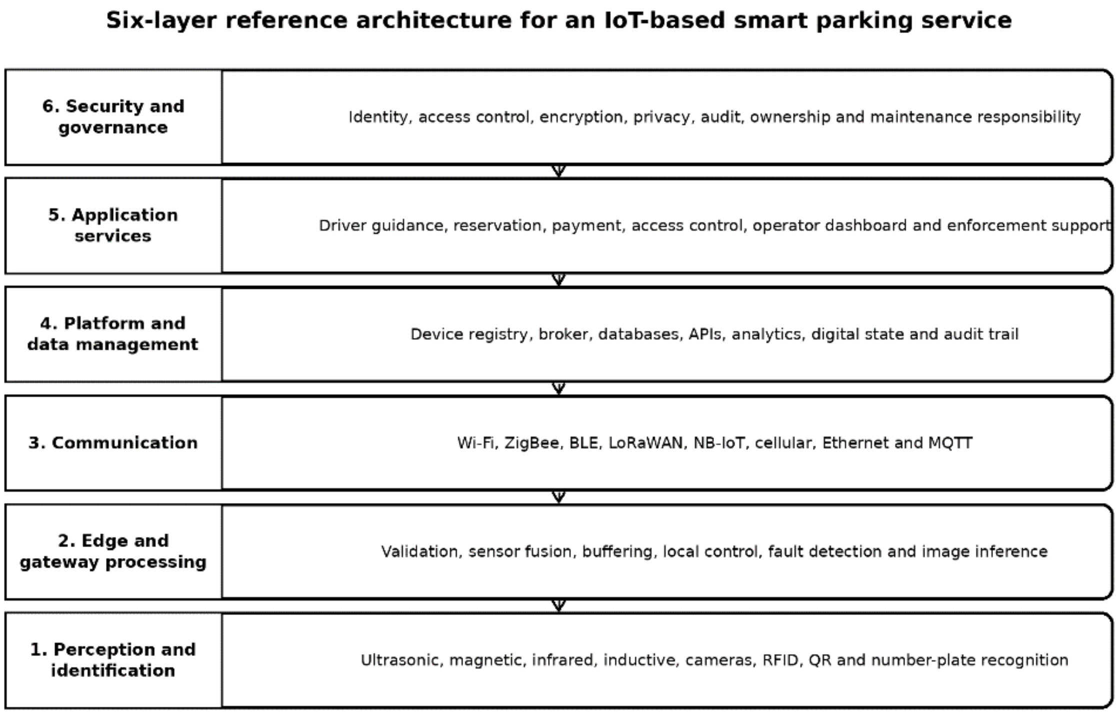

Figure 2: Six-layer reference architecture for an IoT-based smart parking service

Perception and Identification Layer

The perception layer observes the physical parking environment. It includes ultrasonic, magnetic, infrared, inductive and camera-based sensors, together with RFID readers, QR-code scanners and automatic number-plate recognition. Its principal output is a time-stamped occupancy or identity event linked to a unique space, zone, vehicle or access point. Device choice should follow site conditions rather than laboratory specifications: outdoor nodes require protection against rain, dust, heat, flooding, vibration and vandalism, while indoor facilities may permit overhead installation and continuous power (Paidi et al., 2018; Perković et al., 2020).

Occupancy and identity should be treated as different data types. A system may know that a vehicle entered without knowing where it parked, or may know that a space is occupied without identifying the vehicle. Combining the two can support permits, enforcement and ticketless payment, but identifiable information should be collected only where there is a clear operational purpose. Sensor health, battery level, calibration status and communication quality should also be monitored because an undetected device failure can leave a space falsely occupied or falsely vacant for long periods.

Edge and Gateway Processing Layer

Edge devices aggregate field messages, authenticate devices, filter unstable readings, combine sensors, perform camera inference and buffer events during connectivity loss. A gateway should not merely forward raw data; it should support local time synchronisation, fault detection, secure configuration, software updates and controlled recovery. Essential functions such as permit verification, barrier operation and local display should continue through cached rules when the remote platform is temporarily unavailable (Balfaqih et al., 2021; Lee et al., 2022).

Local processing is particularly valuable for camera systems because raw images can be analysed at the site and replaced with occupancy states or anonymised metadata. This reduces bandwidth and privacy exposure. However, edge intelligence also creates responsibilities for model updates, hardware capacity, local security and consistency between distributed nodes.

Communication Layer

The communication layer transports events among sensors, gateways, servers and applications. Wi-Fi, ZigBee and Bluetooth Low Energy are appropriate for bounded facilities, whereas LoRaWAN, NB-IoT and conventional cellular networks support dispersed deployments. Wired Ethernet remains suitable for fixed gateways, cameras and barrier controllers where cabling is feasible. The selection involves trade-offs among range, throughput, energy use, infrastructure dependence, recurring cost and latency (Barriga et al., 2020; Kadusic et al., 2022).

Compact occupancy and health messages can travel over low-power networks, while video requires higher bandwidth and usually local processing. MQTT is widely adopted because its publish-subscribe model decouples devices from applications, but dependable operation requires appropriate quality-of-service settings, acknowledgement, retained-message policies, buffering, transport encryption and credential management (OASIS, 2019).

Platform and Data Management Layer

The platform maintains the authoritative digital state of the parking environment. It includes device registries, message brokers, databases, application programming interfaces, analytics services and administrative tools. Raw readings should be distinguished from validated occupancy states, and important changes should retain an audit trail. Each space, device, reservation and transaction requires a stable identifier, while timestamps must allow delayed and out-of-order events to be reconciled (Ji et al., 2014).

Interoperability depends on more than a common communication protocol. Systems must agree on identifiers, units, event meanings, error handling and state transitions. Open, documented interfaces and export capability reduce vendor dependence and permit integration with payment, navigation, access-control and municipal systems. A balanced architecture keeps latency-sensitive or privacy-sensitive processing near the site while using cloud services for historical analysis, model training and cross-facility coordination.

Application Services Layer

Application services convert parking data into actions for drivers, operators and authorities. Driver interfaces may display availability, recommend a facility, guide a user, reserve a space, calculate charges and confirm payment. Operator dashboards may show occupancy, turnover, queue conditions, device faults, revenue and enforcement status. Roadside displays and assisted channels are necessary for users without smartphones, mobile data or bank cards.

Applications should communicate uncertainty rather than imply absolute precision where updates may be delayed. A facility-level probability or availability band may be more honest than advertising one exact space that may be occupied before the driver arrives. Reservation rules should define booking duration, grace periods, cancellation, expiry and penalties, and must prevent duplicated allocation (Geng & Cassandras, 2013; Kotb et al., 2016).

Security and Governance Layer

Security and governance cut across all other layers. Devices require unique credentials, protected configuration, secure update procedures and, where feasible, secure boot. Communication should use authentication and encryption, while platforms require least-privilege access, role separation, logging, backup and incident response. Baseline controls should be aligned with recognised guidance for IoT devices, consumer IoT security and transport security (ETSI, 2024; IETF, 2018; NIST, 2020).

Governance determines who owns the data, replaces batteries, calibrates sensors, approves software changes, responds to faults and authorises access to identifiable records. Anonymous occupancy detection presents lower privacy risk than number-plate recognition, mobile tracking or payment records. Data minimisation, defined retention, local image processing and auditable access should therefore be incorporated at design stage rather than added after deployment.

Enabling Technologies and Design Trade-offs

Occupancy Sensing and Vehicle Identification

Ultrasonic sensors estimate the distance between a transducer and the nearest object. They are inexpensive and straightforward to integrate, especially in covered parking facilities, but performance can be affected by mounting angle, temperature, irregular vehicle surfaces and environmental turbulence. Outdoor installation requires waterproof enclosures and careful calibration.

Magnetic sensors detect changes in the local magnetic field produced by a vehicle. Their low energy demand makes them attractive for outdoor slot-level monitoring, but installation may require civil work and readings can be influenced by nearby metal structures, electromagnetic interference and differences in vehicle construction. Infrared sensors are also inexpensive, although sunlight, dust, rain, alignment and obstruction can reduce reliability. Inductive loops are mature and dependable at entrances and exits but require pavement cutting and are costly to install at every space (Paidi et al., 2018; Perković et al., 2020).

Camera-based systems can observe multiple spaces and may also support classification, security and number-plate recognition. Decentralised deep-learning approaches demonstrate that compact models can operate near the camera, reducing transmission requirements (Amato et al., 2017). Nevertheless, camera performance depends on lighting, weather, occlusion, viewing angle and lens cleanliness, and identifiable images create stronger privacy obligations. Hybrid sensing can reduce false detection by combining complementary observations, but it increases hardware, integration and maintenance complexity.

RFID is suitable for permit-controlled facilities because a passive or active tag can identify an authorised vehicle or user. QR codes and mobile tokens provide low-cost temporary access, whereas automatic number-plate recognition supports contactless entry, enforcement and ticketless payment. Identification should not be collected by default merely because a system is technically capable of doing so; the data should be proportionate to a defined operational need (Ditta et al., 2025).

Table 2: Comparison of Common Parking Occupancy Technologies

Technology	Coverage	Strengths	Main limitations	Suitable context
Ultrasonic	One space	Low cost; simple integration; effective indoors	Mounting, temperature and weather sensitivity	Indoor and covered facilities
Magnetic	One space	Low energy; suitable for outdoor bays	Civil work, interference and calibration	On-street and open parking
Infrared	One space or lane	Inexpensive and easy to interface	Sunlight, dust, rain and alignment effects	Controlled indoor locations
Inductive loop	Lane or selected bay	Mature and dependable detection	Pavement cutting and repair cost	Entrances, exits and selected bays
Camera vision	Multiple spaces	Wide coverage; classification and ANPR	Lighting, occlusion, processing and privacy	Large facilities with clear sight lines
Hybrid sensing	One or multiple spaces	Improved confidence and fault detection	Higher cost and integration complexity	Critical or environmentally difficult sites

Communication and Computing Options

Wi-Fi provides familiar integration and relatively high throughput, making it appropriate for indoor facilities or campuses with existing coverage. Its disadvantages are higher energy demand, congestion and limited outdoor range. ZigBee supports low-power mesh networking in bounded facilities, although metal structures, node density and routing stability affect performance. Bluetooth Low Energy is useful for proximity services, beacons and local configuration but generally covers a smaller area.

LoRaWAN is well suited to compact status messages from dispersed, battery-powered nodes. Gateway placement, network capacity and regional transmission limits must be considered, and it cannot carry high-volume video. NB-IoT uses licensed cellular infrastructure and can provide managed wide-area coverage and deep penetration, but subscription charges and mobile-operator dependence must be included in lifecycle planning. Conventional 4G or 5G is more appropriate for gateways and cameras than for every battery-powered bay sensor (Barriga et al., 2020; Jabbar et al., 2024; Kadusic et al., 2022).

Edge computing processes data at or near the parking site and supports low latency, reduced bandwidth and continuity during Internet outages. Fog computing coordinates intermediate processing across several zones or facilities. Cloud computing provides elastic storage, central management, historical analytics and model training. Evidence increasingly supports a hybrid arrangement in which immediate control and privacy-sensitive inference remain local while cloud services provide aggregation and wider coordination (Ala'anzy et al., 2025; Balfaqih et al., 2021; Enríquez et al., 2024).

Table 3: Comparison of Communication Options for Smart Parking

Technology	Range	Data rate	Energy use	Main advantage	Main constraint
Wi-Fi	Short to medium	High	Moderate to high	Existing infrastructure and bandwidth	Coverage and battery demand
ZigBee	Short; mesh extendable	Low	Low	Low-power local networking	Mesh planning and interference
Bluetooth Low Energy	Short	Low to moderate	Very low	Phone compatibility and proximity services	Limited area coverage
LoRaWAN	Long	Low	Very low	Wide-area low-power status messages	Payload, capacity and gateway planning
NB-IoT	Wide cellular	Low to moderate	Low	Managed licensed coverage	Subscription and operator dependence
4G/5G	Wide cellular	High	High	Video and gateway connectivity	Cost and energy demand

Operating Workflow and Implementation Framework

A typical operating cycle begins when a sensor or access device records an event. The device attaches its identifier, timestamp and status and transmits the message to a gateway or network service. The gateway validates the source, filters unstable readings and forwards a compact event. The platform then reconciles the event with the authoritative state of the parking space, reservation and payment record before publishing an update to applications, dashboards or displays.

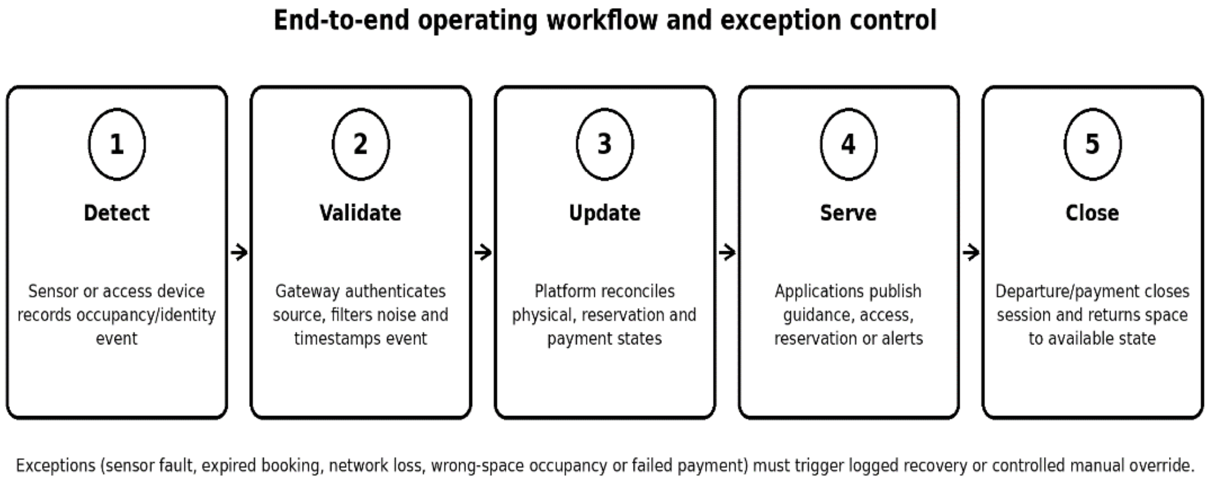

Figure 3: End-to-end operating workflow and exception control

When a driver requests parking, the application may combine current availability with travel time, access restrictions and predicted demand. Where reservation is supported, the platform changes a space from free to reserve and starts an expiry timer. On arrival, the driver may be identified through RFID, a mobile token, number-plate recognition or a ticket. Occupancy sensing verifies the physical event, and the platform should reconcile cases in which a driver uses a different space rather than preserving contradictory records.

At departure, an exit event or sensor transition closes the session, charges are calculated and confirmed, and the space returns to the available state. The workflow must also specify what happens when a sensor fails, a reservation expires, a driver occupies the wrong space, payment is interrupted, connectivity is lost or a barrier cannot open. Controlled manual override should be available and logged because a system that supports only the ideal path will perform poorly in real operations.

Implementation should begin with a clearly defined operational problem, such as unreliable availability information, entrance congestion, revenue leakage, unauthorised parking or weak planning data. Stakeholders should map existing rules, user categories, peak periods and service levels before equipment is purchased. A physical survey should document space layout, surface type, drainage, weather exposure, lighting, power sources, network coverage, cable routes, gateway locations and camera sight lines.

Baseline measures should be collected before installation, including occupancy by time of day, search time, queue length, turnover, violation rate, payment method and user complaints. Technology selection should use a weighted comparison of accuracy, environmental robustness, installation complexity, power demand, coverage, security, interoperability, maintenance skill and lifecycle cost. The architecture should also define data ownership, interfaces, failure modes and which functions continue locally during connectivity loss.

A pilot should test representative and difficult locations rather than only the easiest spaces. It should run long enough to expose weather, battery, enclosure, communication and maintenance problems. Success criteria should be agreed in advance and include more than the appearance of data on a dashboard. Before wider rollout, devices should be issued unique credentials; default passwords should be removed; encryption, access roles, backup, logging and software-update procedures should be tested; and payment or access-control integrations should fail safely.

Rollout should proceed by zone so that defects can be corrected before affecting the whole facility. Operators, attendants and technicians require practical training in sensor diagnosis, controlled override, device replacement, alert interpretation and incident escalation. Maintenance plans should cover inspection, cleaning, calibration, battery replacement, enclosure repair, credential rotation, firmware support and spare parts. Lifecycle cost includes hardware, civil work, gateways, connectivity, cloud services, software support, cybersecurity, staff time and disposal—not purchase price alone.

Performance Evaluation

Detection accuracy is necessary but insufficient. It should be reported through true-positive, true-negative, false-positive and false-negative rates across different vehicle types, weather conditions, times and installation positions. A false vacancy directly misguides a driver, while a false occupancy reduces apparent capacity.

End-to-end latency measures the time between a physical change and its appearance in an application or display. Packet-delivery ratio measures the proportion of expected messages received; service availability measures the time during which required functions remain usable; and recovery time measures how quickly normal operation returns after failure. Energy and maintenance evaluation should include battery life, energy per message, mean time between failures, number of site visits, replacement rate and repair time (Ala'anzy et al., 2025; Jabbar et al., 2024).

Application and operational measures include reservation success, cancellation and expiry, payment completion, user adoption, search-time reduction, occupancy, turnover, queue length, revenue assurance and violation rate. Environmental claims should be based on measured changes in search distance, fuel use or emissions rather than assumed benefits. Laboratory, pilot and operational performance should be reported separately because short controlled tests do not demonstrate city-scale or long-term effectiveness.

Table 4: Recommended Performance Measures For Operational Evaluation

Category	Measure	Purpose
Sensing	False vacancy, false occupancy and confusion matrix	Determines whether information presented to users is trustworthy.
Communication	Packet delivery, latency and message age	Shows whether correct readings arrive completely and on time.
Availability	Service uptime, degraded-mode operation and recovery time	Assesses resilience to gateway, network and platform failure.
Energy	Battery life and energy per event	Tests whether field nodes can be maintained economically.
Maintenance	Failure rate, site visits and repair time	Reveals operational burden that component price may conceal.
User service	Search-time reduction, reservation success and payment completion	Measures practical benefit rather than technical function alone.
Economics	Lifecycle cost, revenue assurance and cost per monitored space	Supports procurement and scale decisions.
Governance	Security incidents, access-log review and privacy compliance	Measures responsible operation and accountability.

Benefits, Limitations and Relevance to Developing Environments

Accurate and timely availability information can reduce unnecessary circulation and direct drivers to facilities or zones with usable capacity. Historical occupancy data can reveal underused spaces, uneven demand and long-stay behaviour, supporting allocation, permits, pricing, staffing and maintenance. Electronic records can also improve revenue assurance and reduce dependence on manual cash handling. These benefits are conditional: information that is late or inaccurate can worsen rather than reduce search behaviour (Biyik et al., 2021; Fahim et al., 2021).

Smart parking can improve accessibility when priority spaces are represented accurately, protected from general allocation and supported by readable interfaces, roadside displays and assisted payment channels. Conversely, mandatory applications and cashless-only payment can exclude users without smartphones, mobile data or bank accounts. Inclusive service design should therefore be treated as a functional requirement rather than an optional addition.

The principal technical limitations are sensor exposure, communication failure, energy demand and scale. Outdoor devices face rain, dust, heat, flooding, vibration, impact and vandalism. Wireless propagation changes as vehicles and structures obstruct signals, gateways may fail, and high event volumes can overload brokers, databases and APIs. Battery replacement across hundreds of bays can become a major operating cost, while cameras, displays and barriers require dependable mains or backup power.

Cybersecurity and privacy risks increase when parking services connect sensors, barriers, payment systems, mobile accounts and number-plate records. Default credentials, insecure firmware, exposed interfaces and weak network separation can permit false occupancy, service disruption or access to connected systems. Identifiable data can reveal movement patterns and should be minimised, protected and retained only for a defined purpose (ETSI, 2024; Lee et al., 2022; NIST, 2020).

Interoperability and institutional capacity are equally important. Proprietary protocols and data formats can lock an organisation into one vendor, while unclear responsibility allows faults and outdated software to accumulate. A modest, maintainable system with documented interfaces is preferable to a sophisticated deployment that the institution cannot support. Procurement should include training, source or interface documentation, spare parts, support periods, export rights and vulnerability-handling procedures.

Developing cities frequently combine rapid vehicle growth with informal parking practices, unstable electricity, uneven communication coverage and constrained public budgets. These conditions do not make smart parking impossible, but they favour phased, low-complexity and locally maintainable designs. Campuses, hospitals and institutional compounds offer manageable starting points because their boundaries, users and parking rules are clearer than those of an entire city. Low-power communication, edge buffering, hybrid power and alternatives to smartphone-only access are especially valuable (Echendu & Okafor, 2021; Nasim et al., 2022).

In Nigeria and comparable settings, early phases can focus on occupancy monitoring, operator dashboards and maintenance discipline before introducing reservation, dynamic pricing or extensive identification. Technology cannot compensate for unclear bay markings, weak enforcement, blocked drainage or contradictory parking rules. Municipal projects should therefore be integrated with road design, enforcement, public transport and data governance.

Research Gaps, Future Directions and Deployment Recommendations

The most persistent research gap is the distance between prototype success and sustainable infrastructure. Future studies should report seasonal performance, device failure, maintenance visits, end-to-end latency, recovery after outage, reservation consistency, user behaviour and lifecycle cost. Common definitions and reporting templates are needed so that evidence from different systems can be compared without treating unlike metrics as equivalent (Alam et al., 2023).

Edge artificial intelligence and sensor fusion can improve local inference and reduce transmission of raw images. Research should compare not only classification accuracy but also energy demand, model-update requirements, environmental generalisation and explainability. Systems should reconcile slot sensors, entry counts, camera observations and transaction records to estimate confidence and identify inconsistent states.

Predictive allocation can estimate whether a facility is likely to remain available when a driver arrives, while digital twins can simulate demand, maintenance and policy changes. Prediction outputs should include uncertainty and be monitored for drift because demand patterns change with events, academic calendars, land use and transport policy (Enríquez et al., 2024).

Parking and electric-vehicle charging will increasingly operate as connected services. A space may be physically vacant but unavailable because its charger is reserved, faulty or required by another vehicle. Future platforms must coordinate occupancy, charging demand, dwell time, electricity price and grid constraints while maintaining fair access.

Connected and autonomous vehicles will require interoperable reservation, localisation and access messages. Near-term research should prioritise interfaces that serve both human-driven and connected vehicles rather than assuming immediate full autonomy. Privacy-preserving analytics, local inference, aggregation and verifiable access controls should be developed alongside these services (Khalid et al., 2021).

For deployment, organisations should first define the operational problem and measurable success criteria; conduct site and baseline surveys; test sensors and communication in representative locations; use stable identifiers and documented interfaces; preserve essential local operation during outages; design security and privacy from the beginning; budget maintenance and training; evaluate pilots with technical, user, economic and governance measures; and expand only after operational defects have been corrected.

CONCLUSION

IoT-based smart parking connects physical occupancy with digital information and services. Its value does not arise from a single sensor, network or application but from the coordinated performance of perception, edge processing, communication, data management, application services, security and governance. The six-layer architecture developed in this review makes these responsibilities explicit and supports the replacement or scaling of individual technologies without redesigning the entire service.

Technology selection must be context-sensitive. Ultrasonic, magnetic, infrared, inductive and camera-based approaches offer different trade-offs in coverage, power, installation and privacy. Wi-Fi, ZigBee, Bluetooth Low Energy, LoRaWAN, NB-IoT and cellular communication suit different scales and data requirements. Edge and fog computing improve responsiveness and resilience, while cloud platforms support historical analysis and multi-site coordination.

The principal barriers are environmental exposure, network and power failure, cybersecurity, privacy, interoperability, lifecycle cost, maintenance capacity and user acceptance. These issues should be addressed through realistic baseline measurement, phased implementation, multidimensional evaluation and clearly assigned institutional responsibility. For developing environments, local skills, power resilience, inclusive access and maintainability are as important as technological sophistication.

Future progress should be judged by sustained improvements in access, utilisation, reliability, cost and public value rather than by short-term prototype accuracy. Longitudinal and context-rich studies, particularly from African cities, are required to determine how smart parking can be operated responsibly as durable urban infrastructure.

REFERENCES

Al-Turjman, F., & Malekloo, A. (2019). Smart parking in IoT-enabled cities: A survey. Sustainable Cities and Society, 49, 101608. https://doi.org/10.1016/j.scs.2019.101608

Ala'anzy, M. A., Abilakim, A., Zhanuzak, R., & Li, L. (2025). Real time smart parking system based on IoT and fog computing evaluated through a practical case study. Scientific Reports, 15, 33483. https://doi.org/10.1038/s41598-025-15507-6

Alam, M. R., Saha, S., Bostami, M. B., Islam, M. S., Aadeeb, M. S., & Islam, A. K. M. M. (2023). A survey on IoT driven smart parking management system: Approaches, limitations and future research agenda. IEEE Access, 11, 119523–119543. https://doi.org/10.1109/ACCESS.2023.3327306

Amato, G., Carrara, F., Falchi, F., Gennaro, C., Meghini, C., & Vairo, C. (2017). Deep learning for decentralized parking lot occupancy detection. Expert Systems with Applications, 72, 327–334. https://doi.org/10.1016/j.eswa.2016.10.055

Balfaqih, M., Jabbar, W. A., Khayyat, M., & Hassan, R. (2021). Design and development of smart parking system based on fog computing and Internet of Things. Electronics, 10(24), 3184. https://doi.org/10.3390/electronics10243184

Barriga, J. J., Sulca, J., León, J. L., Ulloa, A., Portero, D., Andrade, R., & Yoo, S. G. (2019). Smart parking: A literature review from the technological perspective. Applied Sciences, 9(21), 4569. https://doi.org/10.3390/app9214569

Barriga, J. J., Sulca, J., León, J., Ulloa, A., Portero, D., García, J., & Yoo, S. G. (2020). A smart parking solution architecture based on LoRaWAN and Kubernetes. Applied Sciences, 10(13), 4674. https://doi.org/10.3390/app10134674

Biyik, C., Allam, Z., Pieri, G., Moroni, D., O'Fraifer, M., O'Connell, E., Olariu, S., & Khalid, M. (2021). Smart parking systems: Reviewing the literature, architecture and ways forward. Smart Cities, 4(2), 623–642. https://doi.org/10.3390/smartcities4020032

Ditta, A., Ahmed, M. M., Mazhar, T., Shahzad, T., Alahmed, Y., & Hamam, H. (2025). Number plate recognition smart parking management system using IoT. Measurement: Sensors, 37, 101409. https://doi.org/10.1016/j.measen.2024.101409

Echendu, A. J., & Okafor, P. C. C. (2021). Smart city technology: A potential solution to Africa's growing population and rapid urbanization? Development Studies Research, 8(1), 82–93. https://doi.org/10.1080/21665095.2021.1894963

Enríquez, F. J., Mejía-Muñoz, J.-M., Bravo, G., & Cruz-Mejía, O. (2024). Smart parking: Enhancing urban mobility with fog computing and machine learning-based parking occupancy prediction. Applied System Innovation, 7(3), 52. https://doi.org/10.3390/asi7030052

European Telecommunications Standards Institute. (2024). Cyber security for consumer Internet of Things: Baseline requirements (ETSI EN 303 645 V3.1.3).

Fahim, A., Hasan, M., & Chowdhury, M. A. (2021). Smart parking systems: Comprehensive review based on various aspects. Heliyon, 7(5), e07050. https://doi.org/10.1016/j.heliyon.2021.e07050

Geng, Y., & Cassandras, C. G. (2013). New smart parking system based on resource allocation and reservations. IEEE Transactions on Intelligent Transportation Systems, 14(3), 1129–1139. https://doi.org/10.1109/TITS.2013.2252428

Internet Engineering Task Force. (2018). The Transport Layer Security (TLS) protocol version 1.3 (RFC 8446). https://doi.org/10.17487/RFC8446

Jabbar, W. A., Wei, C. W., Azmi, N. A. A. M., & Haironnazli, N. A. (2021). An IoT Raspberry Pi-based parking management system for smart campus. Internet of Things, 14, 100387. https://doi.org/10.1016/j.iot.2021.100387

Jabbar, W. A., Tiew, L. Y., & Shah, N. Y. A. (2024). Internet of Things enabled parking management system using long range wide area network for smart city. Internet of Things and Cyber-Physical Systems, 4, 82–98. https://doi.org/10.1016/j.iotcps.2023.09.001

Ji, Z., Ganchev, I., O'Droma, M., Zhao, L., & Zhang, X. (2014). A cloud-based car parking middleware for IoT-based smart cities: Design and implementation. Sensors, 14(12), 22372–22393. https://doi.org/10.3390/s141222372

Kadusic, E., Zivic, N., Ruland, C., & Hadzajlic, N. (2022). A smart parking solution by integrating NB-IoT radio communication technology into the core IoT platform. Future Internet, 14(8), 219. https://doi.org/10.3390/fi14080219

Khalid, M., Wang, K., Aslam, N., Cao, Y., Ahmad, N., & Khan, M. K. (2021). From smart parking towards autonomous valet parking: A survey, challenges and future works. Journal of Network and Computer Applications, 175, 102935. https://doi.org/10.1016/j.jnca.2020.102935

Kotb, A. O., Shen, Y.-C., Zhu, X., & Huang, Y. (2016). iParker—A new smart car-parking system based on dynamic resource allocation and pricing. IEEE Transactions on Intelligent Transportation Systems, 17(9), 2637–2647. https://doi.org/10.1109/TITS.2016.2531636

Lee, C. P., Leng, F. T. J., Habeeb, R. A. A., Amanullah, M. A., & Rehman, M. H. (2022). Edge computing-enabled secure and energy-efficient smart parking: A review. Microprocessors and Microsystems, 93, 104612. https://doi.org/10.1016/j.micpro.2022.104612

Nasim, S., Oussalah, M., Outila, T., & Jutila, J. (2022). Smart parking system based on IoT architecture and intelligent sensors. In SMART 2022: The Eleventh International Conference on Smart Cities, Systems, Devices and Technologies (pp. 1–6). IARIA.

National Institute of Standards and Technology. (2020). IoT device cybersecurity capability core baseline (NISTIR 8259A). https://doi.org/10.6028/NIST.IR.8259A

OASIS. (2019). MQTT version 5.0. OASIS Standard.

Ozkaya, M., & Turunc, A. (2025). A reference architecture for smart car parking management systems. Systems, 13(2), 70. https://doi.org/10.3390/systems13020070

Paidi, V., Fleyeh, H., Håkansson, J., & Nyberg, R. G. (2018). Smart parking sensors, technologies and applications for open parking lots: A review. IET Intelligent Transport Systems, 12(8), 735–741. https://doi.org/10.1049/iet-its.2017.0406

Perković, T., Šolić, P., Zargariasl, H., Čoko, D., & Rodrigues, J. J. P. C. (2020). Smart parking sensors: State of the art and performance evaluation. Journal of Cleaner Production, 262, 121181. https://doi.org/10.1016/j.jclepro.2020.121181