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ANALYSIS OF MODERN IOT SOLUTIONS FOR AUTOMATION OF URBAN PARKING SPACES

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Introductions

Rapid urbanization, which has swept through most countries worldwide in recent decades, has led to a significant increase in the number of vehicles in cities. Traditional approaches to parking organization no longer meet the realities of the modern city. Finding a free parking space in dense urban areas requires an average of 8 to 20 minutes for a driver, which, according to researchers, generates up to 30 % of excess traffic in city centers. This, in turn, causes an increase in carbon dioxide emissions, higher noise levels, and a decrease in the quality of life for urban residents. The economic losses from inefficient parking organization amount to billions of dollars annually on the scale of individual countries.

The issue gains particular relevance in the context of the rapid development of the «Smart Cities» concept and global digital transformation, which is a defining trend of our time. Leading countries worldwide are already investing significant funds in the modernization of parking infrastructure, recognizing it as a critically important element of urban mobility.

A promising direction for solving these problems is the introduction of Internet of Things (IoT) technologies into the urban parking management system. The

Internet of Things concept involves the integration of sensor devices, data transmission networks, and software platforms to create intelligent control systems [1-5]. IoT solutions enable real-time collection, transmission, and processing of data on the status of parking spaces, automation of access control and payment processes, as well as integration of parking infrastructure into a single smart city ecosystem [6-8]. Thus, through the use of sensors, wireless data transmission networks, cloud platforms, and mobile applications, it becomes possible to create intelligent parking systems that can significantly increase the efficiency of using existing infrastructure.

Aim

Systematization and comparative analysis of existing IoT solutions for urban parking automation, as well as justification of recommendations for their selection for different types of parking spaces.

Materials and methods

During the research, an analysis of modern hardware and software solutions used for the automation of urban parking spaces based on Internet of Things technologies was conducted. The main research methods included a comparative analysis of the technical characteristics of sensors, a review of data transmission protocols, and a study of architectural approaches to building intelligent parking systems.

A wide range of technologies is used for vehicle detection in modern systems. Inductive loops, installed in the road surface, provide high detection accuracy but require significant construction work during installation. In contrast, magnetometers detect changes in the Earth's magnetic field caused by the passage or parking of a vehicle. They can be installed either on the surface or with minimal intervention in the road surface (by drilling a small hole – a core). This installation method, unlike laying cable trenches, allows the sensor to be placed flush with the asphalt, protecting it from damage, particularly during snow removal operations. A separate group includes ultrasonic and radar sensors, which are mounted above the parking space and do not require intervention in the road surface, simplifying their installation and maintenance. To systematize the considered characteristics and provide a visual comparison of the main sensor types, a summary table has been compiled (Table 1).

Table 1

Comparison of the main types of sensors

Precision	Technology	Unit cost (per seat)	Scope of application	Main limitation
Magnetometers [9, 10]	High (~95-98 %)	Medium	Street parking, on-street zones	Sensitivity to electromagnetic interference (trams, subway)
Ultrasound [10, 11]	High (~95-98 %)	Low / Medium	Indoor parking lots, underground garages	Sensitivity to air turbulence, precipitation, temperature changes
Video analytics [12, 13]	Variable (85-99 %)	Medium (economy of scale)	Shopping malls, large open areas, airports	Dependence on lighting, weather conditions, blind spots
Radar sensors / LiDAR [14, 15]	The highest (> 98 %)	High	Open parking in harsh climates, VIP parking, industrial zones	High equipment cost, data processing complexity

The analysis of the presented data (Table 1) indicates the absence of a universal technological solution, as the choice of a specific sensor type is dictated by the balance between the project budget and the operational conditions of the facility. While magnetometers and ultrasonic sensors remain the most balanced options for mass deployment due to their optimal price-to-accuracy ratio, video analytics systems and radar solutions are advisable for facilities with high functionality requirements, where additional costs are offset by the system's scalability or the need to operate in extreme climatic conditions.

The choice of a specific detection method determines the architecture of the next system level – the network layer. For autonomous sensors (magnetometers), the use of energy-efficient protocols is critical, while video analytics systems require broadband communication channels to transmit video streams to processing servers.

Therefore, an important aspect of IoT system functionality is the selection of a data transmission protocol.

Wireless technologies such as LoRaWAN, Sigfox, and NB-IoT provide low power consumption and long range (up to 5 km in urban areas and up to 15 km in open areas), making them suitable for scalable parking networks. In particular, thanks to the low power consumption of the LoRaWAN protocol, sensors can operate autonomously for 5–7 years without battery replacement. For transmitting large volumes of data, such as video streams, Wi-Fi networks, or cellular communication (4G/5G) are used.

The interconnection between the perception, network, and application layers of the intelligent parking system architecture is shown in Fig. 1.

Data processing in modern systems is increasingly carried out using computer vision technologies. In particular, the YOLO (You Only Look Once) architecture provides high accuracy of vehicle detection in real time, which is critical for systems with high traffic.

Modern versions of YOLO (from YOLOv8 to YOLOv11) demonstrate accuracy exceeding 98% in free parking space detection on specialized test datasets (PKLot, CNRPark) under controlled conditions, with lighter versions (YOLOv11n) providing faster processing with lower resource consumption, while larger models (YOLOv11m) achieve higher accuracy at the cost of longer processing time. An important advantage of video analytics systems is their scalability: a single camera with typical installation at a height of 3–5 meters can simultaneously monitor up to 20 parking spaces, which significantly reduces the unit cost of implementation for large facilities.

Furthermore, modern YOLO models support not only basic object detection but also advanced functions such as instance segmentation, pose estimation, object tracking, and license plate recognition (LPR).

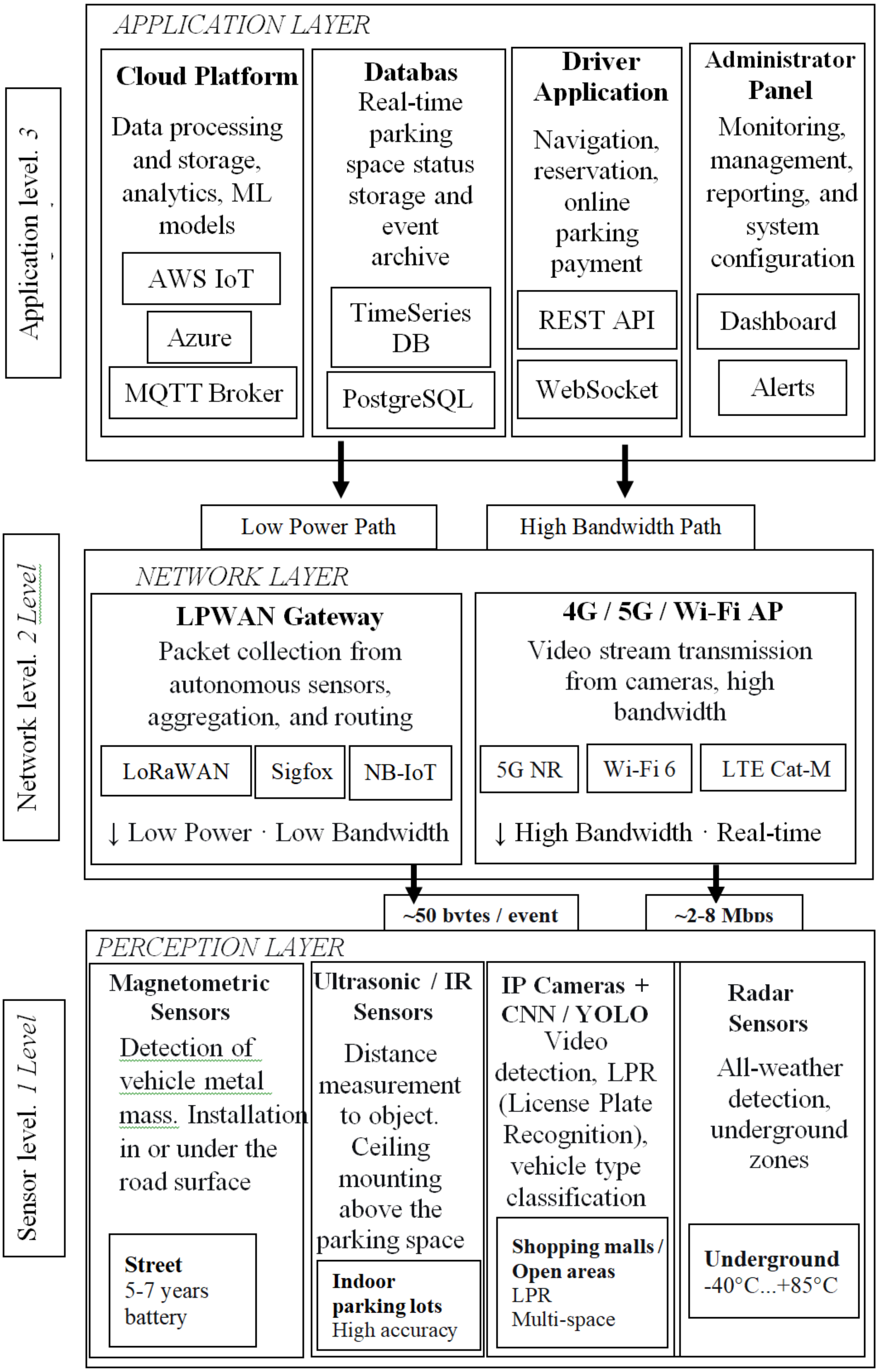

Fig. 1. Interconnection of the perception, network, and application layers of the parking automation system

Results and discussion

The conducted comparative analysis of modern IoT solutions for the automation of urban parking spaces has made it possible to systematize existing technological approaches and identify patterns of their application depending on the type of facility and operating conditions. The results of the sensor technology analysis (Table 1) confirm the absence of a universal solution suitable for all types of parking facilities. Magnetometric sensors and ultrasonic sensors demonstrate similar accuracy indicators (~95 – 98 %) with relatively moderate implementation costs, making them the most sought-after technologies for mass deployment. At the same time, there is a fundamental difference between them in their scope of application: magnetometers are more suitable for open street parking lots due to their resistance to weather conditions and minimal intervention in the road surface, whereas ultrasonic sensors show better results in enclosed parking garages with a stable microclimate. Video analytics systems are distinguished by their broad functionality – in particular, the ability to recognize license plates (LPR) and determine the type of vehicle – however, their effectiveness significantly depends on lighting conditions and weather factors, which causes considerable variability in accuracy within the range of 85–99 %. Radar sensors and LiDAR provide the highest detection accuracy (over 98 %) and are practically independent of climatic conditions, but the high cost of the equipment limits their application to specialized facilities.

The analysis of data transmission protocols revealed a clear correlation between the sensor type and the requirements for network infrastructure. Autonomous sensors generate minimal traffic (up to 50 bytes per event), making them compatible with energy-efficient LPWAN protocols – LoRaWAN and NB-IoT, which provide coverage up to 5 km in urban areas and autonomous operation for up to 5 – 7 years. In contrast, video analytics systems require broadband 4G/5G or Wi-Fi channels with a bandwidth of 2–8 Mbps, which prevents their integration with LPWAN. This fundamental difference is clearly illustrated in Fig. 1.

Based on the obtained results, recommendations for selecting an IoT solution depending on the type of parking facility have been formulated. For on-street parking and zones along roads, the optimal choice is the use of magnetometric sensors combined with the LoRaWAN protocol, which ensures a balance between accuracy, cost, and system autonomy. For covered multi-story parking lots, it is advisable to use ultrasonic sensors with local data transmission networks (Wi-Fi or Zigbee), since the stable microclimate conditions mitigate the main limitations of this technology. For large open areas – shopping malls, airports, stadiums – video analytics systems based on CNN/YOLO are the most effective, as they allow simultaneous monitoring of a significant number of spaces, integrate LPR (License Plate Recognition) functions, and reduce the unit cost per parking space through scaling. In cases where reliability in extreme climatic conditions is a priority or increased security requirements are imposed, the use of radar sensors is justified despite their higher cost.

Promising directions for the further development of intelligent parking systems include integration with predictive analytics platforms to forecast parking demand, the implementation of dynamic pricing based on real-time occupancy data, and the advancement of the Vehicle-to-Infrastructure (V2I) concept, which involves direct interaction between the vehicle and parking infrastructure without driver intervention.

Conclusions

As a result of the conducted research, the main types of IoT solutions for the automation of urban parking spaces — ranging from autonomous sensors to video analytics systems based on deep learning algorithms — have been systematized and compared. It has been established that there is no universal technological solution: the choice of a specific approach is determined by the type of parking facility, project budget, and operating conditions. The architecture of three-tier IoT systems has been analyzed, and a correlation between the sensor type and the requirements for network infrastructure has been identified. Practical recommendations for selecting a technology stack for various implementation scenarios have been formulated. The obtained results can serve as a basis for making informed design decisions in the development and modernization of intelligent parking systems within the context of the Smart City concept.

The analysis showed that the accuracy of modern sensor technologies varies from 85 % for video analytics systems in adverse conditions to over 98% for radar solutions, while magnetometers and ultrasonic sensors provide an optimal balance between accuracy (~95 – 98 %) and cost for mass deployment. A fundamental difference in network infrastructure requirements has been identified: autonomous sensors generate up to 50 bytes per event and can operate for 5 – 7 years on battery power in LPWAN networks, whereas video analytics systems require channels with a bandwidth of 2 – 8 Mbps. Practical recommendations for selecting a technology stack for different types of parking facilities have been formulated. The obtained results can serve as a basis for making informed design decisions in the development and modernization of intelligent parking systems within the context of the Smart City concept.

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