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МРЕЖОВИ ТОПОЛОГИИ И РАЗГРЪЩАНЕ НА ИОТ-БАЗИРАНИ РЕШЕНИЯ ЗА ИНТЕЛИГЕНТНИ ПЪТИЩА

NETWORK TOPOLOGIES AND DEPLOYMENT OF IOT-BASED SOLUTIONS FOR SMART ROADS

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Abstract

IoT technology transforms conventional roads into intelligent, data-driven systems by integrating sensor networks, wireless communication, and cloud processing for real-time monitoring. Choosing a network topology that balances coverage, energy, reliability, and throughput is a core challenge. This work surveys and compares the principal network topologies and deployment strategies for IoT-based smart roads by reviewing recent literature on star/LPWAN, mesh/WSN, and heterogeneous architectures, covering sensors, protocols, data processing, and node placement. Star/LPWAN suits sparse rural deployments; mesh (IEEE 802.15.4/TSCH, LoRa WMN) gives redundancy for dense urban use; heterogeneous 5G+WSN serves high-bandwidth video. A three-layer fog-cloud-mobile model dominates data processing, and spatial optimization of node placement cuts cost while preserving coverage. No single topology fits all scenarios; the paper synthesizes design guidelines for hybrid architectures and node placement within laboratory C4.1 of the Center of Competence "Smart Mechatronic, Eco-and Energy-Saving Systems and Technologies".

Keywords: Internet of Things, smart roads, wireless sensor networks, LoRa, TSCH, LPWAN, network topology, deployment optimization, fog computing.

1. INTRODUCTION

Road infrastructure underpins modern economic activity and social mobility. Road traffic accidents remain a leading cause of death and injury worldwide, with an estimated 2.22 million people injured annually [1]. At the same time, traffic congestion, poor road surface conditions, and inadequate environmental monitoring continue to reduce transport efficiency. Intelligent Transportation Systems (ITS) emerged in response to these challenges, integrating communication, control, and information-processing technologies into the transport infrastructure [1].

The Internet of Things (IoT) has dramatically expanded the possibilities of ITS by enabling low-cost, dense deployments of networked sensors across road environments. Modern smart road deployments collect vibration, temperature, humidity, noise, and optical data from embedded pavement sensors alongside roadside cameras, environmental monitors, and vehicle detectors [2]. These heterogeneous data streams support applications ranging from pavement condition assessment and road accident prevention to autonomous sign control and adaptive traffic management.



A critical design decision in any IoT smart road system is the choice of network topology. Star topologies, where sensors communicate directly with a central gateway over long-range links, offer simplicity and low power consumption but introduce a single point of failure. Mesh topologies, in which nodes relay data through neighboring devices, provide redundancy and extended coverage but increase complexity and energy use. Heterogeneous architectures combine multiple radio technologies cellular, licensed, and unlicensed to meet QoS requirements for high-bandwidth applications such as video surveillance [5].

This paper, prepared as part of the activities of laboratory C4.1 of the Center of Competence "Smart Mechatronic, Eco-and Energy-Saving Systems and Technologies", provides a comparative survey of network topologies and deployment strategies for IoT-based smart road systems. Section 2 describes the sensor infrastructure. Section 3 analyses the principal network topologies. Section 4 discusses data processing architectures. Section 5 examines deployment optimization. Section 6 discusses findings, and Section 7 concludes.

2. SENSOR INFRASTRUCTURE FOR SMART ROADS

IN-ROADWAY SENSORS

In-roadway sensors are embedded directly in the pavement or subgrade and provide data on traffic flow, vehicle weight, and the road's structural condition. Tewolde [1] categorizes them as pneumatic road tube sensors, inductive loop detectors (ILD), magnetic sensors, and piezoelectric sensors. ILDs are the most widely deployed, producing vehicle count, presence, and occupancy data. Piezoelectric sensors measure axle weight and speed, enabling vehicle classification. Magnetic sensors detect perturbations in the Earth's magnetic field caused by passing ferrous vehicles.

Recent IoT-centric deployments complement these classical devices with

micro-electromechanical systems (MEMS). Ye et al. [2] describe an integrated pavement monitoring system where MEMS accelerometers measure road vibration at 1000 Hz sampling frequency, while thermocouple sensors co-located in the same housing capture pavement temperature. The sensors are encased in corrosion-resistant stainless steel and embedded during slip-form paving, eliminating the post-construction groove-cutting that would otherwise shorten pavement service life.

Roadside and environmental sensors

Roadside sensors complement in-pavement devices by monitoring environmental and traffic conditions without requiring pavement integration. Radar sensors operating in the 1-30 GHz range measure vehicle speed, volume, and occupancy from overhead gantries [1]. Active and passive infrared sensors detect vehicle presence and queue length at intersections. Video cameras including night-vision units provide the richest data stream but impose the highest bandwidth demands on the network [1, 4].

Environmental monitoring sensors measuring ambient temperature, humidity, noise level, and wind speed and direction are deployed in gateway enclosures and communicate with the gateway via RS-485 buses [2]. Smart pole infrastructure integrates multiple sensor types CCTV, air-quality sensors, and public Wi-Fi access points into a single roadside mast, reducing installation costs and urban visual clutter [8, 9].

3. NETWORK TOPOLOGIES FOR IoT IN SMART ROADS

Star topology (LPWAN)

In a star topology, each sensor node transmits directly to a central gateway without relying on neighboring nodes for routing. Low Power Wide-Area Network (LPWAN) technologies such as SigFox and LoRa are the dominant implementations. SigFox operates on



unlicensed sub-GHz bands, offers link ranges exceeding 10 km in open terrain, and achieves years of battery life at the cost of very low data rates (~100 bps). LoRa uses chirp spread-spectrum modulation and achieves data rates up to a few kbps with adjustable spreading factors that trade throughput for range [6].

Al-Hamadi et al. [6] formulate an Integer Non-Linear Programming (INLP) optimization problem to maximize the lifetime of SigFox star networks under reliability constraints. Their model draws real-time environmental data from a peered cloud capturing phenomena such as dust storms that degrade radio links and adaptively adjusts the number of redundant transmission paths. The trade-off is explicit: activating additional paths increases the probability of message delivery but depletes battery energy faster. The optimal redundancy level balances these effects to maximize network operational lifetime.

Mesh topology (WSN/WMN)

Mesh networks allow every node to act as a data source and a relay, providing multiple paths between sources and gateways. This inherent redundancy makes mesh topologies well-suited for safety-critical smart road applications where a single node failure must not interrupt service. Two key standards are in common use: IEEE 802.15.4 (ZigBee/6LoWPAN) for short-range dense sensor networks, and TSCH (Time Slotted Channel Hopping, standardized in IEEE 802.15.4e), which schedules transmissions to minimize collisions and duty-cycle energy waste [6].

Torralba et al. [4] deploy a mesh WSN based on IEEE 802.15.4 with a 6LoWPAN adaptation layer in the Autonomous Intelligent Sign Control System (AISCS) for rural and suburban roads. Every fully functional device acts as a router, providing multiple paths from sensing units to the Local Controller Border Router. The mesh serves environmental sensors (luminosity, temperature, rainfall, humidity),

LED sign actuators, and camera image-processing units connected via Ethernet. Backhaul to the Central Controller is provided by a 3G/UMTS link.

For smart pole systems, LoRa-based Wireless Mesh Networks (WMN) are preferred over pure star deployments because multi-hop communication extends coverage without increasing transmission power [8, 9]. Park and Lee [9] define the Multiple Coverage Mesh Network Problem (MC-MNP), which simultaneously optimizes smart pole locations and WMN connectivity. Gateways provide wired links to the city backbone, while smart pole sensors form the mesh with a maximum of five hops to a gateway with a limit derived from LoRa capacity studies. Kaiwartya et al. [7] further address fault tolerance in mesh-based WSN virtualization using an adapted non-dominated sorting genetic algorithm (A-NSGA) that jointly minimizes communication delay while maximizing fault tolerance.

Convergent fog-cloud-mobile model

Finogeev et al. [3] propose a three-level convergent computing model for the Smart Road Environment (SRE). The first level (fog computing) performs real-time sensor data collection and pre-processing at the network edge, executing multi-agent tasks data cleaning, clustering, and anomaly detection directly within the heterogeneous sensor network. The second level (cloud computing) aggregates pre-processed data in a server cluster, where computationally intensive analytics, including neural network-based accident forecasting, are performed. The third level (mobile computing) delivers visualization and decision-support interfaces to field personnel via smartphones and tablets.

The multi-agent fog architecture assigns specialized software agents to distinct tasks: polling photo-radar complexes via SNMP, maintaining local event logs in distributed hierarchical databases, uploading violation data



in XML format, and aggregating time-series statistics in CSV hyper-tables [3]. The cloud backend in [2] uses MongoDB for sensor data storage and exposes a RESTful API to a web-based visual interface that displays sensor status, road imagery, and vibration time-series in real time.

4. DEPLOYMENT STRATEGIES AND OPTIMISATION

Spatial optimization of node placement

The placement of IoT nodes and gateways strongly influences coverage, cost, and network connectivity. The authors [9] formalize smart pole siting as the MC-MNP: given a set of candidate sites, a fixed number of smart poles, p , and gateways, q , must be selected to maximize the population served (de facto population demand) while satisfying WMN connectivity constraints. Three sensor types with distinct coverage radii - air quality, CCTV, and public Wi-Fi are co-optimized; each gateway must be reachable from its associated sensors within five hops. Applied to the central business district of Seoul, the model shows that optimal locations cluster in high-demand commercial zones, with lower-demand peripheral areas covered as the number of poles increases.

A three-stage sequential analysis further reduces infrastructure cost: Wi-Fi pole locations determined in stage one serve as candidate sites for CCTV and air quality sensors in subsequent stages, exploiting the co-location opportunities of multi-functional smart poles [9]. The resulting coverage and cost trade-offs demonstrate that consolidating multiple services into a single pole significantly reduces the total number of installations required.

Network lifetime optimization

Battery-operated IoT nodes have finite energy budgets, and network lifetime defined as the time until the first node depletes its battery

constrains the deployment's operational period. Al-Hamadi et al. [6] model lifetime maximization as an INLP problem for both star (SigFox) and mesh (TSCH) topologies. Their model uses environmental cloud data to estimate node/link failure probabilities and determines the optimal number of redundant transmission paths. In harsh environments (dust, extreme humidity), more paths are activated to maintain reliability at the cost of shorter lifetimes; in benign conditions, fewer active nodes conserve energy. Experimental evaluation shows that this adaptive approach outperforms static baseline models for both SigFox and TSCH.

Self-powered deployments sidestep battery constraints by harvesting ambient energy. Ye et al. [2] equip their pavement monitoring gateway with a 450 W solar panel combined with a lithium iron phosphate battery pack managed by a Battery Management System (BMS) implementing the Maximum Power Point Tracking (MPPT) algorithm. The battery autonomy exceeds five years and is field-replaceable, enabling operation in remote road sections without external power lines.

Fault tolerance and resilience

Smart road networks must remain operational during node failures, radio interference, and physical damage. Kaiwartya et al. [7] address this through fault-tolerant virtual network embedding (VNE) in WSNs. Their A-NSGA solves a bi-objective optimization: maximizing fault tolerance - the probability that at least one path between source and destination remains operational after a link failure while minimizing communication delay. The algorithm discovers alternative path endpoints when a link or node fails, thereby supporting re-embedding without pre-allocating backup resources.

At the topology level, mesh networks inherently provide multi-path redundancy. AISCS [4] exploits this by routing sensor and actuator traffic through the mesh, so that the failure of any single relay node does not



interrupt communication between sensing units and the local controller. The 6LoWPAN/IPv6 addressing scheme assigns unique 128-bit network addresses to all wireless nodes, enabling transparent rerouting at the network layer.

5. DISCUSSION

The literature reviewed reveals that no single network topology is universally optimal for smart road IoT deployments. Table 1 summarises the key characteristics of the three principal topologies identified.

Characteristic	Star (LPWAN)	Mesh (WSN/WMN)	Heterogeneous
Coverage	Wide-area, km-scale	Dense, local	Flexible, multi-band
Data rate	Low (< 1 kbps)	Medium ($\leq$ 250 kbps)	High (Mbps-Gbps)
Energy	Years on battery	Months-years	Grid or solar required
Resilience	Single GW failure risk	Multi-path redundancy	Handover-based

Table 1. Comparison of IoT network topologies for smart road deployments.

Rural and suburban roads favor star/LPWAN topologies due to low node density, long distances between monitoring points, and the absence of mains power. AISCs [4] supplements its WSN mesh with a 3G/UMTS backhaul, reflecting the practical reality that rural areas often lack fiber infrastructure. In urban corridors, mesh WMNs based on LoRa or IEEE 802.15.4 provide the path redundancy demanded by safety-critical sign control and intersection monitoring. At the same time, 5G links carry high-resolution video to the traffic management center.

The convergent fog-cloud-mobile model of Finogeev et al. [3] addresses the data

processing challenge across all topology types by distributing computation: time-critical reactions (anomaly alerts, sign activation) execute at the fog layer within milliseconds, while resource-intensive analytics (accident forecasting, cross-city traffic modeling) run on cloud infrastructure. This architecture [2] closely mirrors the gateway-level processing, confirming its generality across different hardware platforms and sensor modalities.

6. CONCLUSION

This paper has surveyed network topologies and deployment strategies for IoT-based smart road systems, synthesizing findings from nine recent works spanning sensor technology, communication protocols, data processing architectures, and spatial optimization. Star/LPWAN topologies are appropriate for sparse, energy-constrained rural deployments where coverage range is paramount. Mesh topologies based on IEEE 802.15.4/TSCH or LoRa WMN provide the resilience required for safety-critical urban road environments. Heterogeneous multi-radio architectures are necessary when high-bandwidth sensors such as video cameras must coexist with low-bandwidth environmental monitors. The convergent three-layer fog-cloud-mobile computing model emerges as a broadly applicable data processing framework.

Optimal node placement formalised as a maximal coverage mesh network problem is a key lever for reducing infrastructure cost while maintaining service quality. Adaptive redundancy management and self-powering with solar energy further extend network lifetime and reduce maintenance burden. Future work should focus on the integration of 5G-V2X (Vehicle-to-Everything) communication with existing IoT sensor networks, AI-driven adaptive network management, and the development of standardised benchmarks for comparing smart road deployments across different urban and rural contexts.



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