Universitatea Națională de Știință și Tehnologie
POLITEHNICA din București
Facultatea de Automatică și Calculatoare
Departamentul Calculatoare

RAPORT Q1 DISERTAȚIE

Comunicație oportunistă în orașe inteligente

Alexandru Micu

Coordonator științific:
Conf. dr. ing. Radu-Ioan Ciobanu

BUCUREȘTI
2025

National University of Science and Technology
POLITEHNICA Bucharest
Faculty of Automatic Control and Computers
Computer Science and Engineering Department

MASTER THESIS Q1 REPORT

Opportunistic Communication in Smart Cities

Alexandru Micu

Thesis advisor:

Conf. dr. ing. Radu-Ioan Ciobanu

BUCHAREST

2025

CONTENTS

LIST OF FIGURES

ABSTRACT

Opportunistic communication in smart cities offers a cost-effective alternative to traditional cellular networks by leveraging existing infrastructure and placing edge entities. With the number of connected IoT devices projected to reach 40 billion by 2030, and 5G networks facing scalability challenges due to bandwidth limitations and deployment costs, this approach addresses critical gaps in urban digital transformation.

The placement of edge nodes can be influenced by various factors, including the number of users or data sources that need to be served, the types of applications being supported, and the available network infrastructure. Effective edge node placement can lead to significant improvements in the performance and efficiency of applications and services, making it a critical aspect of modern network design and management.

SINOPSIS

Comunicarea oportunistă în orașele inteligente oferă o alternativă rentabilă la rețelele celulare tradiționale, prin utilizarea infrastructurii existente și plasarea entităților edge (la marginea rețelei). Cu un număr de dispozitive IoT conectate proiectat să ajungă la 40 de miliarde până în 2030, și cu rețelele 5G care se confruntă cu provocări de scalabilitate din cauza limitărilor de lățime de bandă și a costurilor de implementare, această abordare abordează lacune critice în transformarea digitală urbană.

Amplasarea nodurilor edge poate fi influențată de diverși factori, inclusiv numărul de utilizatori sau surse de date care trebuie deservite, tipurile de aplicații care sunt suportate și infrastructura de rețea disponibilă. Amplasarea eficientă a nodurilor de margine poate duce la îmbunătățiri semnificative în performanța și eficiența aplicațiilor și serviciilor, ceea ce o face un aspect critic al proiectării și gestionării rețelelor moderne.

Keywords: Edge Computing, Sustainable Costs, Reduced Latency

1 INTRODUCTION

1.1 Context

The global smart city market is projected to reach $6.4 trillion by 2030, driven by IoT deployments for infrastructure monitoring, traffic management, and energy efficiency. However, cellular connectivity costs remain prohibitive—mid-sized cities like Louisville, Kentucky, spend up to $2.3M annually on cellular plans for IoT sensors. While 5G RedCap offers reduced-capability IoT devices (50 Mbps upload, $<$100 ms latency), its deployment faces urban coverage gaps and energy inefficiencies, particularly for non-urgent data like waste management or air quality metrics [1] [2].
Opportunistic D2D networks mitigate these costs by repurposing mobile entities as data relays. For instance, Chapel Hill's public buses have been used to relay traffic sensor data to edge nodes at transit hubs with a latency reduction of over 20 minutes due to their predictable routes (85% predictability) [2]. Similarly, Barcelona's garbage trucks have reduced cellular costs by 62% by collecting bin fill-level data via IEEE 802.11p protocols with a store-carry-forward delay tolerance of $\leq$ 4 hours [3].
Citizen participation also plays a crucial role; Fargo has incentivized smartphone users to share bandwidth for environmental monitoring projects using opt-in blockchain frameworks like Ethereum's zero-knowledge proofs for GDPR compliance. This approach achieved a significant offload of cellular traffic during peak hours—up to 40% [3].

1.1.1 Technical Challenges

Traditional centrality metrics such as betweenness fail in transient networks because they do not account for dynamic mobility patterns during rush hours or unexpected events like road closures or natural disasters. For example, Ahmedabad's bus network experienced a notable increase in data loss when static edge nodes were used during monsoon-induced route detours [3].
Hybrid network orchestration is another challenge; while 5G RedCap improves grid reliability through "hard slicing" techniques suitable for critical services such as solar PV systems (e.g., China's high-voltage distribution networks), integrating opportunistic links requires sophisticated software-defined networking (SDN) solutions that can dynamically route traffic based on real-time congestion levels [1] [4].

Scalability versus cost remains a significant trade-off; deploying one edge node per forty IoT devices in Gandhinagar achieved nearly full coverage at an annual cost of approximately $18K—a reduction of about 77% compared to traditional cellular-only models according to simulations conducted using the ONE Simulator tool [3].

1.1.2 Emerging Solutions

Blockchain technology is also being integrated into these systems primarily through platforms like Hyperledger Fabric which was tested successfully in Skudai Malaysia where it resolved 92% of GDPR compliance issues related to anonymizing crowdsourced air quality data from citizen-participatory networks [5].
Lastly disaster resilience strategies combining satellite backhaul with VANETs (Vehicular Ad-Hoc Networks) have been implemented effectively; Japan's "Never Die Network" maintained 68% connectivity even during earthquakes using cars as ad-hoc edge nodes demonstrating potential applications beyond urban settings into emergency response scenarios globally [6].

1.2 Problem Statement

The exponential growth of IoT devices in smart cities poses significant challenges for traditional cellular networks, particularly in terms of scalability, cost, and energy efficiency. While 5G RedCap and opportunistic communication networks (OppNets) offer partial solutions, several unresolved issues impede their widespread adoption:

1. **Static Edge Node Placement in Dynamic Environments**
   Centrality-based edge node placement strategies (e.g., betweenness, in-degree) assume fixed network topologies, leading to suboptimal performance during real-world disruptions like traffic detours or weather events. For instance, Ahmedabad's bus network experienced 22% data loss during monsoon-induced route deviations, highlighting the need for dynamic adaptation [3].

2. **Inefficient Hybrid Network Orchestration**
   Hybrid architectures combining 5G RedCap for critical services (e.g., grid reliability) and OppNets for non-critical data lack standardized protocols to balance cost and quality of service (QoS).

3. **Absence of Sustainability Metrics**
   Existing frameworks prioritize coverage and latency but neglect environmental impacts. Deploying energy-intensive edge nodes in urban areas could offset OppNets' cost savings by increasing carbon footprints—a trade-off unaddressed in current research.

1.3 Objectives

1. **Develop Algorithmic Edge Node Placement Strategies**
   Design deterministic algorithms (e.g., greedy or graph-based methods) to select optimal edge node locations based on real-world transit network datasets, evaluate these algorithms against traditional centrality metrics under simulated scenarios of varying network dynamics and reduce latency by $\leq$20% compared to static placement methods while maintaining deployment costs as low as possible.

2. **Enhance Disaster Resilience in Opportunistic Networks**
   Investigate how local storage mechanisms can ensure continuous operation during disasters by analyzing buffer sizes required at bus nodes, propose protocols for prioritizing critical infrastructure-related data transmission over non-critical traffic during emergencies and achieve $\leq$50% cellular cost reduction without violating 100 ms latency for critical services.

3. **Optimize Network Configuration for Municipal Infrastructure Support**
   Model different configurations of OppNet architectures tailored specifically for urban infrastructure monitoring (e.g., waste management), compare performance metrics such as coverage area and packet delivery ratio across various configurations using simulation tools like ONE Simulator and achieve $\geq$90% coverage with optimized configurations.

4. **Integrate Sustainability Metrics into Cost Models**
   Quantify the carbon footprint of solar-powered edge nodes deployed at transit hubs or edge nodes built on existing infrastructure to reduce infrastructure costs by $\leq$25% while maintaining $\geq$90% coverage.

2 STATE OF THE ART

REFERENCES

[1] GSMA, “5G RedCap Case Studies Smart Grid — Smart City — Smart Manufacturing,” 2024. [Online]. Available: https://www.gsma.com/about-us/regions/greater-china/wp-content/uploads/2024/06/GSMA-5G-RedCap-Case-Studies.pdf.

[2] O. Madamori, E. Max-Onakpoya, G. D. Erhardt, and C. E. Baker, “Enabling Opportunistic Low-cost Smart Cities By Using Tactical Edge Node Placement,” in *2021 16th Annual Conference on Wireless On-demand Network Systems and Services Conference (WONS)*, IEEE, Mar. 2021, pp. 1–8. DOI: 10.23919/wons51326.2021.9415579.

[3] J. Gandhi and Z. Narmawala, “A Case Study on Estimation of Sensor Data Generation in Smart Cities and the role of Opportunistic Networks in Sensor Data Collection,” Jun. 2023. DOI: 10.21203/rs.3.rs-2996750/v1.

[4] J. Liu, X. Wu, and P. Yuan, “A Dynamic Edge Server Placement Scheme Using the Improved Snake Optimization Algorithm,” *Applied Sciences*, vol. 14, no. 22, p. 10 130, Nov. 2024, ISSN: 2076-3417. DOI: 10.3390/app142210130.

[5] N. Alasbali *et al.*, “Rules of Smart IoT Networks within Smart Cities towards Blockchain Standardization,” *Mobile Information Systems*, vol. 2022, H. A. Khattak, Ed., pp. 1–11, Feb. 2022, ISSN: 1574-017X. DOI: 10.1155/2022/9109300.

[6] K. Andersson and V. P. Kafle, “Disaster-resilient mobile network architecture,” in *2014 IEEE 11th Consumer Communications and Networking Conference (CCNC)*, IEEE, Jan. 2014, pp. 157–162. DOI: 10.1109/ccnc.2014.6866564.