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MASTER THESIS S1 REPORT

Opportunistic Communication in Smart Cities

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RAPORT S1 DISERTAȚIE

Comunicație oportunistă în orașe inteligente

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CONTENTS

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% [4].

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 [4].
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] [5].

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 [4].

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 [6].
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 [7].

1.2 Problem Statement

The integration of vast numbers of IoT devices into smart city environments presents a complex challenge, particularly concerning the limitations of traditional cellular networks in terms of scalability, cost-effectiveness, and energy efficiency. While emerging technologies like 5G RedCap and opportunistic communication networks (OppNets) offer promising partial solutions, their widespread adoption is hindered by several key unresolved issues.
Firstly, many existing network deployments rely on static edge node placement strategies, which are ill-suited for the dynamic conditions of real-world urban environments. Techniques such as centrality-based node placement assume fixed network topologies. These assumptions break down when facing disruptions like traffic detours or adverse weather conditions. For example, a study of Ahmedabad's bus network found that the use of static edge nodes led to a significant 22% data loss during monsoon-induced route deviations [4]. This underscores the critical need for dynamic adaptation to maintain reliable connectivity.
Secondly, the architecture of hybrid networks, which combine 5G RedCap for time-sensitive services with OppNets for less critical data, lacks standardized protocols to effectively balance cost and quality of service (QoS). This absence of clear guidelines makes it challenging to optimally manage network resources and ensure the reliable delivery of data across different service types.
Thirdly, current approaches often prioritize network coverage and latency while neglecting environmental impacts. The deployment of energy-intensive edge nodes in urban areas could potentially undermine the cost savings achieved by OppNets, if this is coupled with a higher carbon footprint. Therefore, there is a critical need for research that addresses this trade-off.
Finally, opportunistic networks need robust failover mechanisms to maintain operation during disaster scenarios. The limitations of current approaches were highlighted during a disaster scenario when Japan's VANET-based "Never Die Network" maintained only 68% connectivity during earthquakes [7]. This exposed gaps in resilience planning, indicating the need for better designs.

1.3 Objectives

This thesis aims to tackle key challenges in the implementation of opportunistic communication networks for smart city applications. By focusing on cost-effective and resilient solutions for municipal infrastructure, this research seeks to provide practical guidance for future smart city deployments. The core objectives are as follows.

1.3.1 Algorithmic Edge Node Placement for Dynamic Networks

The primary goal here is to design and evaluate deterministic algorithms that can strategically position edge nodes within opportunistic networks, particularly those leveraging public transit systems. This will involve developing practical methods, such as greedy or graph-based algorithms, capable of adapting to the constantly changing conditions typical of urban environments.

To achieve this, the algorithms will be assessed using real-world transit datasets. This real-world data will provide a foundation for simulating various network conditions and comparing the performance of the newly developed algorithms against traditional, static centrality metrics. The ultimate aim is to create solutions that not only minimize latency but also keep deployment costs manageable.

1.3.2 Enhancing Resilience in the Face of Disasters

A significant aspect of this thesis involves exploring how to make opportunistic networks robust enough to withstand infrastructure disruptions. To do this, I intend to thoroughly analyze how local storage capabilities on bus nodes can ensure data remains accessible, even during disaster scenarios. The plan is to develop protocols that prioritize the transmission of essential data related to critical infrastructure services over less urgent traffic during emergencies. By focusing on these targeted strategies, I intend to provide a pathway toward reducing cellular dependency by up to 50% without compromising the responsiveness of essential city services.

1.3.3 Optimized Network Configurations for Municipal Infrastructure:

The thesis will also focus on optimizing opportunistic network architectures for specific urban infrastructure monitoring applications. This involves modelling different network setups tailored to needs such as waste management. To evaluate the effectiveness of these setups, performance metrics like coverage area and packet delivery ratio will be compared using simulation tools such as ONE Simulator. The aim is to achieve at least 90% coverage with configurations that are specifically designed to support efficient and cost-effective monitoring of municipal services.

1.3.4 Integrating Sustainability into Cost-Effective Models:

Finally, this thesis will investigate how sustainability metrics can be integrated into the economic analysis of opportunistic networks. This includes quantifying the carbon footprint associated with deploying solar-powered edge nodes and nodes built on existing infrastructure. The aim here is to reduce infrastructure costs by 25% compared to traditional cellular deployments while maintaining at least 90% network coverage and prioritizing environmentally responsible design choices.

2 STATE OF THE ART

Opportunistic networks (OppNets) have emerged as a cost-effective alternative to traditional cellular networks for IoT deployments in smart cities. By leveraging existing infrastructure like public transit vehicles and citizen devices as data relays, OppNets reduce reliance on expensive cellular connectivity. This section highlights recent advancements in edge node placement strategies and hybrid network architectures.

2.1 Edge Node Placement Strategies

Effective edge node placement is pivotal for achieving optimal performance within Opportunistic Networks (OppNets). In particular, placement significantly influences both the minimization of latency and the maximization of network coverage. Conventional centrality metrics, such as betweenness centrality, often fall short in these dynamic contexts because they do not adequately account for the constantly changing patterns of mobility exhibited by network participants. This limitation has motivated researchers to investigate algorithmic solutions that can more dynamically adapt to these changes and maintain network efficiency.

One notable approach has been the formulation of edge node selection as an Influence Maximization problem, resulting in the Minimal Delivery Delay (MDD) algorithm. This algorithm is explicitly designed to select optimal edge nodes based on datasets derived from real-world transit systems, such as those found in cities like Chapel Hill and Louisville [8]. Notably, this approach has been shown to outperform traditional centrality metrics, achieving a significant reduction in end-to-end latency.

Another strategy that has gained attention is the Improved Snake Optimization (ISO) algorithm. The ISO algorithm functions by dynamically adjusting server locations in response to predicted traffic flows. This dynamic adaptation enables the algorithm to reduce infrastructure deployment costs by approximately 30% when compared to static, non-adaptive deployment strategies [5].

2.2 Hybrid Network Architectures

The hybridization of 5G Reduced Capability (RedCap) technology with Opportunistic Networks (OppNets) represents a balanced and promising approach for smart city deployments, integrating the strengths of both technologies. This hybrid model seeks to leverage the cost efficiencies provided by OppNets while capitalizing on the guaranteed Quality of Service (QoS) offered by 5G RedCap.

5G RedCap case studies have underscored its suitability for critical services, such as smart grids, and provide evidence of its integration with opportunistic links for more delay-tolerant IoT applications. For instance, China's high-voltage distribution networks are deploying hard slicing techniques through 5G RedCap that provide robust grid reliability [1].

In a different context, the city of Barcelona's innovative waste management system leveraged opportunistic communication by equipping its fleet of garbage trucks with IEEE 802.11p protocols. This enabled the trucks to collect data from smart bins using store-carry-forward mechanisms, leading to a substantial cellular cost reduction of sixty-two percent [3].

2.3 Disaster Resilience Implementations

The capacity to maintain continuous operation during disaster scenarios stands as a critical requirement for any robust smart city infrastructure. The effects of disasters can severely compromise communication networks, underscoring the need for innovative solutions that ensure connectivity is preserved. A noteworthy example of such a solution is Japan's "Never Die Network," designed with disaster resilience as a central tenet. This network strategically combines satellite backhaul with vehicular ad-hoc networks (VANETs), leveraging vehicles as impromptu edge nodes to maintain functionality during emergencies such as earthquakes. Andersson and Kafle's (2014) research highlights the success of this architecture, reporting that it could maintain approximately 68% connectivity even under severe disruption [7]. The ability to maintain a degree of connectivity under the most challenging circumstances highlights the significance of the Never Die Network in the implementation and design of emergency communication networks.

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