RESEARCH PAPER

SYSTEM FOR EMERGENCY VEHICLE CLEARANCE USING NDN-BASED MANET

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ABSTRACT

Background

Fast emergency response saves lives; however, severe traffic congestion and poorly coordinated road infrastructure often cause critical delays. In highly mobile vehicular networks, traditional IP-based communication protocols struggle to maintain stable data paths, leading to high transmission latency.

Objective

To solve this, we propose an intelligent traffic management system for emergency vehicle clearance that deploys Named Data Networking (NDN) over a Mobile Ad Hoc Network (MANET). Unlike standard location-dependent routing, MANET provide a self-configured, decentralized wireless backbone. The NDN complements this architecture by retrieving data based on content names rather than static IP addresses.

Materials and Methods

When an emergency vehicle approaches, it broadcasts hierarchically named interest packets containing its identity and intended path. The system utilizes NDN forwarding structures, specifically the Forwarding Information Base (FIB) and Pending Interest Table (PIT), to enable controlled flooding. This strategy propagates alerts quickly across the network without causing broadcast storms or duplicate transmissions. Consequently, civilian vehicles receive advance warnings to yield, and traffic signals are dynamically pre-empted to green to establish a clear travel corridor. Furthermore, in-network caching via the Content Store (CS) handles redundant data requests locally, sharply reducing network congestion.

Results

Simulations conducted in ndnSIM indicate that our NDN-MANET framework significantly outperforms the standard IP routing. The results demonstrate lower packet delay, higher delivery ratios, reduced network overhead, and ultimately faster travel times for emergency vehicles in infrastructure-independent smart city environments.

Keywords: NDN-driven vehicular communication, MANET emergency clearance, data-centric traffic preemption, infrastructure-independent route coordination, content-aware ad hoc networks, dynamic traffic signal preemption, interest packet propagation strategies.

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I. INTRODUCTION

As cities grow and vehicular traffic increases, managing urban road networks has become a highly complex challenge for urban planners. One of the most critical issues is ensuring that emergency vehicles, such as ambulances, fire trucks, and police cars, can navigate congested streets quickly. In emergency scenarios, the response time directly impacts the chances of saving lives and limiting property damage. However, current urban infrastructure is prone to severe congestion, which frequently delays these vital services [7], [11], [17]. Currently, emergency drivers primarily rely on sirens and flashing lights to clear their path. This traditional method often fails to give surrounding drivers enough time to react and pull over safely, especially at busy intersections or on crowded, multi-lane roads. These bottlenecks severely hinder rescue operations. To address this, researchers in Intelligent Transportation Systems (ITS) have investigated automated communication and traffic pre-emption systems to clear routes ahead of time [7], [12]. Most existing vehicular communication frameworks rely on traditional Internet Protocol (IP) architectures. IP networks are inherently host-centric and require stable end-to-end connections tied to specific location-dependent addresses. In a vehicular network, nodes are constantly moving at different speeds, which continuously alters the topology of the network. Maintaining stable IP routes in this highly dynamic environment is difficult. This mobility leads to frequent connection drops, lost data packets, and high network overhead, as the system constantly tries to recalculate routes. Therefore, standard IP protocols struggle to provide the low-latency communication necessary for mission-critical traffic pre-emption. Mobile Ad Hoc Networks (MANETs) offer a much better physical framework for vehicular environments. Because they are decentralized and self-configuring, MANETs allow vehicles to act as independent routing nodes without requiring fixed roadside towers or cellular infrastructure [11], [20], [21]. Although MANETs solve the structural problem of mobility, running legacy IP routing over them still results in poor performance. There is a fundamental disconnect between the constantly changing physical layout of a MANET and the static, destination-based routing required by Internet Protocol (IP) protocols [11], [15].

To bridge this architectural gap, this study proposes the integration of Named Data Networking (NDN) within a MANET environment. NDN is a data-centric architecture that shifts the focus from *the location of data* to *the nature of* the data. Instead of targeting specific IP addresses, NDN routes queries (called interest packets) using hierarchical, descriptive content names. In this proposed model, when an emergency vehicle generates an interest packet detailing its identity and route, surrounding nodes forward the request based strictly on that named data [1], [2], [3]. Additionally, NDN features built-in in-network caching through its Content Store (CS). This allows intermediate vehicles to cache data locally and immediately fulfil repeated requests, which significantly reduces redundant duplicate transmissions and saves valuable network bandwidth [2], [21]. This paper presents a novel System for Emergency Vehicle Clearance that combines NDN and MANETs to build a responsive, decentralized traffic pre-emption network. By broadcasting named route information, an emergency vehicle can alert both civilian drivers and smart traffic signals downstream. Utilizing NDN forwarding strategies guided by the Forwarding Information Base (FIB) and Pending Interest Table (PIT), receiving nodes intelligently propagate these alerts while avoiding broadcast storms. This allows civilian vehicles to yield autonomously and traffic lights to dynamically switch to green, thereby establishing a safe and uninterrupted travel corridor. The remainder of this paper is organized as follows: Section II reviews related work, Section III details the proposed system architecture, and Section IV evaluates the simulation results [4], [8], [9].

II. RELATED WORK

In recent years, considerable research has focused on improving emergency vehicle routing methods and reducing response times in heavily congested urban road networks. The timely arrival of emergency services, such as ambulances, fire brigades, and police vehicles, is critical for minimizing casualties and preventing the escalation of hazardous situations. Early technological approaches for facilitating emergency vehicle movement were largely implemented through centralized Intelligent Transportation Systems (ITS). These systems attempt to coordinate traffic signals using a dedicated sensing infrastructure deployed at major intersections. Common mechanisms include acoustic siren detectors, optical sensors capable of identifying emergency strobe lights, and short-range radio transmitters installed in emergency vehicles [12], [17]. When an emergency vehicle approaches an intersection, these detection systems attempt to identify the signal and temporarily adjust the traffic lights to permit the vehicle to pass safely. Although such mechanisms offer an improvement over the traditional reliance on driver awareness alone, they exhibit several operational limitations. Many of these systems depend on a direct line of sight between the emergency vehicle and the sensing device, making them susceptible to interference caused by environmental noise, buildings, weather conditions, or improper sensor alignment. Furthermore, their deployment was typically limited to selected intersections where specialized hardware was installed, leaving large segments of the urban road network without emergency response support. Another major drawback of early ITS solutions was their heavy dependence on a centralized traffic management infrastructure. Within these centralized architectures, data captured by roadside sensors must be transmitted to a remote traffic management center, where the information is processed before commands are issued to adjust the relevant traffic signals [11], [20]. This multistage communication process often introduces additional delays, particularly during periods of heavy network loads. In emergency situations where the response time is extremely critical, such delays can significantly impact the effectiveness of rescue operations. In addition, centralized control systems are inherently prone to single points of failure. If the communication backbone or central controller becomes unavailable owing to technical faults or network disruption, the entire traffic coordination system may cease to operate effectively [4], [16], [19]. As urban traffic conditions continue to become more complex with increasing vehicle density, these limitations have encouraged researchers to explore more adaptive and decentralized communication solutions. One promising direction involves distributed vehicular communication models based on Mobile Ad Hoc Networks (MANETs) and Vehicular Ad Hoc Networks (VANETs). In these decentralized networking environments, vehicles communicate directly with each other through wireless links, enabling rapid information dissemination without requiring fixed infrastructure support. Several studies have proposed employing traditional Internet Protocol (IP) routing protocols, such as Ad hoc On-Demand Distance Vector (AODV), Destination-Sequenced Distance Vector (DSDV), and Dynamic Source Routing (DSR), to facilitate both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [4], [5], [6]. Using these routing mechanisms, emergency vehicles can broadcast warning messages that notify surrounding vehicles and nearby infrastructure of their presence and intended path. The primary objective of such communication is to enable surrounding drivers to yield the right-of-way while allowing traffic signal controllers to adjust the signal phases in advance of the approaching emergency vehicle. Despite the conceptual advantages of these IP-based routing methods, numerous experimental and simulation studies have revealed that their performance degrades significantly in highly dynamic vehicular environments [11], [20]–[21]. Traditional IP networking relies on maintaining stable end-to-end communication paths between specific hosts. However, vehicular networks are characterized by continuous topology changes as vehicles accelerate, decelerate, and move between lanes.

Consequently, routing paths frequently break, forcing routing protocols to repeatedly initiate route discovery procedures. These repeated route discoveries generate additional control traffic, which increases the network overhead and contributes to congestion. During emergency scenarios, such communication delays or packet loss can compromise the reliability required for safety-critical message dissemination. Consequently, although IP-based routing may perform adequately in relatively stable networks, it often struggles to maintain its efficiency in highly mobile vehicular environments. Recognizing these limitations, recent research has shifted toward alternative networking paradigms that are better suited to dynamic and data-oriented communication environments. One prominent approach is Information-Centric Networking (ICN), within which Named Data Networking (NDN) has emerged as a widely studied architecture. Unlike conventional host-centric communication models that depend on specific device addresses, NDN emphasizes named data retrieval. In this framework, a consumer sends an interest packet specifying the name of the required data, and the network retrieves the corresponding data packet from any node capable of providing it. This approach eliminates the need to maintain persistent host-to-host communication paths, making it particularly advantageous for networks experiencing frequent topology changes [1], [2], [3]. The NDN architecture employs several fundamental data structures that support efficient packet forwarding and content retrieval processes. These structures include the Forwarding Information Base (FIB), Pending Interest Table (PIT), and Content Store (CS). The FIB maintains information about potential forwarding paths associated with different data names, whereas the PIT records pending interest packets along with the interfaces from which they are received. Once the requested data packet becomes available, it is delivered along the reverse path indicated by the corresponding PIT entry. Additionally, the Content Store enables nodes to locally cache previously transmitted data so that future requests for the same information can be satisfied immediately without requiring additional transmissions across the network [1], [2], [24]. This capability of in-network caching significantly reduces redundant data transmissions and improves communication efficiency in distributed networks. Previous studies have investigated the application of NDN in vehicular environments for purposes such as infotainment distribution, cooperative sensing, and collision avoidance messaging [16], [22], [26]. These investigations indicate that the data-centric design of NDN can enhance scalability and reduce packet overhead compared with conventional IP-based communication protocols. The hierarchical naming structure used in the NDN also allows information to be organized according to geographic regions, service categories, or application contexts [8], [9], [10]. When combined with stateful forwarding mechanisms, these characteristics enable efficient data dissemination, even under high mobility conditions. Simulation results from various studies demonstrate that NDN-based communication models can effectively mitigate broadcast storms while maintaining higher packet delivery ratios in rapidly changing vehicular environments. Although these findings highlight the suitability of NDN for vehicular networking, its application to the specific challenge of emergency vehicle traffic clearance remains limited. Most prior studies have primarily focused on general data dissemination, infotainment delivery, or cooperative safety messaging, rather than the targeted coordination required to clear a traffic corridor for an approaching emergency vehicle. Achieving effective emergency clearance requires not only the rapid distribution of warning messages but also coordinated action among nearby vehicles and infrastructure components. Such coordination must occur in real time to ensure that surrounding vehicles move aside while traffic signals adapt their timing to facilitate an uninterrupted passage [7], [26]. Another limitation of existing research is the absence of integrated frameworks that simultaneously address vehicle behaviour adaptation and intelligent traffic signal control. In many proposed systems, either the vehicles respond to received alerts by adjusting their movement, or the infrastructure independently modifies traffic signal phases. Without such coordination, emergency vehicles may encounter delays due to incomplete traffic dispersion or inefficient signal phase transitions. To overcome these limitations, this study proposes an integrated framework that combines the decentralized communication capabilities of MANET architectures with the data-centric principles of Named Data Networking. The proposed approach introduces a location-aware constrained-flooding strategy tailored specifically for emergency vehicle scenarios. By incorporating spatial proximity and directional forwarding constraints, the system enables interest packets to propagate efficiently toward relevant traffic signal nodes while minimizing redundant transmissions across the network [4], [8], [9]. Simultaneously, the architecture supports real-time interaction between vehicles and infrastructure, enabling traffic signals to enter emergency priority modes while allowing nearby vehicles to respond appropriately. By integrating MANET mobility characteristics with the name-based data retrieval mechanisms of NDN, the proposed system aims to provide a low-latency and reliable communication framework for emergency traffic management. By prioritizing emergency-related messages, optimizing packet forwarding strategies, and enabling cooperative interaction among vehicles and infrastructure, the framework offers a scalable solution for intelligent traffic preemption in congested urban environments. In doing so, this study contributes to bridging the gap between theoretical research on NDN-based vehicular networking and practical implementations for emergency vehicle clearance within modern smart city transportation systems [7], [17], [26].

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IV. PERFORMANCE ANALYSIS

A. Routing Efficiency and Clearance Delay Analysis

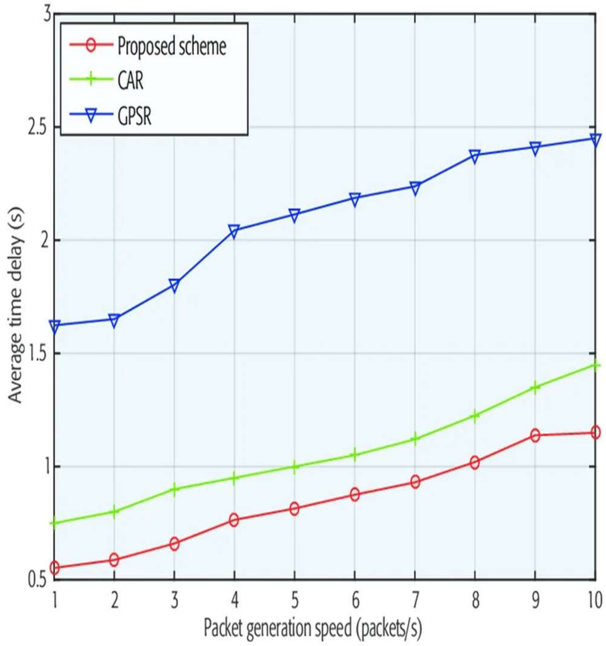

Fig. 3. Comparison of Average Time Delay

The average route clearance delay is obtained by dividing the total delay observed across all simulation runs by the number of successful preemption events. This metric represents the time taken for the system to respond after an emergency vehicle sends its initial interest packet.

In practical terms, the delay measures the interval between the emergency vehicle requesting route clearance and the traffic infrastructure adjusting the signal to allow the vehicle to pass. Lower delay values indicate that the system can respond quickly to emergency situations, thereby improving the overall effectiveness of the traffic management process.

$$\text{Average Delay} = \frac{\sum(\text{Time}_{\text{DataReceived}} - \text{Time}_{\text{InterestSent}})}{\text{Total Successful Preemptions}} \tag{3}$$

B. Scalability Analysis

Scalability pertains to a system's capacity to sustain stable performance as the number of vehicles within the network increases. In urban settings, where traffic density can fluctuate considerably, it is crucial for the MANET to operate efficiently even amidst a high presence of civilian vehicles. The outcomes of the scalability assessment are depicted in Fig. 4, illustrating the correlation between routing overhead and network size. The findings indicate that the proposed approach effectively mitigates broadcast storms, even under conditions of heavy traffic. To assess performance, the proposed data-centric routing approach is also compared with traditional IP-based routing protocols, such as AODV.

Fig. 4. Scalability Analysis: Routing Overhead vs. Network Size

C. Communication Reliability

Communication reliability refers to the system's ability to consistently deliver Interest and Data packets within a highly dynamic vehicular environment. Given that vehicles frequently change their positions, communication links between nodes may unexpectedly break.

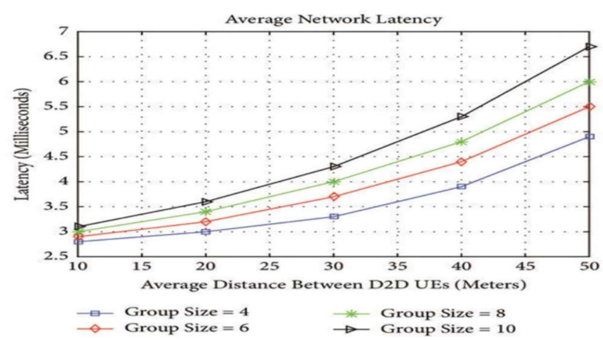

Fig. 5. Average Latency comparison with network size

The proposed forwarding strategy effectively addresses this challenge by permitting packets to be transmitted solely through nodes that are geographically proximate to the destination. This spatial filtering enhances the likelihood that Interest packets will reach the designated traffic signal and that the corresponding Data packets will successfully return to the emergency vehicle. Consequently, reliable communication can be sustained even when vehicles are traveling at high velocities.

D. Network Resource Efficiency

Network resource efficiency evaluates how effectively the routing protocol utilizes available communication bandwidth. In dense vehicular networks, uncontrolled broadcasting can lead to excessive redundant packets and increased channel congestion.

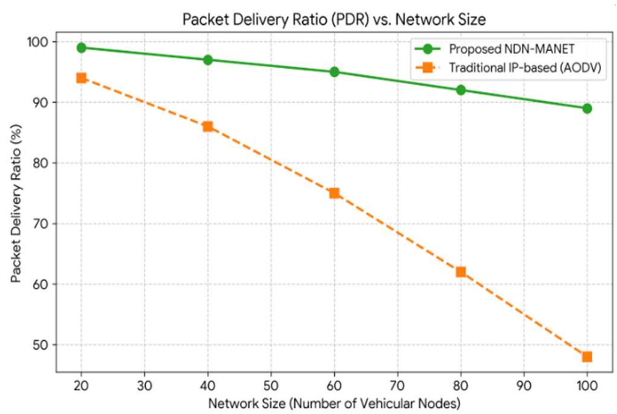

Fig. 6. Packet Delivery Ratio comparison with network size

V. CONCLUSION

The proposed constrained forwarding method reduces this problem by allowing only suitable nodes to retransmit Interest packets based on spatial conditions. By minimizing unnecessary packet transmissions, the system lowers routing overhead while still ensuring that emergency routing information spreads quickly throughout the network. This controlled packet dissemination helps maintain stable network performance even during periods of heavy traffic. Optimized, name-based routing decisions have not only led to a higher PDR by efficiently directing Interest packets toward the intelligent traffic infrastructure, but have also minimized blind flooding through spatial constraints, resulting in drastically reduced network overhead. The findings indicate that the proposed NDN-MANET architecture can significantly improve emergency response times, offering decreased urban congestion, highly reliable V2V communication, and immediate dynamic signal preemption. As a result, route clearance within these dynamic vehicular environments becomes strictly autonomous and highly dependable. Looking towards the future, this project establishes a solid foundation for further exploration of data-centric intelligent transportation systems. Potential areas for future research include investigating the integration of 5G/V2X communication standards to further minimize propagation delay. Additionally, developing AI-based traffic prediction models could allow the system to preemptively clear multiple intersections in advance. Finally, exploring cryptographic signature techniques to incorporate secure authentication of emergency vehicles will be vital to prevent malicious actors from broadcasting fake clearance directives and compromising network integrity. Future research will evaluate the proposed NDN-MANET architecture under highly dynamic mobility models to further validate its robust scalability and low-latency performance in dense urban environments. Additionally, integrating this routing protocol with intelligent traffic management frameworks could provide a highly optimized, real-time communication layer for automated emergency vehicle clearance.

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