Engineering, 2025, 17(1), 136-154
https://www.scirp.org/journal/eng
ISSN Online: 1947-394X
ISSN Print: 1947-3931

Impact of Interference and Mobility on MAC Layer Performance in VANETs, FANETs

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How to cite this paper: Kouraogo, P.J., Omar, H.H. and Guel, D. (2025) Impact of Interference and Mobility on MAC Layer Performance in VANETs, FANETs. *Engineering*, **17**, 136-154.
https://doi.org/10.4236/eng.2025.171009

Received: December 13, 2024
Accepted: January 23, 2025
Published: January 26, 2025

Abstract

Vehicular Ad Hoc Networks (VANETs) play a pivotal role in advancing Intelligent Transportation Systems (ITS), facilitating real-time communication among vehicles and infrastructure. However, VANETs face challenges arising from high mobility, dynamic topologies, and significant interference levels. This study proposes a novel cross-layer framework incorporating channel prediction and adaptive resource management to address these challenges. By leveraging a Software-Defined Radio (SDR) platform, the framework is evaluated under diverse mobility and interference conditions. Key contributions include an analysis of multi-code and multi-modulation schemes, identification of critical trade-offs in receiver diversity, and the introduction of mechanisms to optimize Quality of Service (QoS). Simulation results demonstrate significant improvements in throughput, packet delivery ratio, and network resilience, highlighting the framework's potential for real-world applications such as autonomous vehicles and smart city communication networks. The study concludes with actionable recommendations for future research, emphasizing scalability, real-time adaptation, and hardware implementation to further enhance VANET performance.

Keywords

VANET, Cross-Layer Design, Channel Prediction, QoS Optimization, Interference Management, Mobility Models

1. Introduction

Vehicular Ad hoc Networks (VANETs) have emerged as a critical component of Intelligent Transportation Systems (ITS), enabling enhanced road safety, traffic management and infotainment applications. Despite significant advancements in

VANET technologies, several challenges persist, particularly in managing the dynamic nature of vehicular environments and addressing interference in communication systems. The inherent high mobility, rapidly changing topologies and diverse quality-of-service (QoS) requirements of VANETs create substantial complexities in network design and performance optimization.

Existing studies have extensively explored Medium Access Control (MAC) protocols, including contention-based and contention-free approaches and their applications in VANETs [1]-[3]. However, the integration of these protocols often falls short of addressing critical issues such as interference management, scalability under high-density traffic and efficient resource allocation. For instance, traditional MAC designs struggle to ensure reliable communication in scenarios with high user density and co-channel interference [2] [4]. Furthermore, the lack of effective cross-layer designs limits the ability to optimize system performance across different layers of the communication stack [5] [6].

This study addresses these gaps by proposing a cross-layer framework that integrates advanced channel prediction techniques with adaptive MAC mechanisms. Specifically, the proposed approach leverages inter-layer collaboration to enhance system performance under varying traffic densities and mobility scenarios. The framework introduces innovative methods for real-time channel state estimation and interference mitigation, ensuring robust and reliable communication even in high-density vehicular networks.

The key contributions of this work are summarized as follows:

- **Research Gap Identification:** Identification and analysis of the limitations in existing MAC protocols and their inability to handle dynamic interference and mobility challenges effectively.
- **Proposed Framework:** Development of a novel cross-layer mechanism that combines predictive channel modeling and adaptive MAC protocols to address interference and improve throughput.
- **Evaluation and Validation:** Comprehensive simulation-based evaluation of the proposed framework under realistic vehicular scenarios, demonstrating significant improvements in packet delivery ratio, latency and overall network performance.

To illustrate the challenges addressed by the proposed framework, consider a scenario where high vehicular density leads to frequent collisions and degraded communication reliability. Traditional MAC protocols, such as IEEE 802.11p, often exhibit reduced performance due to their static channel allocation strategies [7] [8]. By introducing dynamic channel prediction and adaptive resource allocation, the proposed framework mitigates these issues and enhances the efficiency of VANET communication systems.

In the following sections, we provide a detailed discussion of the methodology, simulation setup and performance analysis of the proposed framework. The insights derived from this study contribute to advancing the design of VANET systems and paving the way for their effective deployment in real-world ITS applications.

2. Background and State of the Art

Vehicular Ad Hoc Networks (VANETs) have emerged as a cornerstone for enabling intelligent transportation systems, promising significant advancements in road safety and traffic efficiency. This section presents a comprehensive review of the state-of-the-art technologies and methodologies categorized into thematic subsections to enhance clarity and cohesion.

2.1. Interference Management in VANETs

Interference remains a primary challenge in VANETs due to the dynamic nature of vehicular environments and the high density of nodes. Various approaches have been proposed to address this issue, as shown in **Table 1**:

- **Multi-user Detection:** Techniques such as linear multiuser receivers [3] [6] and interference cancellation strategies [2] have been explored to mitigate co-channel interference and enhance signal-to-interference ratios.
- **Channel Allocation:** Dynamic channel allocation schemes, such as those proposed in [4], leverage cross-layer designs to optimize resource utilization while minimizing interference.
- **Cognitive Radio Integration:** Studies such as [8] discuss the role of cognitive radio in enabling dynamic spectrum access and reducing interference.

Table 1. Comparison of interference management techniques.

Technique	Strengths	Limitations	References
Multi-user Detection	High SIR improvement	Computational complexity	[3] [6]
Channel Allocation	Optimized resource utilization	Dependency on network topology	[4]
Cognitive Radio	Flexible spectrum access	Hardware complexity	[8]

2.2. Mobility Management and Handling

Mobility poses unique challenges in VANETs, such as frequent topology changes and variable communication link quality, as shown in **Table 2**.

- **Mobility Models:** Realistic models like those proposed in [9] integrate vehicular mobility with communication simulations to accurately reflect real-world dynamics.
- **Dynamic Slot Allocation:** Approaches such as [10] optimize time slot usage to handle rapid changes in network topology.
- **Cross-layer Optimization:** Combining mobility and communication layers, studies like [5] highlight the benefits of cross-layer designs in enhancing network resilience.

Table 2. Comparison of mobility management techniques.

Technique	Strengths	Limitations	References
Mobility Models	Realistic simulation	High computational cost	[9]
Dynamic Slot Allocation	Efficient resource usage	Limited scalability	[10]
Cross-layer Optimization	Enhanced network resilience	Increased design complexity	[5]

2.3. Medium Access Control (MAC) Protocols

The design of MAC protocols is critical to ensuring reliable communication in VANETs. Various strategies have been developed to meet the unique demands of vehicular environments, as shown in Table 3:

- **Contention-based Protocols:** Protocols like IEEE 802.11p [1] use CSMA/CA mechanisms to handle channel access.
- **Hybrid Protocols:** Approaches such as [11] combine contention-based and contention-free mechanisms to enhance performance.
- **Time Division Multiple Access (TDMA):** TDMA-based schemes [12] allocate dedicated time slots to reduce collisions and improve reliability.

Table 3. Comparison of MAC protocols.

Protocol	Strengths	Limitations	References
IEEE 802.11p	Simple implementation	High collision rates	[1]
Hybrid Protocols	Balanced performance	Design complexity	[11]
TDMA	Reduced collisions	Fixed slot assignment	[12]

2.4. Advancements in Cross-Layer Design

Cross-layer design has gained traction as an effective approach to address the multi-faceted challenges of VANETs, as shown in Table 4.

- **Resource Allocation:** Studies like [13] demonstrate how resource allocation strategies can optimize network throughput and quality of service (QoS).
- **Adaptive Mechanisms:** Adaptive frameworks [14] dynamically adjust network parameters to improve performance under varying conditions.
- **Integration of Machine Learning:** Emerging works [15] explore the potential

Table 4. Comparison of cross-layer design approaches.

Approach	Strengths	Limitations	Reference
Resource Allocation	Improved throughput	Complexity in real-time applications	[13]
Adaptive Mechanisms	Resilience to dynamic conditions	Implementation challenges	[14]
Machine Learning	Enhanced decision-making	Requires extensive training data	[15]

of machine learning to enhance decision-making in cross-layer designs.

This comprehensive review highlights the advancements and challenges in interference management, mobility handling, MAC protocols and cross-layer design for VANETs, setting the stage for the proposed methodologies discussed in subsequent sections.

3. Methodology

The adopted methodology utilizes a structured approach to model VANETs in diverse scenarios through simulations using an SDR platform. The methodology is detailed below with visual representation, discussion of potential limitations and justification for selected channel prediction models.

3.1. Overview of the Methodology

The methodology, illustrated in Figure 1 follows these key steps:

- **Interference Impact Analysis:** Simulate environments with varying interference levels to analyze their impact on transmission quality and network robustness.
- **Node Mobility Modeling:** Model vehicle movement using urban, highway and mixed mobility patterns to assess network resilience under realistic conditions.
- **Multi-Code and Multi-Modulation Schemes:** Evaluate network performance using schemes such as Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) compared to traditional methods.
- **Diversity Reception Techniques:** Implement techniques to reduce errors due to interference and mobility, enhancing reliability.
- **Comparative Analysis:** Compare different medium access mechanisms based on node mobility and interference to provide comprehensive insights.

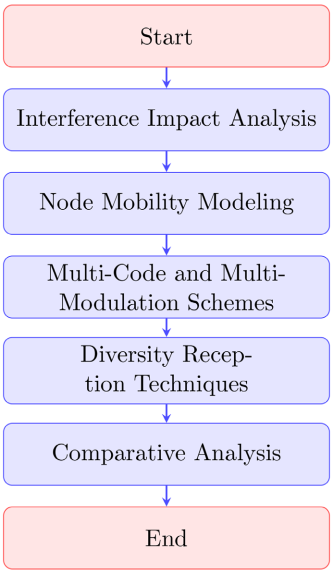

Figure 1. Methodology process flow.

3.2. Cross-Layer Mechanism with Channel Prediction

The cross-layer mechanism integrates radio and physical access layers to optimize resource management in interference-prone environments. The steps involved are:

1) Neighborhood Listening: Listen for Connection Confirmation (CTS) packets to detect active transmitters.

2) RTS Packet Header Analysis: Analyze headers to extract destination addresses for identifying incoming streams.

3) Extracting QoS Requests: Extract QoS requirements such as throughput and delay tolerances.

4) Channel Gain Estimation and Prediction: Estimate and predict channel gains to anticipate conditions.

5) Rate Allocation and Loss Calculation: Allocate transmission rates and calculate packet loss rates based on predictions.

6) Training Sequence Update: Update training sequences with calculated rates and loss metrics for efficient transmission.

7) Transmitter Scheduling: Optimize scheduling based on throughput, loss, delay and priority.

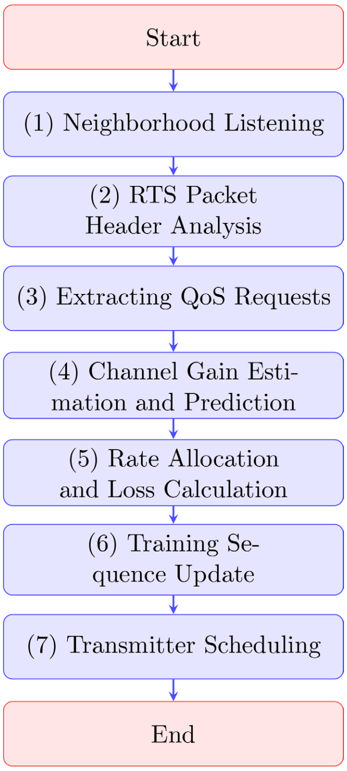

Figure 2. Inter-layer mechanism for channel prediction.

Figure 2 provides a detailed process flow, highlighting the sequential steps in the cross-layer mechanism. Starting with neighborhood listening and RTS packet header analysis, it progresses through QoS request extraction, channel gain prediction, rate allocation, training sequence updates, and finally transmitter scheduling. Each step is designed to optimize resource allocation and ensure efficient communication in interference-heavy scenarios. At the same time, Figure 3 demonstrates the interaction between channel prediction and adaptation mechanisms. The figure emphasizes the dynamic adaptation process in response to predicted interference levels, showcasing the ability of the system to maintain robust performance by preemptively adjusting transmission parameters and resource allocations.

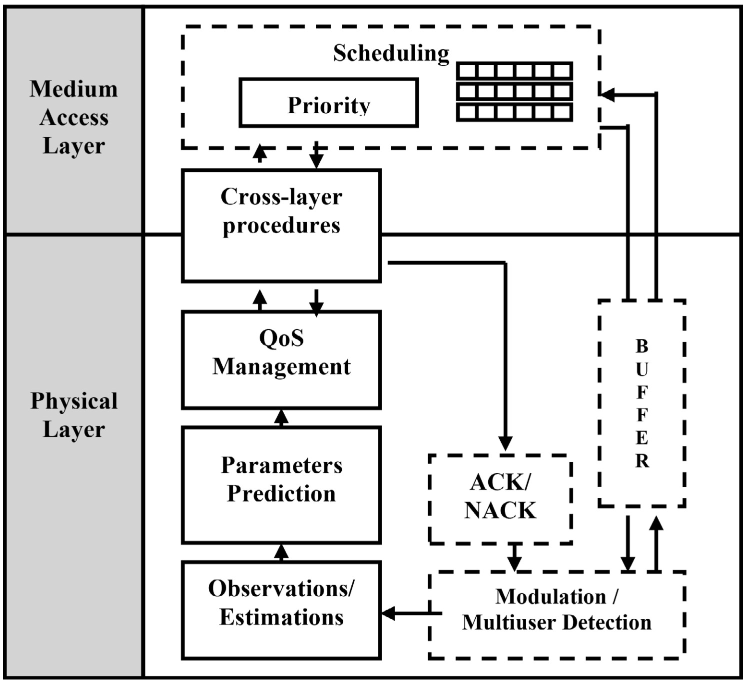

Figure 3. Prediction adaptation et interference.

3.3. Rationale for Channel Prediction Models

The selection of channel prediction models is based on the following considerations:

- **Realistic Modeling:** The models used are validated against empirical data to ensure applicability to real-world VANET scenarios.
- **Performance Optimization:** Prediction models with lower computational complexity and high accuracy are prioritized.
- **Scalability:** The models are chosen to accommodate varying network densities and mobility patterns.

3.4. Limitations and Trade-Offs

The methodology has some inherent limitations and trade-offs:

- **Computational Overhead:** Real-time channel prediction increases computational complexity.
- **Scalability Challenges:** High-density networks may require further optimization

to maintain prediction accuracy.

- **Assumptions in Mobility Models:** Simplified mobility models may not capture all real-world dynamics.

This comprehensive methodology combines theoretical rigor with practical relevance to address key challenges in VANET communication.

4. Simulation and Results

To provide a comprehensive evaluation of the proposed framework, this section outlines the simulation setup, performance metrics and results analysis. By mimicking real-world VANET conditions and testing the system under various mobility speeds and network densities, the simulations aim to validate the robustness, scalability and practical viability of the framework. The results highlight the impact of key parameters on network performance and demonstrate the advantages of incorporating channel prediction algorithms into the MUD-MAC protocol.

4.1. Performance Evaluation Scenarios and Metrics

This section presents the simulation scenarios and the metrics used to evaluate the system's performance under realistic conditions. The selection of metrics and simulation parameters was carefully tailored to align with the research objectives.

4.1.1. Metrics at the Physical Layer in Multipath Channels

This subsection details the evaluation of Bit Error Rate (BER) and other metrics at the physical layer, focusing on multipath channel scenarios. These metrics were prioritized due to their direct impact on signal reliability and communication efficiency in VANETs.

The receiver architecture is divided into two main components:

1) Bra**nch Operations:**

- Includes matched filter reception, successive interference suppression and decorrelation, which are linear processes crucial for noise and interference mitigation.

- The Signal-to-Noise and Interference Ratio (SINR) expressions remain consistent with those for single-path channels, as defined in [16].

- BER is calculated using modulation-specific formulas for BPSK, QPSK and M-QAM. For instance:

$$P_{e,k}^{I/Q} \approx \frac{\sqrt{M_k}-1}{\sqrt{M_k}} \cdot \left(1-\sqrt{\frac{\gamma_k}{\gamma_{k+1}}}\right).$$

2) P**ath Combination Methods:**

- Two methods are analyzed: maximizing SINR and applying equal gain (value 1).

- The SINR maximization approach calculates the total symbol error probability as:

$$P_{e,k}^{I/Q} = \left(P_{b,k}^{I/Q}\right)^{L_p} \sum_{i=0}^{L_p-1} \binom{L_p-1+i}{i} \left(1-P_{b,k}^{I/Q}\right)^{i},$$

where L_p is the number of paths.

- For detectors employing interference suppression or decorrelation, performance is modeled using eigenvalues of the covariance matrix, as in equations:

$$P_{Rate}^{I/Q} = \sum_{i=1}^{L_p} \frac{\beta_i}{2} \left[\frac{1}{\sqrt{1+\frac{N_0}{\lambda_i}}} \right],$$

and modulation-specific formulas such as:

$$P_{Rate}^{I/Q,M-\mathrm{QAM}} \approx 2\left(\frac{\sqrt{M}-1}{\sqrt{M}}\right)\prod_{i=1}^{L}\frac{1}{2\gamma_i}.$$

4.1.2. Metrics at the Radio Access Layer

Metrics at this layer quantify overall network performance, balancing reliability and efficiency.

- **Packet Loss Rate:** Reflects the combined impact of BER, SINR and channel conditions. Defined as:

$$PER_k = 1-\left(1-BER_k\right)^{N_b},$$

where N_b is the number of bits in a packet.

- **Throughput:** Measures the rate of successfully delivered packets:

$$Goodput = \sum_{k=1}^{N_{\mathrm{user}}} \frac{N_{\mathrm{packets},k} - \mathrm{Loss}_k}{t_k}.$$

- **Network Delay:** While calculated using:

$$Delay = \frac{1}{N}\sum_{k=1}^{N_{\mathrm{user}}}\sum_{l_{\mathrm{slot}}=1}^{N_{\mathrm{slot}}} \delta l_{l_{\mathrm{slot}}}\left(L_{i,c} PER_{i,c}^{l_{\mathrm{slot}}}\right),$$

Its analysis is beyond the scope of this study.

4.1.3. Simulation Scenarios and Parameters

Simulations are performed under various conditions to mimic real-world scenarios, including:

- **Mobility Speeds:** Speeds range from 10 km/h to 120 km/h to represent urban and highway settings. These values were chosen to explore the effects of mobility on communication reliability.
- **User Densities:** Scenarios include low (10 nodes), medium (50 nodes) and high (100 nodes) densities, ensuring coverage of sparse and congested network conditions.
- **Channel Models:** Multipath fading is modeled to reflect realistic urban environments, justifying the use of BER and SINR as primary metrics.

This methodology provides a comprehensive framework for evaluating VANET performance across diverse and challenging operational conditions.

4.2. Simulation Scenarios

To evaluate the performance and scalability of the proposed framework, simulations were designed to reflect real-world Vehicular Ad Hoc Network (VANET) conditions while assessing network behavior under varying user loads and mobility patterns. The scenarios are detailed below:

1) Fixed-to-Mobile Scenario:

- This scenario models a fixed infrastructure communicating with mobile nodes, replicating typical urban and highway environments.

- Transmitter speeds of 20 m/s, 30 m/s and 50 m/s (corresponding to 72 km/h, 108 km/h and 180 km/h, respectively) were used to represent diverse mobility patterns. These speeds are indicative of realistic vehicular movement in urban and high-speed freeway settings.

2) Mobile-to-Mobile Scenario:

- In this scenario, both the transmitter and receiver are mobile, simulating direct vehicle-to-vehicle (V2V) communication.

- Relative mobility indices v_1, v_2 and v_3 were considered, where these indices represent various relative velocities between the communicating nodes. These settings allow for the study of link stability under dynamic movement conditions.

4.2.1. Simulation Framework and Scalability Analysis

The simulations were conducted with 15 superframes (150 frames), progressively increasing the number of users from 32 to 256. This variation in network density allows for the evaluation of scalability and load-handling capacity under diverse conditions.

The load at the central node was assessed using the following formulas, illustrating the impact of multi-rate and single-rate systems on network performance:

$$\text{Load}^{APG} = \sum_{i=1}^{K} \frac{1}{G_t}, \quad \text{Load}^{MC} = \sum_{i=1}^{K} \frac{N_{\text{code}_i}}{G_0}, \quad \text{Load}^{MM} = \sum_{i=1}^{K} \frac{\log_2\left(M_i\right)}{G_0}, \tag{1}$$

where:

- G_t and G_0 are spreading factors.
- N_{code_i} represents the number of codes allocated to user i.
- M_i is the modulation order for user i.

4.2.2. Real-World Relevance and Scalability Insights

- **Mimicking Real-World VANETs:** The scenarios incorporate realistic mobility patterns, including high-speed freeway and congested urban traffic conditions, ensuring that the findings are applicable to real-world VANET deployments.
- **Scalability of the Framework:** The framework demonstrates robustness across varying network loads, with multi-rate systems showing higher efficiency in supporting dynamic user densities. However, it is noted that as the user density increases, the system must balance resource allocation to maintain acceptable quality of service (QoS) levels.

This comprehensive simulation setup provides valuable insights into the behavior and scalability of VANETs under realistic and diverse operational scenarios.

4.3. Key Observations and Results

1) Impact of transmission parameters:

- Users with high spreading factors, a large number of parallel codes, or large constellation sizes contribute significantly to receiver load.

- Rate adaptation generates load variability, changing performance at the data slot level.

2) Performance of reception methods:

- The simulated methods include matched filter, successive interference suppression and decorrelation.

- The results show that the SINR maximization method is optimal to minimize the BER and maximize the useful throughput.

3) Transmission without guarantee of quality of service:

- The results of the simulations, although carried out on high user loads, converge towards similar conclusions.

- Longer simulations would increase complexity without providing significant improvements to the results.

4.4. Simulation Results

This section presents the performance evaluation of the enhanced Multi-User Detection MAC (MUD-MAC) protocol, incorporating the conceptual framework, compared to the baseline protocols. The baseline includes the basic MUD-MAC protocol (without prediction) and two additional cases where the cross-layer framework with channel prediction and estimation algorithms is implemented. Monte Carlo simulations were used to assess performance under varying transmission conditions and user mobility.

4.4.1. Evaluation Context

The superiority of the basic MUD-MAC protocol over the matched filter receiver, parallel multi-channel protocol and IEEE 802.11 protocol has been established in prior work [17]. However, limited studies exist on complete multi-user detection protocols, requiring further comparison. This study evaluates the impact of the proposed conceptual framework on throughput and error rates, aiming to make the protocol more operational.

Key aspects of the evaluation include:

- **Comparison Scenarios:** The baseline protocol without prediction and the enhanced protocol with prediction algorithms.
- **Simulation Metrics:** Average reception rate and aggregate useful throughput.
- **Simulation Platform:** CDMA system with variable spreading factor transmitters.
- **Simulation Parameters:** Detailed in Table 5.

4.4.2. Simulation Parameters

Table 5 outlines the parameters used in the simulations, including bandwidth, transmitter power, code lengths and rates for different transmission techniques. Notable parameters include:

Table 5. Parameters used in the simulation.

Parameter	Value
Signal bandwidth	2.25 MHz
Transmitter threshold signal-to-noise ratio	20, 25 dB
Average transmitter power	0.1, 0.63 mW
Code lengths (multi-factor transmission)	[2, 4, 16, 32, 64, 128, 256, 512]
Carrier frequency	2.4 GHz
Channel sampling frequency	10^6 Hz

A detailed summary of the simulated channels and their respective link parameters is presented in Table 5 focusing on multipath channels and fixed-to-mobile conditions.

4.4.3. Performance Metrics

The performance was evaluated by varying the data slot length from 1 to 8 ms and measuring:

1) **Average Reception Rate:** The percentage of successfully received packets.

2) **Aggregate Useful Throughput:** The total useful data received per unit time.

These metrics were analyzed under three conditions for channel information acquisition:

- Using the proposed channel prediction algorithm.
- Using the estimation algorithm only.
- Assuming perfect channel knowledge.

4.5. Results and Analysis

This section evaluates the performance of the proposed framework through a comprehensive analysis of simulation results under varying user densities and mobility speeds. The results provide critical insights into the interplay between interference, mobility, and network performance, highlighting the advantages of integrating channel prediction algorithms with the MUD-MAC protocol.

4.5.1. Mobility and Increasing User Density

Simulations were conducted under fixed-to-mobile multipath channels with a 25 MHz bandwidth. Figures 4-9 illustrate the reception rate and aggregate useful throughput for varying user densities at mobility speeds of 20 m/s, 35 m/s and 50 m/s. Key observations include:

- **Variable Spread Factor Transmission:** This approach consistently outperformed others in reception rate.
- **Receiver Performance:** Matched-filter receivers and SIC exhibited low reception rates compared to decorrelator detectors in multi-code transmission scenarios.
- **Interference and Complexity:** Increasing the number of users elevated interference, reducing reception rates and aggregate throughput. Multi-code trans-

mission yielded high complexity and lower resistance to interference.

4.5.2. Fixed-to-Mobile Channel at 20 m/s

- **Reception Rate:** Figure 4 illustrates the packet delivery ratio (PDR) as a function of the number of connected users for a fixed-to-mobile multipath channel with a mobility speed of $v = 20$ m/s. The decorrelator (DEC) receiver consistently outperforms other methods, maintaining high PDR even as the number of users increases. It demonstrates higher rates for variable spreading factor transmitters.
- **Aggregate Throughput:** Figure 5 depicts the aggregate useful throughput as a function of the number of connected users for a fixed-to-mobile multipath channel with a mobility speed of $v = 20$ m/s. The decorrelator (DEC) detector consistently achieves higher throughput compared to other methods, particularly as the number of users increases. It shows superior throughput using the decorrelator detector.

4.5.3. Fixed-to-Mobile Channel at 35 m/s

- **Reception Rate:** Figure 6 illustrates the reception rate (PDR) as a function of the number of connected users for a fixed-to-mobile multipath channel at a speed of $v = 35$ m/s. The decorrelator (DEC) detector maintains the highest reception rates across varying user densities, showcasing its resilience to interference and mobility effects. It demonstrates the decorrelator detector's robustness under moderate mobility conditions.
- **Aggregate Throughput:** Figure 7 presents the aggregated useful throughput as a function of the number of connected users for a fixed-to-mobile multipath channel at a speed of $v = 35$ m/s. The decorrelator (DEC) detector consistently achieves the highest throughput, outperforming other methods across all user densities. It confirms the decorrelator detector's consistent performance with channel prediction algorithms, even under moderate mobility conditions.

4.5.4. Fixed-to-Mobile Channel at 50 m/s

- **Reception Rate:** Figure 8 illustrates the packet reception rate as a function of the number of connected users for a fixed-to-mobile multipath channel at a speed of $v = 50$ m/s. The decorrelator (DEC) detector demonstrates superior resilience to increasing user density, maintaining high performance compared to other methods. It highlights the decorrelator detector's robustness under high mobility conditions and significant user loads.
- **Aggregate Throughput:** Figure 9 presents the aggregate useful throughput for various detection methods as the number of connected users increases in a fixed-to-mobile multipath channel at a speed of $v = 50$ m/s. The decorrelator (DEC) detector consistently outperforms other methods, maintaining higher throughput even under high user densities. It confirms the superior efficiency of the decorrelator detector in managing throughput in high-mobility and high-user scenarios.

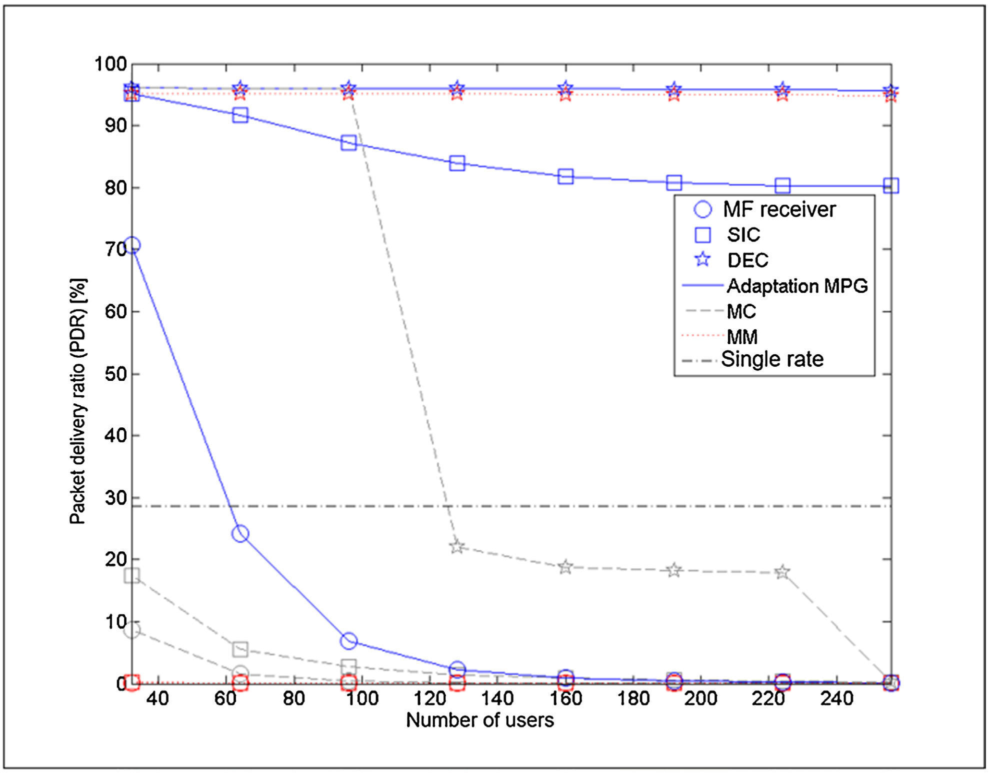

Figure 4. Reception rate as a function of the number of connected users, fixed-to-mobile multipath channel $v = 20$ m/s.

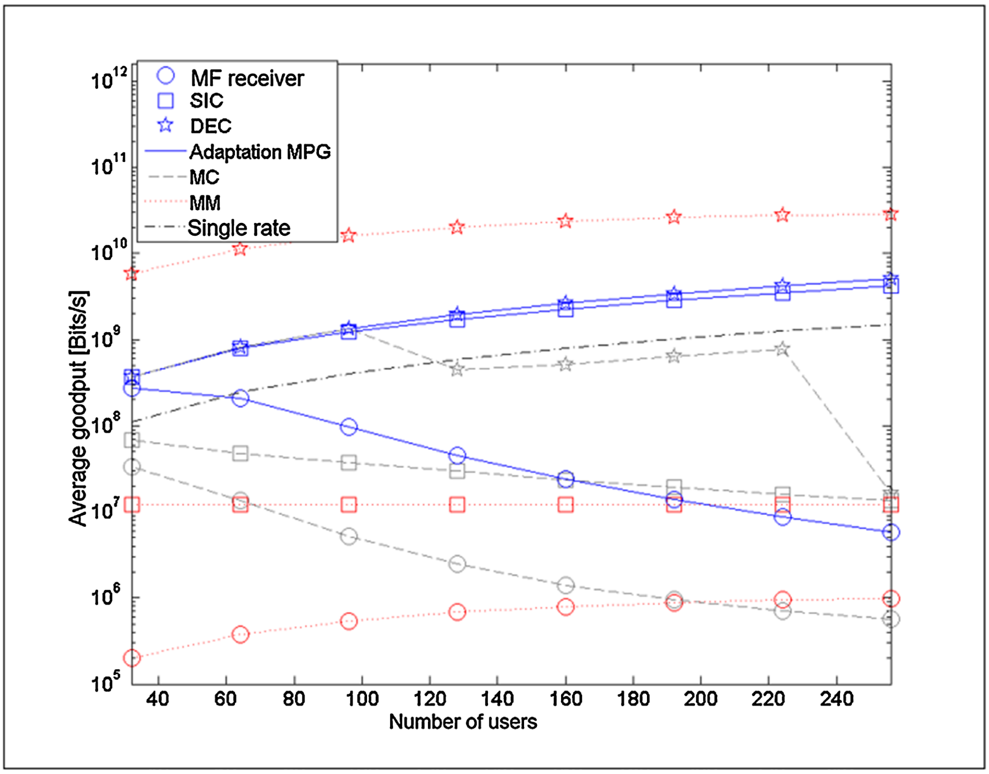

Figure 5. Aggregate useful throughput as a function of the number of connected users, fixed-to-mobile multipath channel $v = 20$ m/s.

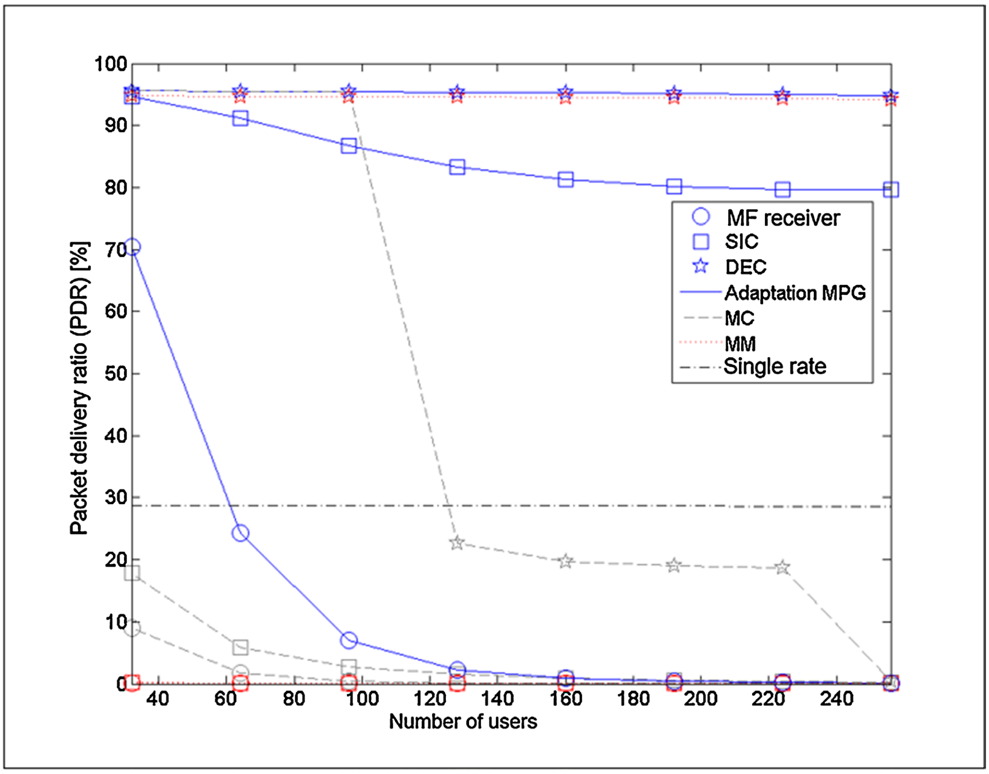

Figure 6. Reception rate as a function of the number of connected users, fixed-to-mobile multipath channel $v = 35$ m/s.

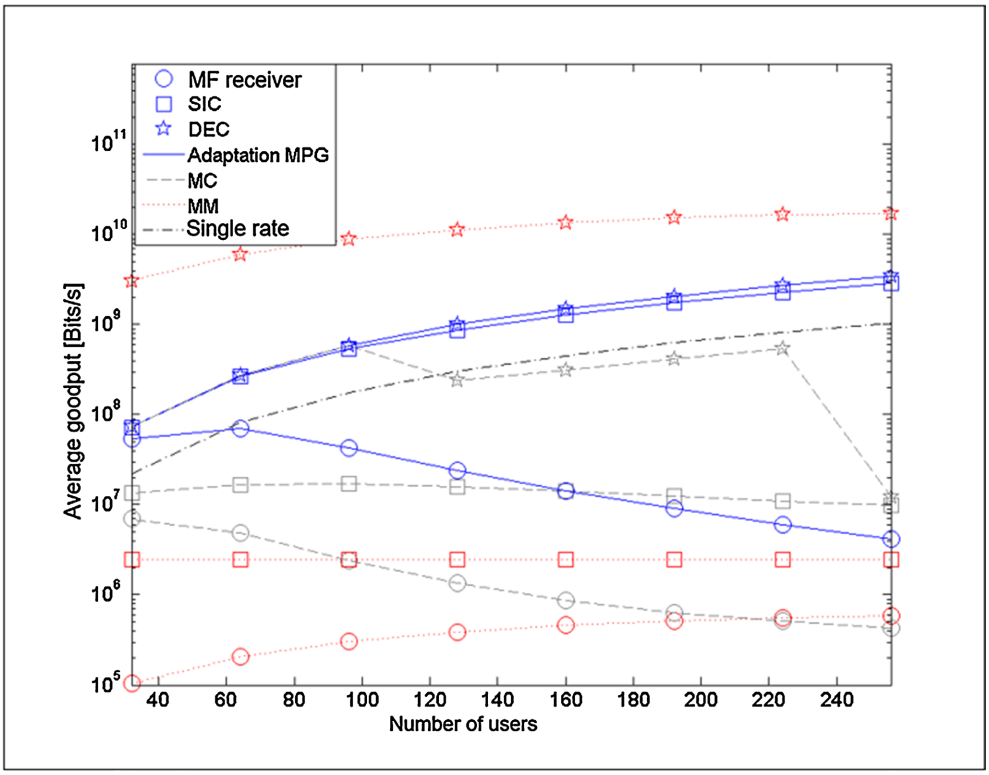

Figure 7. Aggregated useful throughput as a function of the number of connected users, fixed-to-mobile multipath channel $v = 35$ m/s.

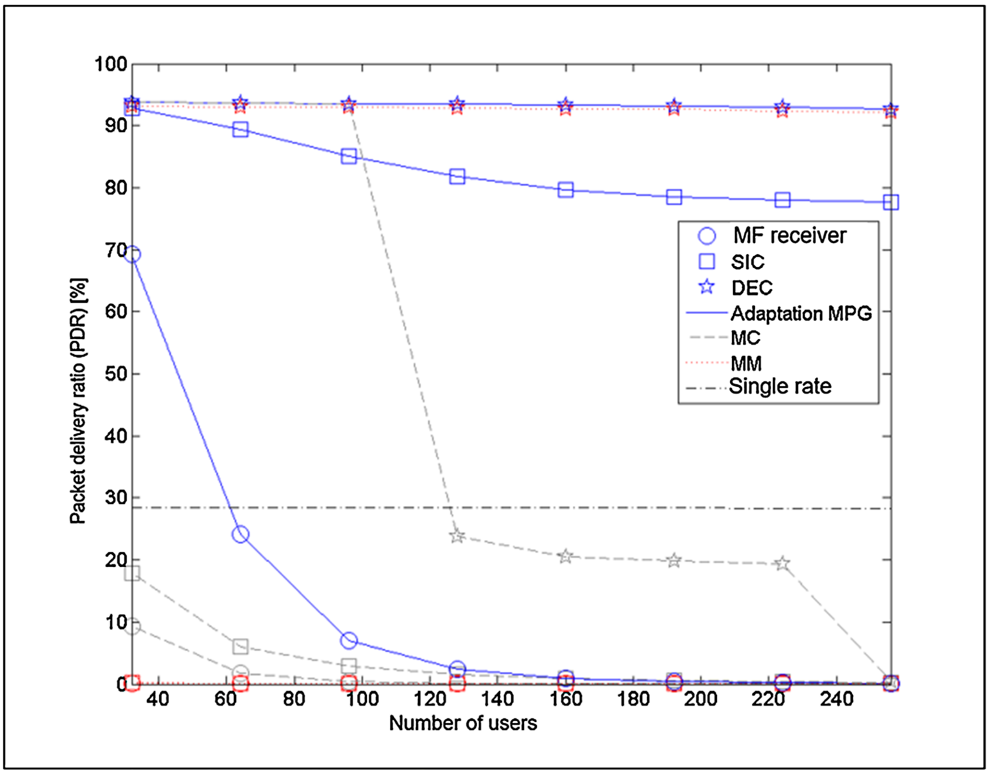

Figure 8. Packet reception rate as a function of the number of connected users in a fixed-to-mobile multipath channel with $v = 50$ m/s.

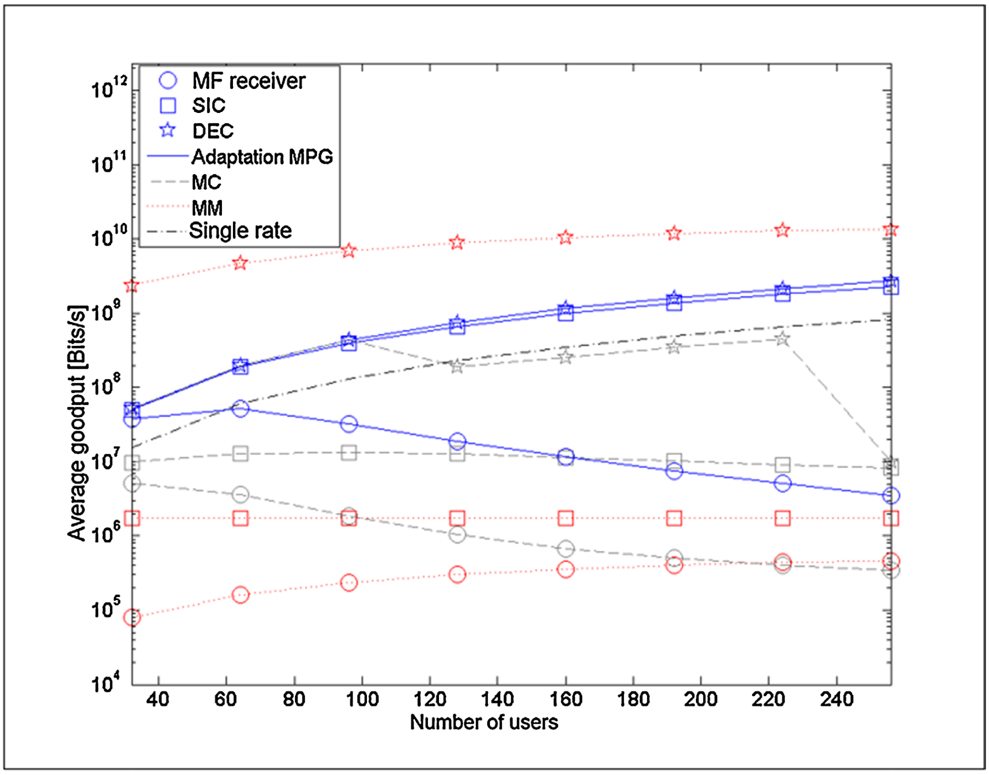

Figure 9. Aggregate useful throughput as a function of the number of connected users, fixed-to-mobile multipath channel at $v = 50$ m/s.

The results highlight the benefits of integrating the conceptual framework with the MUD-MAC protocol, particularly in dynamic environments with varying user densities and mobility speeds. The use of channel prediction algorithms significantly enhances both reception rates and aggregate throughput, demonstrating the operational viability of the enhanced protocol.

5. Conclusions

This study investigated the performance of vehicular ad hoc networks (VANETs) under varying interference and mobility conditions, focusing on the interplay between node mobility, interference intensity and transmission quality. A cross-layer conceptual framework based on channel prediction was proposed, aiming to optimize network resource management in environments characterized by high mobility and significant interference. Detailed simulations revealed critical insights into the limitations and trade-offs of multi-code and multi-modulation schemes in multipath channels, particularly in the presence of complex diversity receivers.

The results underscore that while receiver diversity is essential for mitigating interference effects, it may also lead to performance degradation under extreme conditions. The proposed framework demonstrated its potential by dynamically managing network resources through channel prediction and meeting Quality of Service (QoS) requirements, offering a robust solution for optimizing VANET performance in complex operational scenarios.

5.1. Broader Impact

The proposed framework has significant implications for advancing VANET technology, particularly in applications such as autonomous vehicle communication, intelligent transportation systems and emergency response networks. By addressing the challenges posed by high mobility and intense interference, this approach enhances the reliability and efficiency of vehicular communications, paving the way for safer and more efficient transportation systems.

5.2. Applications and Implementation Scenarios

The framework can be implemented in a variety of real-world scenarios, including:

- **Autonomous Vehicle Networks:** Enhancing communication reliability for real-time decision-making in autonomous vehicle systems.
- **Smart Cities:** Supporting intelligent transportation systems for traffic management and urban mobility optimization.
- **Emergency Response:** Improving communication in disaster recovery operations where vehicular networks are critical for coordination.
- **Highway Communication:** Optimizing long-range vehicle-to-vehicle and vehicle-to-infrastructure communication on highways.

5.3. Future Directions

To address the identified limitations and further enhance the framework, the following actionable next steps are proposed:

- **Resilience Mechanisms:** Investigate the integration of resilience strategies to handle extreme interference and network congestion more effectively.
- **Real-Time Adaptation:** Develop mechanisms for dynamic adaptation to real-time network conditions, ensuring consistent QoS in rapidly changing environments.
- **Scalability Testing:** Extend simulations to include larger-scale networks with diverse mobility patterns and user densities, validating the framework's scalability and robustness.
- **Hardware Implementation:** Transition from simulations to prototype development using Software-Defined Radio (SDR) platforms to validate the framework in real-world settings.

To conclude, this research contributes a robust foundation for optimizing VANET systems in challenging scenarios, highlighting the potential for further advancements in vehicular communication technologies to support safer and more efficient mobility in both urban and rural contexts.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Yousefi, S., Mousavi, M. and Fathy, M. (2006) Vehicular Ad Hoc Networks (VANETs): Challenges and Perspectives. 2006 6*th International Conference on ITS Telecommunications*, Chengdu, 21-23 June 2006, 761-766. https://doi.org/10.1109/itst.2006.289012

[2] Hui, A.L.C. and Letaief, K.B. (1998) Successive Interference Cancellation for Multiuser Asynchronous DS/CDMA Detectors in Multipath Fading Links. *IEEE Transactions on Communications*, **46**, 384-391. https://doi.org/10.1109/26.662644

[3] Tse, D.N.C. and Hanly, S.V. (1999) Linear Multiuser Receivers: Effective Interference, Effective Bandwidth and User Capacity. *IEEE Transactions on Information Theory*, **45**, 641-657. https://doi.org/10.1109/18.749008

[4] Zhou, L., Zheng, B., Geller, B., Wei, A., Xu, S. and Li, Y. (2008) Cross-Layer Rate Control, Medium Access Control and Routing Design in Cooperative VANET. *Computer Communications*, **31**, 2870-2882. https://doi.org/10.1016/j.comcom.2007.12.006

[5] Setton, E., Yoo, T., Zhu, X.Q., Goldsmith, A. and Girod, B. (2005) Cross-Layer Design of Ad Hoc Networks for Real-Time Video Streaming. *IEEE Wireless Communications*, **12**, 59-65. https://doi.org/10.1109/mwc.2005.1497859

[6] Tse, D.N.C. and Hanly, S.V. (1999) Linear Multiuser Receivers: Effective Interference, Effective Bandwidth and User Capacity. *IEEE Transactions on Information Theory*, **45**, 641-657.

[7] Bhoi, S.K. and Khilar, P.M. (2014) Vehicular Communication: A Survey. *IET Networks*, **3**, 204-217. https://doi.org/10.1049/iet-net.2013.0065

[8] Singh, K.D., Rawat, P. and Bonnin, J. (2014) Cognitive Radio for Vehicular Ad Hoc Networks (CR-VANETs): Approaches and Challenges. *EURASIP Journal on Wireless Communications and Networking*, **2014**, Article No. 49.

https://doi.org/10.1186/1687-1499-2014-49

[9] Wang, L., Iida, R. and Wyglinski, A.M. (2019) Vehicular Network Simulation Environment via Discrete Event System Modeling. *IEEE Access*, **7**, 87246-87264. https://doi.org/10.1109/access.2019.2922766

[10] Latva-aho, M. (1998) Bit Error Probability Analysis for FRAMES WCDMA Downlink Receivers. *IEEE Transactions on Vehicular Technology*, **47**, 1119-1133. https://doi.org/10.1109/25.728482

[11] Dharsandiya, A.N. and Patel, R.M. (2016) A Review on MAC Protocols of Vehicular Ad Hoc Networks. 2016 *International Conference on Wireless Communications*, *Signal Processing and Networking* (*WiSPNET*), Chennai, 23-25 March 2016, 1040-1045. https://doi.org/10.1109/wispnet.2016.7566295

[12] Omar, H.A. and Zhuang, W.H. (2014) Time Division Multiple Access for Vehicular Communications. Springer. https://doi.org/10.1007/978-3-319-09504-2

[13] Huang, W., Ding, L., Meng, D., Hwang, J., Xu, Y. and Zhang, W. (2018) QOE-Based Resource Allocation for Heterogeneous Multi-Radio Communication in Software-Defined Vehicle Networks. *IEEE Access*, **6**, 3387-3399. https://doi.org/10.1109/access.2018.2800036

[14] Chrysostomou, C., Djouvas, C. and Lambrinos, L. (2011) Applying Adaptive QoS-Aware Medium Access Control in Priority-Based Vehicular Ad Hoc Networks. 2011 *IEEE Symposium on Computers and Communications* (*ISCC*), Kerkyra, 28 June-1 July 2011, 741-747. https://doi.org/10.1109/iscc.2011.5983928

[15] Hossain, M.A., Noor, R.M., Yau, K.A., Azzuhri, S.R., Z'aba, M.R. and Ahmedy, I. (2020) Comprehensive Survey of Machine Learning Approaches in Cognitive Radio-Based Vehicular Ad Hoc Networks. *IEEE Access*, **8**, 78054-78108. https://doi.org/10.1109/access.2020.2989870

[16] Ottosson, T. and Svensson, A. (1995) Multi-Rate Performance in DS/CDMA Systems. CiteSeerX.

[17] Zhang, J.F., Dziong, Z., Gagnon, F. and Kadoch, M. (2009) Multiuser Detection Based MAC Design for Ad Hoc Networks. *IEEE Transactions on Wireless Communications*, **8**, 1836-1846. https://doi.org/10.1109/t-wc.2008.071449