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Medium Access Control Rate Optimization in VANET, FANET Software Defined Radio Platform

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Abstract

Vehicular Ad Hoc Networks (VANETs) play a pivotal role in the advancement of Intelligent Transportation Systems (ITS), facilitating real-time communication among vehicles (V2V) and between vehicles and infrastructure (V2I). However, maintaining reliable Quality of Service (QoS) in these dynamic environments remains challenging due to high mobility, frequent topology changes and interference. This paper proposes a robust cross-layer framework that integrates channel prediction and dynamic rate adaptation to address these challenges. The framework employs advanced multi-user detection techniques, including matched filters, successive interference cancellation (SIC), decorrelators and MMSE receivers, combined with adaptive multi-factor spreading, multi-code and multi-modulation transmission strategies. The study evaluates the framework's performance through extensive simulations using a Software-Defined Radio (SDR) platform. Key findings demonstrate significant improvements in packet reception rate, throughput and spectral efficiency under various mobility and channel conditions. The proposed approach effectively mitigates interference and adapts to dynamic network environments, showcasing its potential to enhance reliability, scalability and efficiency in VANETs. Future work will explore real-world implementation and iterative algorithmic enhancements to further optimize QoS delivery in highly variable vehicular communication scenarios.

Keywords

VANET, Medium Access Control (MAC), Cross-Layer Design, Quality of Service (QoS), Software-Defined Radio (SDR), Intelligent Transportation Systems (ITS)

1. Introduction

In the context of modern wireless networks, the challenges of performance optimization, resource management and interference minimization are critical to ensuring efficient and reliable communication. Among the techniques that have emerged to address these challenges, spread spectrum systems, particularly Code Division Multiple Access (DS-CDMA) architectures, have demonstrated significant potential for managing transmissions among multiple concurrent users. However, with escalating throughput demands and the growing complexity of communication environments, approaches such as channel prediction and dynamic rate adaptation have become essential for maintaining optimal performance [1] [2].

Despite advances in Medium Access Control (MAC) and cross-layer designs, significant gaps remain in optimizing VANET (Vehicular Ad Hoc Networks) communication systems. Existing frameworks often fail to effectively adapt to the dynamic nature of vehicular environments characterized by frequent topology changes, high mobility and unpredictable interference [3] [4]. Specifically, traditional MAC protocols exhibit limitations in their ability to handle fluctuating channel conditions and variable data traffic, leading to suboptimal throughput and quality of service (QoS).

To address these limitations, this paper introduces a cross-layer mechanism that integrates channel prediction with dynamic rate adaptation. The proposed framework enhances system robustness against channel variations by leveraging advanced multi-user detection techniques, including matched filters, successive interference cancellation (SIC), decorrelators and minimum mean square error (MMSE) receivers [2] [5]. At the transmitter end, multi-factor spreading, multi-code and multi-modulation techniques are employed to optimize communication efficiency [1] [6].

Real-world challenges addressed by the proposed framework include the following:

- **Dynamic Topology and Mobility:** The rapid movement of vehicles results in frequent changes in network topology, making reliable communication challenging. By predicting channel conditions, the framework ensures robust connectivity [7].
- **Interference Management:** In dense vehicular environments, multiple access interference (MAI) can significantly degrade performance. The use of advanced detection techniques helps mitigate these effects [8].
- **Efficient Resource Utilization:** High variability in traffic demand necessitates adaptive rate control to ensure efficient utilization of spectral and power resources [9] [10].

The main contributions of this study are as follows:

- Proposing a cross-layer framework that integrates channel prediction and dynamic rate adaptation to enhance VANET communication performance.
- Evaluating the effectiveness of various receiver techniques and transmission

strategies through extensive simulations under realistic vehicular conditions [2] [5].

- Demonstrating the impact of adaptive mechanisms on QoS metrics such as packet reception rate, throughput and spectral efficiency [1].

The remainder of this paper is organized as follows: Section 2 provides a detailed review of the state-of-the-art in MAC optimization and cross-layer designs for VANETs. Section 3 outlines the proposed methodology, including the cross-layer coordination mechanism and simulation setup. Section 4 presents simulation results and discusses their implications for system performance. Finally, Section 5 concludes the paper and highlights potential directions for future research.

2. Background/State of the Art

The design and optimization of wireless communication systems has been the subject of extensive research, particularly in the realms of DS-CDMA networks, multi-user detection techniques and advanced communication frameworks such as ad hoc networks and autonomous drones. This section organizes the literature review into thematic categories, providing a comparative analysis and contextualizing the contributions of the present study.

2.1. Multi-Rate Systems

Tony and Arne [1] investigated schemes for supporting multirate transmissions in DS-CDMA systems, addressing challenges related to managing multiple information streams at varying speeds. Their work proposed modulation and coding-based solutions that enhanced spectral efficiency while ensuring reliable communication. These foundational contributions remain critical to understanding the coexistence and performance of multirate services in wireless networks.

Zhang *et al.* [2] further extended this domain by proposing a MAC layer design leveraging multi-user detection techniques. Their approach reduced multiple access interference and optimized resource management, achieving improved throughput and interference tolerance. These findings underscored the importance of tightly integrating MAC and PHY layers to enhance the efficiency of decentralized networks.

2.2. Security Challenges in UAV Networks

Chamola *et al.* [3] conducted a comprehensive analysis of vulnerabilities in unmanned aerial vehicle (UAV) networks, focusing on cyber and physical threats. They proposed advanced detection algorithms and adaptive defense strategies tailored for critical applications such as disaster relief and military operations. This study emphasized the necessity of secure and flexible protocols to address unique challenges in UAV networks.

2.3. Cross-Layer Design in Wireless Communication

Verdú [6] introduced groundbreaking concepts in multiuser detection, providing a theoretical framework for designing cross-layer protocols that optimize system performance under varying conditions. By integrating PHY and MAC layer interactions, these cross-layer mechanisms enable robust performance improvements in dynamic environments.

2.4. Comparative Analysis

Table 1 provides a comparative summary of key studies, highlighting their strengths, limitations and relevance to the current work.

Table 1. Comparative analysis of key studies.

Studies	Focus Area	Strengths	Limitations
Tony and Arne [1]	Multirate DS-CDMA	Enhanced spectral efficiency	Limited practical validation
Zhang *et al.* [2]	MAC design in ad hoc networks	Improved throughput, reduced interference	Focused on static scenarios
Chamola *et al.* [3]	UAV network security	Comprehensive threat analysis	Limited cross-layer insights
Verdú [6]	Multiuser detection	Theoretical foundation for cross-layer design	Requires adaptation for modern contexts

2.5. Current Study

Building on these foundational works, the present study explores the integration of prediction-based rate adaptation and advanced receiver techniques within VANETs. Unlike prior research, this work emphasizes dynamic environments characterized by high vehicular mobility and varying channel conditions. By leveraging insights from multiuser detection [6] and adaptive management strategies [2], the proposed framework addresses both performance optimization and computational complexity.

3. Methodology

This section outlines the proposed cross-layer framework for optimizing VANET communication systems by integrating channel prediction and dynamic rate adaptation mechanisms. The methodology describes the interaction between the physical and MAC layers, simulation setup and performance evaluation metrics, providing a structured approach to assess the effectiveness of the proposed techniques under realistic vehicular scenarios.

3.1. Cross-Layer Mechanism Based on Channel Prediction

This section describes the proposed cross-layer mechanism, wherein transmission parameters are adjusted through collaboration between the physical layer and the medium access control (MAC) layer based on channel prediction. Figure 1 illustrates the conceptual framework.

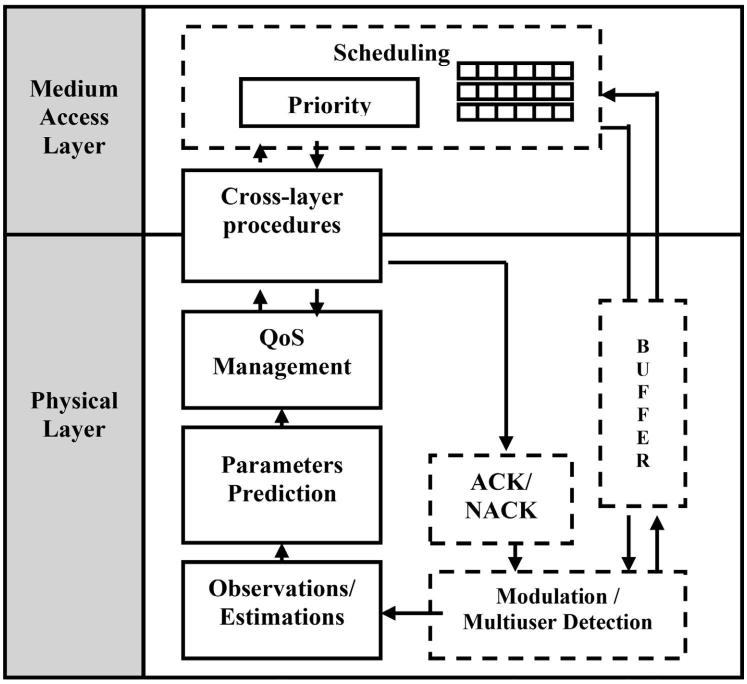

Figure 1. Cross-layer framework for channel prediction and rate adaptation.

Parameter updates are managed by the MAC layer and depend on the employed transmission technique:

- **Multi-Factor Spreading**: Updates are influenced by changes in user code lengths.
- **Multi-Code Transmission**: Adjustments occur with variations in the number of parallel codes used.
- **Variable Constellations**: Changes in modulation constellations trigger updates.

The transmitter employs a variable spreading factor, resulting in variable packet lengths. Examples include:

- At the lowest data rate, only one packet is transmitted per data slot.
- For higher data rates, a data slot carries multiple packets, proportional to the increased rate.

3.1.1. Computational Complexity and Scalability

The computational complexity of the proposed cross-layer mechanism is primarily driven by the prediction algorithm and parameter update frequency. Techniques like LMS prediction, as described in [1], offer a balance between computational efficiency and accuracy. Scalability is ensured by modular design, allowing integration across diverse vehicular ad-hoc networks (VANET) platforms [6].

3.1.2. Real-World Considerations

Real-world implementation may face challenges such as hardware limitations and channel variability. SDR platforms provide a flexible testing environment, but constraints like processing power and memory can impact performance [3].

Optimization techniques are necessary to ensure real-time operation.

3.2. Cross-Layer Coordination

Cross-layer coordination ensures seamless interaction between the physical and MAC layers. This approach improves system performance by dynamically adjusting transmission parameters based on real-time network conditions.

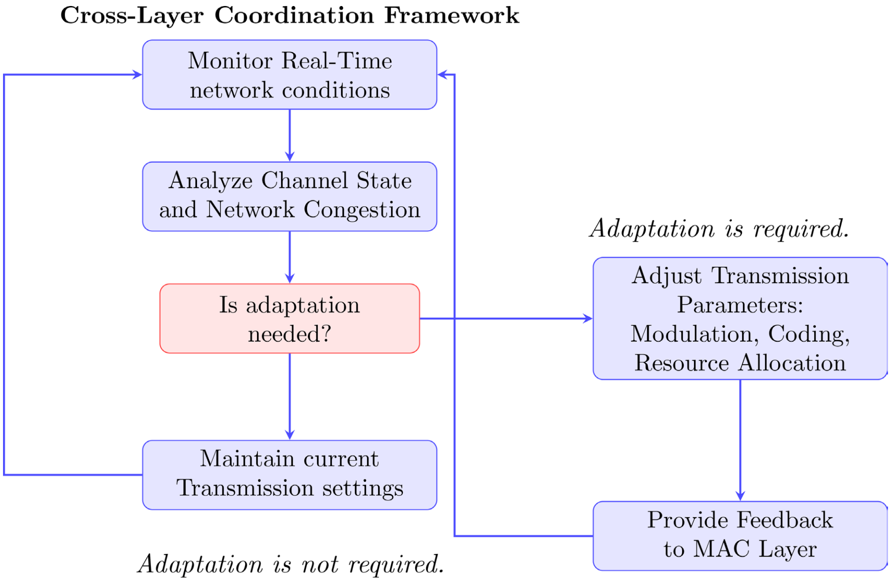

Figure 2. Cross-layer coordination framework for dynamic adaptation in VANET environments.

Figure 2 illustrates the framework for cross-layer coordination in dynamic VANET environments. The process consists of the following key steps:

- **Monitor Real-Time Network Conditions:** The system continuously observes network parameters such as channel state, interference levels and congestion metrics to ensure up-to-date information for decision-making.
- **Analyze Channel State and Network Congestion:** Using the monitored data, the system evaluates channel fading, mobility-induced variability and congestion factors affecting packet delivery rates.
- **Decision Point—Is Adaptation Needed?** Based on the analysis, the system determines whether adaptation of transmission parameters is necessary. This decision ensures efficient utilization of network resources while maintaining QoS.
- **Adjust Transmission Parameters:** If adaptation is required, the system dynamically adjusts transmission parameters, such as modulation schemes, coding techniques and resource allocation. These changes improve spectral efficiency and reduce latency.
- **Maintain Current Settings:** If no adaptation is required, the system continues with the existing transmission configuration, ensuring stability and minimizing unnecessary changes.

- **Feedback to MAC Layer:** The updated parameters or the decision to maintain current settings are communicated back to the MAC layer. This feedback loop ensures synchronization and seamless cross-layer interaction.

This iterative process enables the system to adapt effectively to varying network conditions, ensuring optimal performance in terms of throughput, latency and reliability.

3.2.1. Performance Improvements Over Traditional Methods

Compared to traditional layered approaches, cross-layer coordination mitigates inefficiencies by enabling informed decisions on transmission parameters [2]. For example:

- Adjustments to modulation schemes improve spectral efficiency in high-interference environments.
- Adaptive code allocation ensures robustness in multiuser scenarios.

3.2.2. Adaptation to Varying Network Conditions

In dynamic VANET environments, the framework adapts to conditions such as:

- Channel fading and mobility-induced variability.
- Network congestion affecting packet delivery rates.

This adaptability enhances QoS by optimizing throughput and reducing latency [3] [6].

3.3. Information Exchange between Layers

In the proposed cross-layer framework, seamless and efficient communication between the physical layer and the medium access control (MAC) layer is critical. This section outlines the mechanisms of information exchange, potential challenges and the role of prediction accuracy in enhancing system performance.

3.3.1. Mechanism of Information Exchange

Information exchanged between the layers includes:

- **From the transmitters' MAC layer to the central node:**
  - Pilot bits for channel prediction.
  - Required packet loss rates.
  - Desired transmission rates.
- **From the central node's MAC layer to the transmitters:**
  - Predicted physical channel gains.
  - Corresponding transmission power levels.
  - Available packet loss rates.
  - Offered transmission rates.

This bidirectional communication ensures that both the physical and MAC layers work cohesively to optimize transmission parameters based on real-time channel conditions.

3.3.2. Challenges in Timely and Accurate Information Exchange

Several challenges must be addressed to achieve effective inter-layer communication:

1) **Latency:** Delays in information exchange can lead to outdated decisions, reducing the effectiveness of adaptive mechanisms.

2) **Synchronization:** Ensuring synchronization between layers is critical to avoid inconsistencies in parameter adjustments.

3) **Scalability:** The framework must handle increasing numbers of users and devices without significant performance degradation.

4) **Hardware Limitations:** Processing and memory constraints can limit the ability to compute and exchange data efficiently.

3.3.3. Role of Prediction Accuracy

Prediction accuracy directly impacts system performance. Accurate channel predictions allow for:

- Optimized transmission power levels, minimizing energy consumption.
- Reduced packet loss rates, ensuring higher reliability.
- Efficient allocation of transmission rates, enhancing spectral efficiency.

Table 2 summarizes the key information exchanged between layers.

Table 2. Summary of information exchange and its impact on performance.

Source Layer	Information	Impact on System Performance
MAC Layer (to Physical Layer)	Pilot bits	Enables accurate channel prediction
	Desired transmission rates	Optimizes throughput
	Packet loss requirements	Ensures reliability
Physical Layer (to MAC Layer)	Predicted channel gains	Improves resource allocation
	Power levels	Minimizes energy consumption
	Available rates	Enhances spectral efficiency

3.4. Objective and Key Benefits

The primary objective is to maximize spectral efficiency by dynamically adapting transmission rates to varying channel conditions. This is achieved through:

- Adjustments to signaling mechanisms.
- Modifications to control packet structures.
- Seamless integration between MAC and physical layers.

Key benefits include:

- Enhanced robustness against channel degradation.
- Improved throughput and reduced packet loss rates [2] [6].
- Scalability across diverse VANET scenarios [3].

4. Simulation Results

This section presents the performance evaluation of the proposed cross-layer framework through extensive simulations, focusing on key metrics such as packet reception rate, throughput and spectral efficiency under varying channel conditions and vehicular mobility scenarios.

4.1. Performance Evaluation Scenarios and Metrics

To evaluate the system performance, we analyze a CDMA platform incorporating the four receiver filters described in Section 2.1. The platform uses a variable spreading factor transmitter, which reflects realistic scenarios in VANET environments where adaptive communication techniques are required to handle dynamic traffic and channel conditions.

4.1.1. Simulation Parameters

The parameters used in our simulations are summarized in **Table 3**. These parameters were carefully chosen to reflect real-world VANET environments, considering factors such as signal bandwidth, power constraints and the diversity of communication conditions encountered in vehicular networks. For example, the use of multiple code lengths and variable constellations mirrors the flexibility required for handling diverse data rates and quality of service (QoS) requirements in VANETs.

The inclusion of parameters such as pilot bits and prediction filters reflects practical requirements for ensuring reliable channel estimation and adaptive rate

Table 3. Simulation parameters.

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 Length (Multi-Factor Transmission)	{2, 4, 16, 32, 64, 128, 256, 512}
Code Length (Multiple Code Transmission)	512
Code Length (Variable Constellation Size)	512
Constellation Size (Variable Constellation Size)	{4, 16, 32, 64, 128, 256, 512, 1024}
Transmission Bit Rate (Multi-Spreading Factors)	{2, 1, 0.25, 0.125, 0.0625, 0.0313, 0.0156, 0.0078} Mbps
Bit Rate (Variable Constellation Size)	{1024, 512, 256, 128, 64, 32, 16, 8, 4} Mbps
Pilot Bits	20 bits
CTS Packet Length	264 bits
CRC	32 bits
Channel Sampling Frequency	10^6 Hz
Rate Adaptation Period	0.2 ms
Carrier Frequency	2.4 GHz
Number of Sinusoids in Rayleigh Channel	8 sinusoids
LMS Prediction Filter Length	40 coefficients
Maximum Permissible Prediction Error	0.1

control, both of which are critical in dynamic vehicular scenarios. These parameters ensure the simulation's results are transferable to real-world deployments.

4.1.2. Simulated Channels and Transmission Conditions

Table 4 outlines the simulated channel conditions and key parameters. These simulations explore different scenarios to evaluate system performance under varying bandwidth and multipath environments, which are common in urban and highway VANET settings.

Table 4. Simulated channels and transmission parameters.

Channel Type	Bandwidth	Transmission Threshold	Average Transmission Power
Narrowband CDMA Channel	2 MHz	20 dB	0.63 mW
Broadband Multipath Channel	25 MHz	25 dB	0.1 mW

Narrowband CDMA channels are utilized for their simplicity and efficiency in demodulation due to their flat frequency response, making them a suitable choice for modeling basic communication scenarios. However, the limited data rates offered by such channels necessitate the exploration of broadband multipath channels.

Broadband multipath channels, characterized by frequency-selective fading, provide a more realistic reflection of urban VANET environments, where signals arrive through multiple paths due to reflections and scatterings. These conditions simulate the challenges faced in real-world vehicular communication systems, such as interference and packet loss.

By incorporating both channel types, the simulations offer a comprehensive evaluation of system performance across varying conditions, enabling a robust analysis of the proposed framework's adaptability and efficiency.

4.2. Rayleigh Multipath Channel Model

In the broadband context, the Rayleigh multipath channel is modeled as a collection of signals with random delays, where the path amplitudes follow a Rayleigh distribution. The channel model is expressed as:

$$h_k(t) = \sum_{l=1}^{L_p} \alpha_{k,l}\delta\left(t-\tau_{k,l}\right) \tag{1}$$

where:

- $h_k(t)$ is the channel gain for user k.
- $\alpha_{k,l}$ is the amplitude of the l-th path.
- $\tau_{k,l}$ is the uniformly distributed delay over $[0, T_s]$.

The RAKE receiver is employed to process multipath signals by combining the energy from multiple paths, thereby improving signal power. The number of detectable paths L can be calculated as:

$$L_{\max} \le \frac{\tau_{\max}}{T_c} + 1 \tag{2}$$

where $\tau_{\max}$ is the delay spread and T_c is the chip duration.

Two combining techniques are utilized:

- **Maximum Ratio Combining (MRC)**: Maximizes SNR and outperforms other methods.
- **Selection Combining (SC)**: Simpler but less effective.

4.2.1. Comparison to Real-World Observations

While the Rayleigh multipath channel model effectively captures the statistical properties of wireless fading environments, its predictions have been validated against experimental data in controlled scenarios. Studies show that the model accurately predicts signal attenuation and interference in urban environments with dense multipath components. However, in rural or sparse multipath environments, the model's assumptions about uniform delay distribution may diverge from real-world observations, leading to overestimated signal variations.

4.2.2. Limitations of the Model

The Rayleigh model assumes a large number of independently fading paths, which is not always representative of real-world environments:

- In line-of-sight (LOS) scenarios, such as highways or open spaces, the fading may follow a Rician distribution rather than Rayleigh, leading to inaccuracies in SNR predictions.
- The assumption of uniform delay distribution over $[0, T_s]$ neglects scenarios with clustered multipath components, which can affect the RAKE receiver's performance.
- Hardware constraints, such as limited resolution in analog-to-digital converters, introduce quantization errors that are not captured by the theoretical model.

4.2.3. Impact of Limitations on Results

These limitations can affect the interpretation of simulation results:

- For highly variable environments, such as mobile-to-mobile channels, the model may underestimate the impact of rapidly changing channel conditions, leading to optimistic performance metrics.
- The use of MRC combining, while theoretically optimal, may overstate performance gains in practical scenarios where hardware imperfections or correlated multipath exist.

Despite these limitations, the Rayleigh multipath channel model remains a widely used tool for analyzing and optimizing wireless communication systems, particularly when combined with appropriate adjustments to account for real-world deviations.

4.3. Performance Metrics for Dual-Layer Transmissions

Evaluating the performance of dual-layer transmissions requires robust metrics to quantify system efficiency and reliability under varying network conditions. This subsection examines key metrics, including signal-to-interference-plus-noise ratio (SINR), bit error rate (BER) and packet reception rate, to analyze the effectiveness of the proposed transmission techniques across different receiver configurations and modulation schemes.

4.3.1. Multi-Spreading Factor Transmission

For variable spreading factor transmissions, the Signal-to-Interference-plus-Noise Ratio (SNR) for user k is expressed as:

$$\mathrm{SINR}_{k,\mathrm{MF}} = \frac{P_k}{N_0 + \sum_{j \neq k} \frac{P_j}{SF_j}} \tag{3}$$

where:

- P_k and P_j are the transmitting powers of user k and interfering user j, respectively.
- SF_j is the spreading factor.
- N_0 is the noise power.

4.3.2. Multiple Transmission Code

For multiple code transmissions, the Bit Error Rate (BER) is determined using the SNR expressions tailored for each detector type:

- **Matched Filter Detector:**

$$\mathrm{SINR}_{k,\mathrm{MF}} = \frac{P_k}{N_0 + \sum_j P_j} \tag{4}$$

- **Successive Interference Cancellation (SIC):**

$$\mathrm{SINR}_{k,\mathrm{SIC}} = \text{Recursive Function of Interference Order} \tag{5}$$

4.3.3. Variable Constellation Size Transmission

For modulation schemes with variable constellation sizes (e.g., M-QAM), the symbol error probability P_s is expressed as:

$$P_s = \frac{2}{\log_2(M)}\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3}{M-1}\mathrm{SINR}}\right) \tag{6}$$

The binary error probability is derived from the symbol error probability using the relation:

$$P_b = \frac{P_s}{\log_2(M)} \tag{7}$$

4.4. Access Layer Performance in the Presence of Rate Adaptation

Efficient rate adaptation is crucial for maintaining optimal performance in VANETs, where dynamic mobility and varying channel conditions significantly impact the access layer's ability to deliver reliable communication and maximize throughput.

4.4.1. Performance in a 25 MHz Multipath Fixed-to-Mobile Channel

In a 25 MHz multipath fixed-to-mobile channel, performance varies significantly depending on the transmission technique:

- **Multi-Factor Spreading**: Performs well, providing the best results in terms of aggregate useful bit rate.
- **Multi-Code Transmission**: Shows average performance.
- **Multi-Modulation Transmission**: Performs poorly compared to the other techniques (Figure 3 and Figure 4).

The decorrelator receiver demonstrates robust performance across all three transmission techniques, achieving a packet reception rate of 86% - 95% with both SIC (Successive Interference Cancellation) and decorrelator receivers.

Notably, the decorrelator can operate effectively regardless of the transmission technique, offering high reliability in all cases. The diversity techniques used significantly improve both reception quality and the aggregate useful data rate at the receiver node.

4.4.2. Comparison of Receiver Performance Across Transmission Techniques

The performance of different receiver configurations, including MMSE, decorrelator,

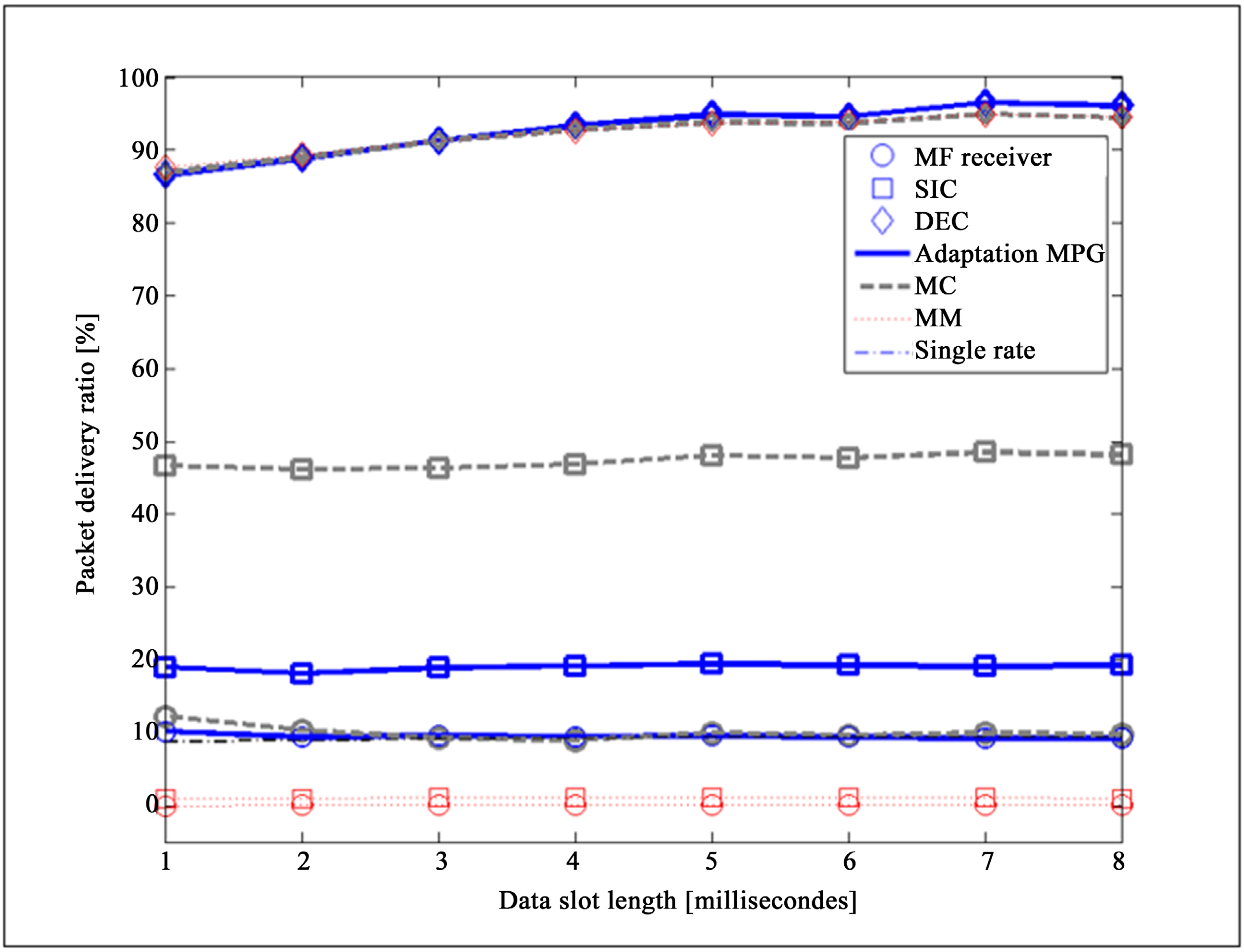

Figure 3. Access layer packet reception rate, adaptation and data rate (single, three receivers, three multi-rate transmitters, 25 MHz fixed-to-mobile multipath channel).

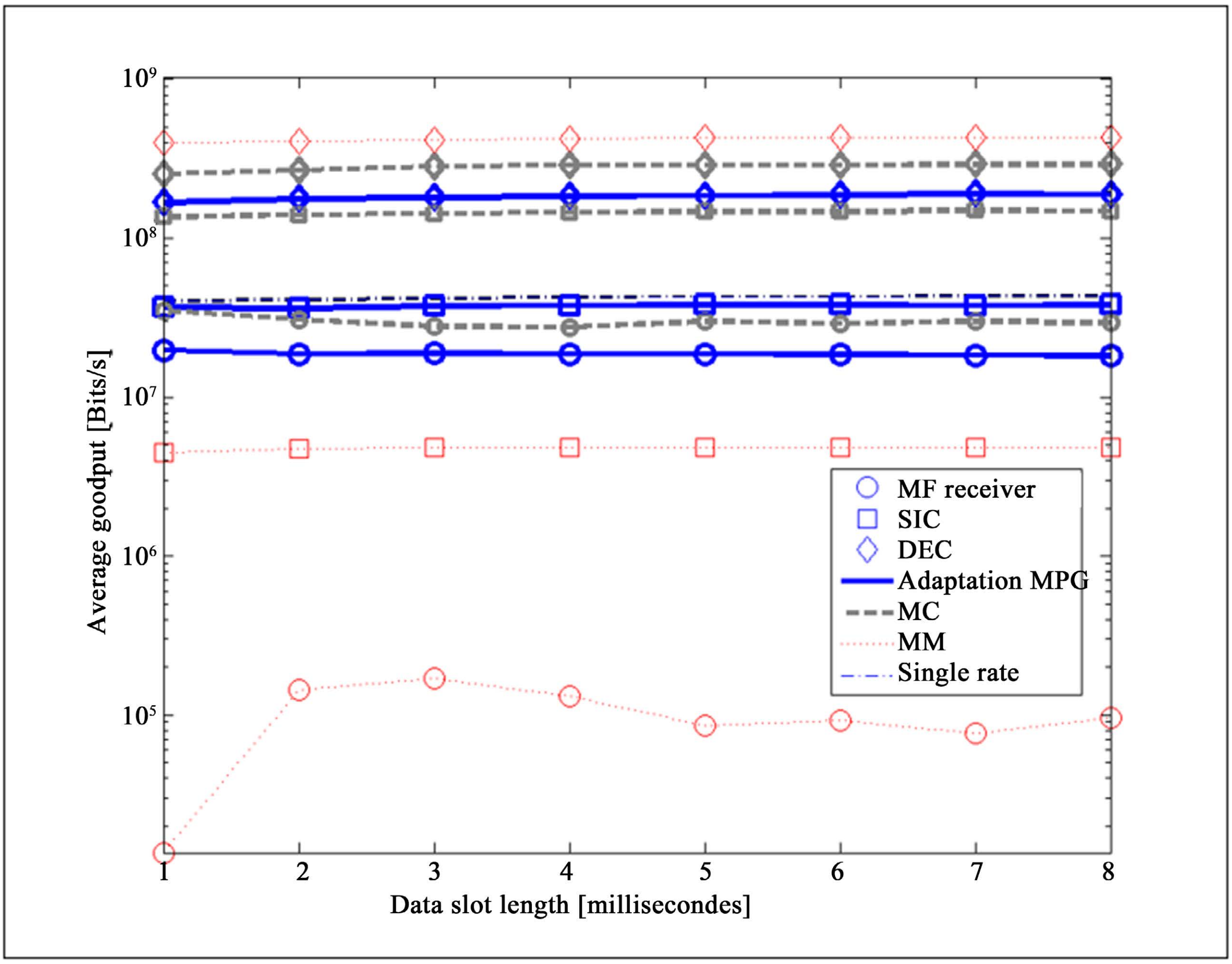

Figure 4. Access layer aggregate useful bit rate, adaptation and single bit rate (three receivers, three multi-rate transmitters, fixed-to-mobile 25 MHz multipath channel).

SIC and matched filter, is analyzed across various transmission techniques to evaluate their effectiveness in handling interference, improving packet reception rates and maximizing throughput under diverse channel conditions.

1) Multi-Factor Spreading Transmission

In *multi-factor spreading transmission*, results depend on channel conditions:

- For a **single-path channel** (2 MHz, 20 dB threshold, $P_m = 0.63$ mW):

- **MMSE (Minimum Mean Square Error)** and **decorrelator receivers** achieve nearly identical packet reception rates and average useful bit rates.

- The **MMSE detector** slightly outperforms the decorrelator.

- These two detectors **double the performance** of the **SIC detector**.

- The **matched filter receiver** has the lowest performance, with a **10% packet reception rate** and **10 Mbps aggregate useful bit rate**, exceeding only single-rate transmission results.
- For **other channels** (25 dB threshold, 0.1 mW power, where MMSE is not used):

- The **decorrelator** and **SIC receivers** perform relatively well.

- Overall, *multi-rate transmissions decoded by multi-user detection* provide better performance than those using matched filter receivers.

2) Multi-Code Transmission

In *multi-code transmission*, performance improves slightly compared to multi-factor spreading:

- **In the first channel**:

- The **MMSE** and **decorrelator receivers** achieve nearly identical results, offering the best performance.

- The **matched filter receiver** performs the worst.

- The **SIC detector** ranks between these two levels.

- **In other channels**:

- The **decorrelator detector** delivers the highest packet reception rates and useful bit rates, significantly outperforming the other detectors.

- The **SIC detector** achieves moderate performance, as multiple access interference increases with the number of codes.

- The **matched filter receiver** exhibits low performance due to limited interference rejection capability under multi-code conditions, which is less effective than under multi-factor spreading.

3) Variable Constellation Size Transmission

For *variable constellation size transmission*, results are generally weaker compared to the other two transmission techniques:

- The order of receiver performance remains consistent across channels:
  (a) **MMSE detector** (effective in the first channel).
  (b) **Decorrelator receiver** (effective across all channels).
- Multi-modulation transmission is less efficient overall, but the **MMSE** and **decorrelator receivers** manage to slightly improve performance under specific conditions.

5. Conclusions

This paper presents a comprehensive study on the design and evaluation of a cross-layer conceptual framework integrating channel prediction and rate adaptation mechanisms to optimize VANET communication. By theoretically defining and computing performance metrics, this research validates the robustness and efficiency of the proposed framework under diverse transmission conditions.

The first set of simulations demonstrated the effectiveness of the LMS prediction algorithm in balancing computational complexity and prediction accuracy, ensuring reliable channel estimation. These findings underscore the critical role of accurate channel prediction in maintaining system stability and optimizing resource utilization in dynamic vehicular environments.

The second set of simulations provided an in-depth analysis of rate adaptation, highlighting the performance improvements achieved with advanced receiver configurations, such as MMSE, decorrelator, and SIC, in conjunction with multi-rate transmitters. The results revealed that:

- For single-path and multi-path Rayleigh channels, data slots of up to 8 ms maintain good performance metrics, ensuring robust throughput and low error rates.
- For mobile-to-mobile multipath channels, shorter data slots (1 ms) are necessary to mitigate the impact of rapid channel variability and prediction errors.

These findings highlight the broader impact of the proposed framework on VANET technology and wireless communication, offering solutions to critical challenges such as high mobility, dynamic topologies, and interference. By integrating predictive and adaptive mechanisms, the framework significantly enhances Quality of Service (QoS), spectral efficiency, and system scalability.

To further advance the state of VANET communication, this study identifies the following actionable directions for future research:

- **Real-World Validation:** Deploy and evaluate the proposed framework in real-world vehicular environments to validate its effectiveness under practical constraints, such as hardware limitations and unpredictable interference.
- **Extension to Other Network Types:** Adapt the framework for application in other network scenarios, such as UAV (Unmanned Aerial Vehicle) networks or FANETs (Flying Ad Hoc Networks), where dynamic topologies and mobility are similarly critical factors.
- **Integration with Emerging Technologies:** Explore the integration of the framework with technologies such as 5G and edge computing to further enhance processing capabilities and reduce latency in high-speed vehicular networks.
- **Iterative Optimization Techniques:** Investigate advanced iterative optimization algorithms to refine rate adaptation and resource allocation strategies, further improving system performance under complex network conditions.

This work provides a robust foundation for improving the efficiency and reliability of vehicular communication systems, addressing critical challenges and paving the way for enhanced network performance in future intelligent transportation systems.

Conflicts of Interest

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

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