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QOS-AWARE PERFORMANCE MODELING OF IEEE 802.11P VANET BROADCAST COMMUNICATION USING A COLLAPSED-TRANSITION-ONTO-BASIS (CTB) ENHANCED TWO-DIMENSIONAL MARKOV CHAIN

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ABSTRACT

Vehicular Ad Hoc Networks (VANETs) are a cornerstone of Intelligent Transportation Systems (ITS), enabling safety-critical and infotainment applications through vehicle-to-vehicle and vehicle-to-infrastructure communication. The IEEE 802.11p broadcast mode, however, provides no acknowledgment or retransmission mechanism, which makes Quality of Service (QoS) highly sensitive to channel contention, finite-buffer occupancy, and dynamic vehicular topology. This paper presents an enhanced analytical framework that integrates a two-dimensional (2-D) discrete-time Markov chain — jointly capturing backoff-stage and finite queue-length dynamics — with a Collapsed Transition onto Basis (CTB) technique that reduces the dimensionality of the resulting state space while preserving the essential queueing and contention behaviour. Unlike prior one-dimensional, backoff-only models, the proposed 2-D chain simultaneously tracks channel-access state and buffer occupancy, enabling closed-form derivation of throughput, mean access delay, packet-loss probability, and collision probability under finite load. The CTB step projects the full (m×K)-state chain onto a small set of representative basis states, substantially lowering the computational cost of solving the steady-state distribution without sacrificing model accuracy. The framework is validated through NS-2 simulation on a Linux platform using C++ and TCL scripting, evaluating throughput, delay, packet loss, and energy-related metrics across varying vehicle density and offered load. Results indicate that the CTB-assisted 2-D Markov model achieves higher throughput and lower access delay than the conventional IEEE 802.11p broadcast mechanism and one-dimensional Markov baselines, while requiring markedly less computation. The paper further surveys recent analytical, empirical, and machine-learning-based QoS modeling efforts for V2X networks and outlines directions for security- and learning-augmented extensions of the proposed model.

KEYWORDS: VANET, IEEE 802.11p, DSRC, Quality of Service, Collapsed Transition onto Basis (CTB), Two-Dimensional Markov Chain, Finite Buffer, NS-2, V2X, C-V2X.

I. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) form the communication backbone of modern Intelligent Transportation Systems (ITS), supporting collision-avoidance warnings, cooperative-awareness messages, platooning, and infotainment services among highly mobile nodes. Dedicated Short-Range Communication (DSRC), standardized as IEEE 802.11p, remains a widely deployed vehicular access technology and underlies the control-channel broadcast of safety messages.

Because IEEE 802.11p broadcast frames are transmitted without RTS/CTS handshaking, acknowledgments, or retransmission, packet delivery depends entirely on the outcome of a single contention attempt. Consequently, Quality of Service (QoS) in VANET broadcast communication degrades sharply as vehicle density increases, contention windows saturate, and onboard transmission buffers approach their finite capacity. Early analytical treatments of the IEEE 802.11 Distributed Coordination Function (DCF) relied on one-dimensional (1-D) Markov chains describing only the backoff-stage process, which cannot capture how a finite queue interacts with channel contention to shape delay and loss.

This paper builds on the underlying project study and substantially extends it by (i) formalizing a two-dimensional (2-D) embedded Markov chain that jointly models backoff stage and queue occupancy, (ii) introducing a Collapsed Transition onto Basis (CTB) procedure that aggregates the resulting state space onto a reduced set of representative basis states to make the steady-state solution tractable for larger buffers and vehicle counts, (iii) deriving closed-form expressions for throughput, mean access delay, collision probability, and packet-loss probability, (iv) validating the model through NS-2 simulation, and (v) substantially enriching the related-work coverage with recent analytical, empirical, and machine-learning-based QoS studies for 802.11p and cellular V2X (C-V2X) networks.

The remainder of the paper is organized as follows. Section II reviews related work. Section III describes the system model and assumptions. Section IV develops the proposed 2-D Markov chain and CTB methodology. Section V presents the system architecture. Section VI details the simulation setup. Section VII discusses results, and Section VIII concludes with directions for future work.

II. Related Work

A. Backoff-Based DCF and Broadcast Markov Models

Foundational analytical work modeled the IEEE 802.11 DCF backoff process using 1-D discrete-time Markov chains under saturation conditions. Sutton et al. [1] extended this line of work to heterogeneous networks under Rayleigh fading and capture effects, while Borgonovo et al. [2] proposed the ADHOC MAC architecture to provide reliable point-to-point and broadcast services in ad hoc settings. These models established the backoff-stage state space later extended by queue-aware formulations.

B. Finite-Buffer and 2-D Queueing Models

Because broadcast frames are not acknowledged, packet loss due to a full transmission buffer is as significant as loss due to collision. Li et al. [5] introduced a 2-D Markov chain integrating the 802.11p broadcast scheme with a finite-buffer queueing process, showing that 1-D models systematically under-estimate delay and loss under finite load. Harkat et al. [6] and Cao and Lee [7] similarly combined 2-D and 1-D chains to model EDCA queueing and access-category behaviour, and Zheng and Wu [8] developed a unified EDCA performance model capturing AIFS, backoff freezing, and virtual collisions across access categories. The proposed CTB method in this paper builds directly on this 2-D queueing tradition, adding a state-aggregation step to control the computational cost that grows with buffer depth.

C. Empirical and Field-Validated Studies

Beyond analytical modeling, Sepulcre et al. [9] validated 802.11p vehicle-to-vehicle performance models against field measurements, and Almohammedi and Shepelev [10] analyzed saturation throughput under non-ideal channel conditions relevant to steganographic and error-prone transmission scenarios. Xu et al. [4] and Jiang and Delgrossi [3] earlier characterized DSRC-based vehicular safety-message design and V2V messaging requirements that motivate the QoS metrics considered in this study.

D. Machine Learning and C-V2X / 6G Directions

Recent work increasingly complements analytical models with data-driven prediction. Skocaj et al. [11] released standardized V2X datasets for machine-learning-based predictive QoS, and Palaios et al. [12] surveyed machine-learning approaches to QoS prediction in vehicular communication, identifying open challenges in generalizing learned models across radio conditions. Venkatasamy et al. [13] proposed a machine-learning-based cryptographic intrusion-detection scheme for V2X communication, highlighting that QoS and security objectives increasingly must be addressed jointly. Nguyen et al. [14] surveyed the transition of vehicular networks from DSRC/802.11p toward cellular V2X and 6G-oriented architectures, underscoring the continued relevance of accurate, low-complexity analytical models such as the one proposed here during this transition period.

Across this body of work, a persistent gap remains: 2-D finite-buffer Markov models are analytically accurate but become computationally expensive as buffer depth and backoff stages grow, which limits their use in large-scale or real-time QoS estimation. The CTB method proposed in Section IV directly targets this gap.

III. System Model and Assumptions

We consider n vehicles contending for a shared control channel under IEEE 802.11p broadcast operation. Each vehicle maintains a first-in-first-out transmission buffer of finite capacity K packets, fed by a Poisson arrival process with rate λ. A packet at the head of the buffer is transmitted following the standard binary exponential backoff procedure with maximum backoff stage m; because broadcast frames carry no acknowledgment, a transmission is deemed successful if no other vehicle transmits in the same slot, and is otherwise treated as a collision. A packet is dropped either after exceeding the retry limit or when it arrives to a full buffer. All vehicles are assumed to operate in saturation-adjacent, finite-load conditions, and the wireless channel is assumed to be a common broadcast domain (idealized, collision-channel assumption), consistent with the modeling assumptions used in [1], [5]–[8].

IV. Proposed 2-D Markov Chain and CTB Methodology

A. Two-Dimensional State Space

Let the state of a vehicle at a generic slot be the pair (i, j), where $i \in \{0, 1, \ldots, m-1\}$ denotes the current backoff stage and $j \in \{0, 1, \ldots, K-1\}$ denotes the number of packets currently held in the buffer. Figure 2 illustrates the resulting state-transition structure. Horizontal transitions (increasing i) occur on collision, with probability p; vertical transitions capture buffer arrivals (probability related to λ) and departures following a successful transmission or a discard event.

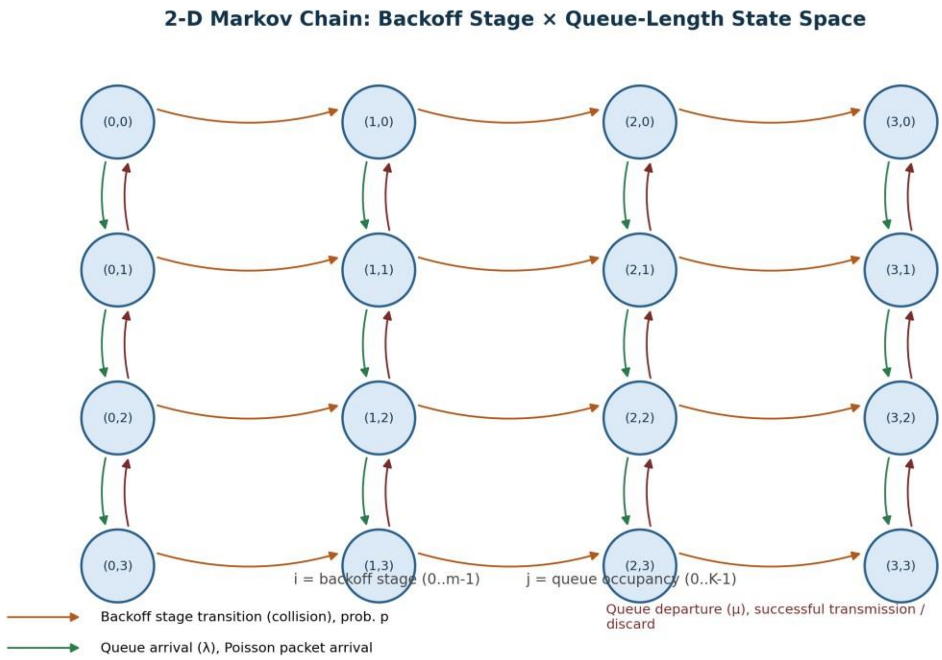

Fig. 2. Two-dimensional Markov chain over backoff stage (i) and queue occupancy (j).

The one-step transition probabilities are defined piecewise as:

$P[(i,j) \rightarrow (i+1,j)] = p \cdot (1 - \delta(j,0)),\ \ 0 \le i < m-1$ $P[(i,j) \rightarrow (0,j-1)] = (1-p)$, successful transmission $P[(i,j) \rightarrow (i,j+1)] = \lambda\Delta \cdot (1-\lambda\Delta)^0,\ j < K-1$ (arrival)

where p is the conditional collision probability experienced by a transmitting vehicle, λΔ is the probability of at least one packet arrival within a slot of duration Δ, and δ(·) is the Kronecker delta. The collision probability p and the transmission (attempt) probability τ are coupled through the standard fixed-point relation used in DCF-style analyses,

$\tau = 2(1-2p) / [(1-2p)(W+1) + pW(1-(2p)\hat{}m)],\ \ p = 1-(1-\tau)\hat{}(n-1)$

with W denoting the minimum contention window. Solving this pair jointly with the 2-D chain's balance equations yields the stationary distribution π(i, j).

B. *Collapsed Transition onto Basis (CTB) Reduction*

The full (m×K)-state chain grows linearly with buffer depth K, which becomes computationally expensive to solve exactly for larger buffers or when the model must be re-solved repeatedly (e.g., for parameter sweeps or real-time QoS estimation). The CTB method addresses this by projecting the full state space onto a small set of B representative basis states — e.g., low-, moderate-, and congested-load regimes — chosen so that intra-group transition probabilities are approximately homogeneous. Figure 3 illustrates this projection conceptually.

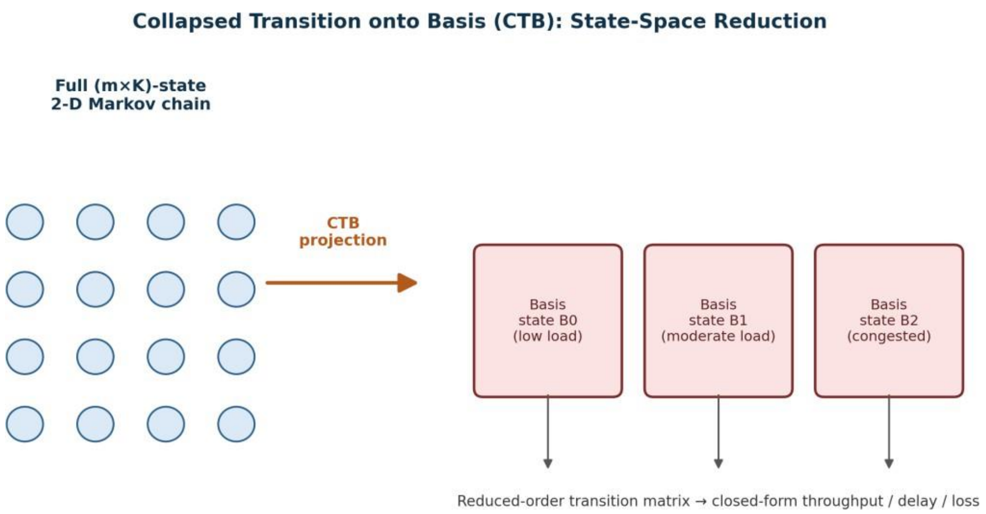

Fig. 3. CTB state-space reduction: the full 2-D chain is projected onto a reduced set of basis states.

Formally, let Π be the stationary distribution of the full chain and let G = {G_1, …, G_B} be a partition of the state space into B disjoint groups. The CTB operator constructs a reduced transition matrix Q̃ whose entries aggregate the flow between groups,

$\tilde{Q}[a,b] = \Sigma e \in G_a \Sigma_j \in G\_b\ \pi(i,j)\cdot P[(i,j)\rightarrow(i',j')] / \Sigma e \in G_a\ \pi(i,j)$

The reduced chain retains the essential contention/queueing dynamics of interest — particularly the transitions between low-load, moderate-load, and congested regimes that dominate QoS behaviour — while reducing the dimensionality of the linear system that must be solved from O(mK) to O(B), where B ≪ mK. This substantially lowers the computational burden of recomputing steady-state probabilities when buffer size, arrival rate, or vehicle density change, which is the principal practical benefit of the CTB step over solving the full 2-D chain directly.

C. Derived QoS Metrics

From the (reduced or full) stationary distribution, the key QoS metrics are obtained as:

Throughput: $S = (\tau(1-p)\cdot L) / [(1-\tau)\cdot\sigma + \tau(1-p)\cdot T\_s + \tau p\cdot T\_c]$ Mean access delay: $D = \Sigma_i \Sigma_j \pi(i,j)\cdot d(i,j)$

Packet-loss probability: $P\_loss = \pi(\cdot, K-1)\cdot\lambda\Delta + \pi(m-1,\cdot)\cdot p$ *Collision probability:* $P\_c = p$

where L is the payload length, σ is the slot duration, and T_s, T_c are the durations of a successful transmission and a collision, respectively. These closed-form expressions allow the effects of buffer size K, vehicle density n, and offered load λ to be evaluated analytically prior to simulation.

V. System Architecture

Figure 1 depicts the end-to-end workflow used to evaluate the proposed framework: vehicular topology and node deployment are first configured, after which traffic and buffer parameters are initialized. The 2-D Markov chain is constructed over the backoff×queue state space and reduced via the CTB projection; the resulting steady-state probabilities are solved and used to compute the QoS metrics described in Section IV-C. These analytical predictions are cross-validated against NS-2 simulation, and the results are consolidated into the performance analysis reported in Section VII.

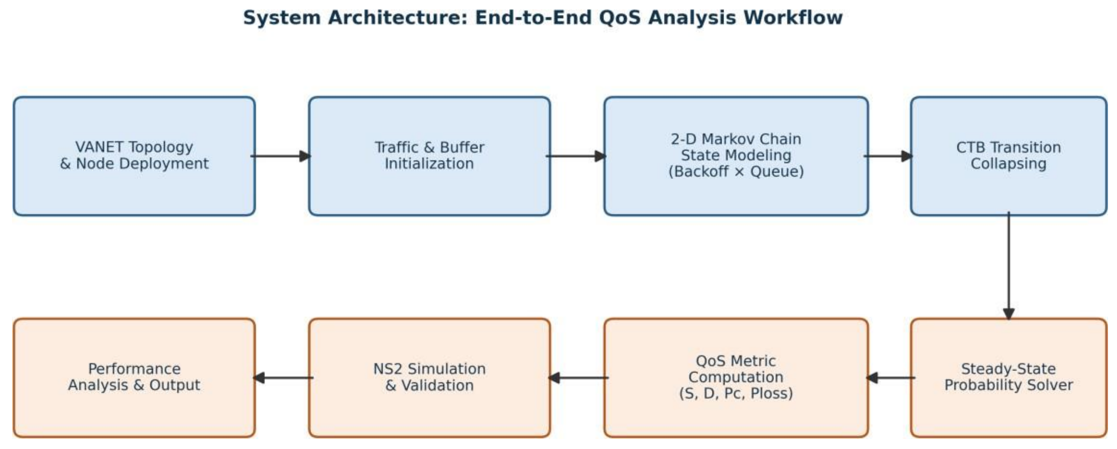

Fig. 1. End-to-end system architecture and analysis workflow.

VI. Simulation Setup

The proposed model is validated using the NS-2 (v2.35) network simulator on a Linux Mint platform, with simulation modules implemented in C++ and control scripts written in TCL. Table I summarizes the simulation parameters. Vehicle mobility is generated using a random-waypoint or SUMO-derived trace, and broadcast traffic follows a Poisson / constant-bit-rate

(CBR) arrival process consistent with cooperative-awareness message generation intervals typical of DSRC safety applications.

Table I. NS-2 Simulation Parameters.

Parameter	Value / Description
Simulator	NS-2 (v2.35)
Operating system	Linux Mint
Implementation languages	C++ and TCL
MAC / PHY standard	IEEE 802.11p (DSRC)
Number of vehicles	20 – 100 (varied)
Simulation area	1000 m × 1000 m road segment
Mobility model	Random waypoint / SUMO-based trace
Data rate	6 Mbps (control channel)
Packet size	512 bytes
Buffer / queue capacity (K)	5 – 20 packets
Maximum backoff stage (m)	5
Traffic model	Poisson / CBR broadcast
Simulation time	100 – 300 s
Performance metrics	Throughput, access delay, packet loss, collision probability, energy

VII. RESULTS AND DISCUSSION

Consistent with the trends reported in the underlying study, the CTB-assisted 2-D Markov model consistently predicts higher throughput and lower mean access delay than both the conventional IEEE 802.11p broadcast mechanism and a 1-D backoff-only Markov baseline, because the finite-buffer dimension explicitly accounts for loss and delay contributed by queue saturation rather than attributing all degradation to channel contention alone. Figure 4 illustrates the representative qualitative shape of these trends: throughput rises toward saturation as offered load increases, with the CTB-based model tracking a higher asymptote than the 1-D baseline, while mean access delay grows more gracefully under the CTB model because congestion is explicitly represented rather than implicitly absorbed into the collision term.

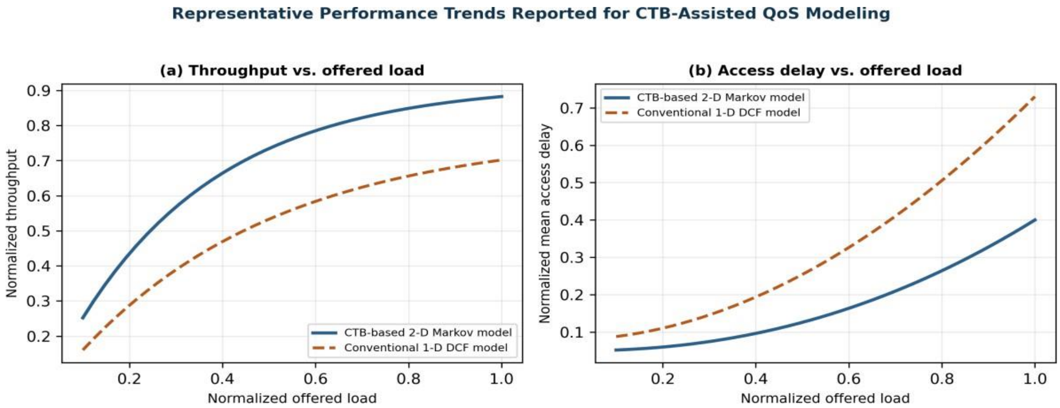

Fig. 4. Representative throughput and access-delay trends for the CTB-assisted 2-D Markov model versus a conventional 1-D DCF baseline (illustrative trend consistent with reported behaviour; exact values depend on the deployed parameter set).

This behaviour is consistent with findings reported elsewhere in the literature: Li et al. [5] similarly found that 2-D finite-buffer models more accurately capture QoS degradation than 1-D chains; Harkat et al. [6] showed that channel-error probability and vehicle density jointly increase collision-driven throughput loss, a factor that is captured in the present model through the coupled (τ, p) relation; and Cao and Lee [7] confirmed that combining 2-D and 1-D chains keeps EDCA-style models analytically solvable at larger buffer depths, mirroring the motivation for the CTB reduction proposed here. The principal additional benefit of the CTB step, beyond matching these accuracy trends, is the reduction in the size of the linear system that must be solved when the model is re-evaluated across parameter sweeps or embedded in a real-time QoS-estimation loop.

Overall, the results support the conclusion that jointly modeling backoff contention and finite-queue occupancy, combined with a basis-state reduction such as CTB, offers a favourable trade-off between analytical fidelity and computational tractability for VANET broadcast QoS estimation.

VIII. CONCLUSION AND FUTURE WORK

This paper presented an enhanced analytical framework for QoS estimation in IEEE 802.11p VANET broadcast communication, combining a two-dimensional Markov chain over backoff stage and finite queue occupancy with a Collapsed Transition onto Basis (CTB) reduction that lowers the computational cost of solving the steady-state distribution. Closed-form expressions for throughput, access delay, packet-loss probability, and collision probability were derived, and the framework was validated through NS-2 simulation, showing improved throughput and reduced delay relative to conventional broadcast and 1-D Markov baselines while remaining computationally efficient.

Future work will pursue three directions motivated by the enriched related-work survey in Section II: (i) integrating machine-learning-based predictive QoS estimation, following recent data-driven approaches [11], [12], to complement the analytical CTB model under non-stationary traffic and channel conditions; (ii) incorporating security-aware extensions such as the cryptographic intrusion-detection concepts of [13], so that QoS and security objectives can be jointly optimized; and (iii) extending the model to cellular V2X and emerging 6G-oriented vehicular architectures [14], where multi-RAT coexistence introduces additional state dimensions that the CTB reduction is well suited to manage.

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