A Systematic Review of Post-Quantum Digital Signature Algorithms with Fragmentation for Secure Electric Vehicle Communication

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Abstract. The rapid advancement of quantum computing poses a significant threat to the security of current asymmetric cryptographic techniques, jeopardizing their availability, confidentiality, and integrity. Given the prolonged lifespan of vehicles, the automotive industry becomes increasingly susceptible to quantum computers once they are operational. Vehicle-to-vehicle (V2V) communication is particularly vulnerable due to its reliance on the Elliptic Curve Digital Signature Algorithm (ECDSA), which is currently secure but may not withstand the threats posed by quantum computing. Post-Quantum Cryptography (PQC) algorithms like CRYSTALS-Dilithium provide robust protection against quantum attacks; however, their high computational requirements and larger key sizes present significant challenges for vehicular systems that have limitations in bandwidth and latency. This study investigates the viability of employing Dilithium for V2V communication through an analysis of IEEE 1609 and ETSI ITS standards, which currently do not encompass PQC guidelines. While Dilithium guarantees security against quantum threats, its sizable key material cannot be accommodated by the existing limits on vehicular messages. To tackle this issue, a hybrid method that merges Dilithium with ECDSA is suggested, bolstered by an innovative key size fragmentation technique that facilitates the secure transmission and reconstruction of extensive keys. This strategy provides a feasible transitional approach to achieving quantum-safe V2V communication, ensuring minimal latency and alignment with current standards.

Keywords: Hybrid Digital Signatures · Post-Quantum Cryptography (PQC) · Fragmentation · Vehicle-to-Vehicle (V2V)

1 Introduction

The swift progress of quantum computing presents a major risk to digital security. by jeopardizing key aspects such as authenticity, confidentiality, and integrity. Cryptographic algorithms that rely on the complexity of problems in number theory, including ECC-based approaches like ECDSA [1], [7], [13], and [29], are notably vulnerable to Shor's algorithm is capable of efficiently addressing problems related to discrete logarithms. While many industries face this challenge, the automotive sector is particularly at risk due to the extended lifespan of vehicles, indicating that existing systems are likely to face the difficulties presented by the quantum era. The breach of digital

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signatures could directly threaten road safety by enabling denial-of-service attacks, impersonation, or message forgery in safety-critical systems like vehicular networks [1], [13], and [30].

The Elliptic Curve Digital Signature Algorithm (ECDSA) is the primary method for authentication and non-repudiation in modern inter-vehicular communication (V2V) systems, as per IEEE 1609.2 and ETSI ITS standards. Although ECDSA works well against classical adversaries [7], [13], and [30], it is not quantum-safe and therefore not suitable for long-term security in vehicular environments. Post-quantum cryptography (PQC) must thus be adopted, but adoption is challenging due to the lack of PQC support in existing standards, the expense of larger key/signature sizes, and the constrained capabilities of in-vehicle hardware [1], [13], and [28].

The U.S. NIST PQC standardization initiative has proposed lattice-based schemes as the leading candidates. Falcon and CRYSTALS-Dilithium have been chosen for digital signatures, while Kyber (ML-KEM) has been standardized for key encapsulation [2, 10, 15, 21]. Dilithium provides strong security through efficient signing and key generation, but it produces larger signatures that may put a burden on bandwidth-constrained vehicular networks [13], [19], and [24]. Falcon's rapid verification and compact signatures make it attractive for V2V scenarios where vehicles must validate multiple incoming messages in real time [3], [13], and [25]. Despite offering strong hash-function-based security, SPHINCS+ is often not appropriate for real-time V2V due to its high computational cost [9], [24], and [25]. Recent benchmarking across platforms such as Nvidia Data Processing Units (DPUs) and ARM Cortex-A devices indicates that PQC integration is achievable with hardware acceleration; however, algorithm selection must be tailored for specific vehicular use cases [11], [20], and [24].

Even with algorithmic improvements, deployment in automotive environments poses unique challenges for hardware/software integration. PQC operations demand significantly more memory, energy, and processing cycles than conventional schemes, and vehicle ECUs, OBUs, and HSMs have limited resources [13], [25]. Co-designing hardware and software has emerged as a key strategy to mitigate these challenges. The FPGA and ASIC implementations of Kyber and Dilithium [2], [10], and [23] demonstrate that pipelining and modular arithmetic accelerators can achieve low-latency, energy-efficient performance. Falcon accelerators on embedded processors accelerate verification times through operation-level optimizations [3]. By employing NEON-based parallelism to achieve significant performance gains, vectorized implementations of Kyber and Dilithium on 32-bit ARM Cortex-A devices further prove their feasibility in automotive- grade processors [20]. However, there are still issues; for instance, if Kyber is implemented carelessly, it could be subject to side-channel and chosen-ciphertext attacks, highlighting the necessity of hardened PQC implementations [22].

Protocol-level adaptation presents another difficulty. The maximum payload size allowed by current vehicle standards is frequently exceeded by PQC signatures. In order to overcome this, a signature-split technique has been put forth that allows Dilithium and Falcon to adhere to IEEE 1609.2 by breaking up lengthy signatures into verifiable chunks without causing authentication to be delayed [28]. By dividing important shares

among several entities, threshold and multi- party structures, like two-party Dilithium (TOPCOAT), offer extra resilience [29]. Promising solutions for fast authentication and vehicular IoT integrity are also provided by lightweight PQC-enhanced ciphers, like Ascon integrated with PQ key exchange [27]. By carefully integrating ML- KEM and Falcon, protocols such as PQ-EDHOC further show how lightweight, limited devices can adopt PQC, albeit at a higher communication overhead [21].

There are still gaps in standardization despite technical limitations. Because of their lack of crypto-agility, current ITS protocols are unable to implement PQC without undergoing major redesign [13], [30]. For this reason, hybrid migration strategies are deemed necessary. By combining ECDSA and Falcon, compact hybrid signature schemes lower the overhead of signature size while maintaining security even in the event that one primitive is compromised [8, 12, 30]. PQC adoption is more feasible within the stringent bandwidth and latency requirements of V2V thanks to partially hybrid V2V authentication protocols, which further optimize radio spectrum usage by removing redundant certificate transmissions [30].

In conclusion, post-quantum alternatives to ECDSA are urgently needed for V2V communications in order to guarantee future-proof authentication. Although lattice-based candidates such as Dilithium and Falcon are promising, standardization gaps, hardware limitations, side-channel resilience, packet-size issues, and performance trade-offs must all be addressed in order to integrate them. New approaches like spectrum optimization, hybrid authentication, and signature-splitting are practical transitional routes. Combining these tactics offers a workable roadmap for defending V2V communications against the quantum threat by balancing long-term quantum safety with near-term interoperability [1], [8], [13], [28], and [30].

1.1 Scope of the Research

The transition from traditional ECDSA-based authentication schemes to lattice-based digital signatures is the specific focus of this study, which sits at the nexus of post-quantum cryptography (PQC) and inter-vehicular communications (V2V). The following is the definition of the scope:

- *Vehicle Standards Context.* The study frames the migration challenge by taking into account the IEEE 1609.2 and ETSI ITS standards, which currently require ECDSA but do not include PQC specifications.
- *Algorithm Focus.* The study evaluates Falcon and CRYSTALS-Dilithium, two NIST-standardized lattice-based digital signature schemes, in the context of V2V.
- *Software/Hardware Restrictions.* The study highlights the viability of implementing PQC on automotive-grade hardware, such as HSMs, OBUs, and ECUs, while also mentioning experimental platforms like FPGAs, DPUs, and ARM Cortex processors.

- *Protocol Adaptation.* The study looks at modifications needed to incorporate PQC into vehicular protocols, like signature-splitting techniques to adhere to IEEE 1609.2 payload limits.

Transitional Approaches. In order to bridge the gap between existing standards and upcoming quantum- safe protocols, hybrid cryptographic models that combine ECDSA and PQC signatures are being considered as a temporary solution.

1.2 Research Contributions

The primary contributions of this work are as follows:

1. Comprehensive Standards Review: Offers an organized analysis of IEEE 1609.02 and ETSI ITS cryptographic specifications, emphasizing the implications for long-lived vehicular systems and the absence of PQC integration.
2. Algorithm Evaluation for V2V: V2V constraints like bandwidth, latency, and high-frequency message validation are mapped to the signature size, signing/verification performance, and key generation overhead of Falcon and Dilithium.
3. Adaptation at the Protocol Level: Determines the effect of signature-splitting on authentication latency and communication reliability in V2V and investigates its suitability for Dilithium/Falcon to satisfy IEEE 1609.2 payload constraints.

2 Background and related work

2.1 Vehicular Communication Systems and Security Requirements

Intelligent Transportation Systems (ITS) are based on Vehicle-to-Vehicle (V2V) and Vehicle-to-Everything (V2X) communication systems. The cryptographic primitives and certificate frameworks for V2V security are defined by IEEE 1609.2 and ETSI ITS [1], [13]. Current deployments make extensive use of the Elliptic Curve Digital Signature Algorithm (ECDSA), which is renowned for producing compact signatures and effective verification under classical conditions. However, these algorithms are basically vulnerable to quantum adversaries, as Shor's algorithm can break discrete logarithm assumptions in polynomial time [7], [13]. Since vehicles will continue to operate for decades and will be susceptible to future quantum threats, it is imperative that V2V security be switched to quantum- resistant primitives [1], [30].

2.2 Post-Quantum Cryptography Algorithms and Standardization

The NIST PQC standardization effort has determined that the most promising family of algorithms for post- quantum resilience is lattice-based cryptography [2], [6], and [13].

Specifically:

- CRYSTALS-Dilithium: Provides effective key generation and signing along with robust security, but generates large signatures that could put a strain on vehicular networks with limited bandwidth [19], [24].
- Falcon: Offers quick verification and small signatures, which makes it appealing for V2V, where vehicles need to validate a lot of BSMs [3], [11], [25].
- Kyber (ML-KEM): a key encapsulation standard that is pertinent to safe V2X key exchange [2], [21].
- SPHINCS+: A hash-based substitute with robust security, but because of its high computational cost, it is not feasible for latency-sensitive vehicular communication [9], [24].

Research has concentrated on hardness assumptions that support lattice schemes, such as Learning With Errors (LWE), Module-LWE, and Ring-LWE, in addition to choosing baseline algorithms [6], [15]. Although surveys and systematic reviews emphasize PQC's increasing maturity, they also point out that lengthy product lifecycles and gaps in standardization cause adoption in the automotive industry to lag [7], [13].

2.3 Hardware and Software Constraints in PQC Deployment

Vehicle systems depend on resource-constrained Hardware Security Modules (HSMs), On-Board Units (OBUs), and Electronic Control Units (ECUs) [13]. Because PQC requires more computation than ECDSA and has larger key sizes and signature lengths, integrating it into these components presents difficulties. A number of studies suggest co- designing software and hardware:

- Using pipelining and operation-level co-design, Falcon optimizations on embedded platforms show notable speedups [3].
- By using SHAKE accelerators and modular arithmetic units, dilithium and kyber accelerators on FPGA and ASIC provide low-latency, energy-efficient execution [2], [10], and [23].
- Kyber and Dilithium vectorized implementations on the ARM Cortex-A show notable enhancements through the use of NEON instructions, which are specifically pertinent to processors of automotive grade [20].
- Parallel PQC verification is further demonstrated by Nvidia Data Processing Units (DPUs), demonstrating suitability for OBUs or RSUs managing numerous concurrent messages [11].

But vulnerabilities still exist. Without careful implementation, Kyber and other lattice schemes are vulnerable to side-channel and chosen-ciphertext attacks, necessitating hardened implementations with countermeasures like shuffling [19], [22].

2.4 Protocol Adaptations for PQC Integration in V2V

PQC adoption in vehicular systems is limited by protocol-level issues in addition to raw performance. Existing ITS protocols lack crypto-agility because they were created for compact ECDSA signatures. The maximum payload size specified in IEEE 1609.2 is

frequently exceeded by large PQC signatures, which causes fragmentation and latency problems [13].

Among the suggested modifications are:

- Signature-Split Method: This technique separates Falcon and Dilithium signatures into verifiable parts while maintaining IEEE 1609.2 compliance [28].
- TOPCOAT (Two-Party Dilithium): Increases the resilience of vehicle authentication by distributing signing operations among several parties [29].
- Hybrid authentication: To balance quantum resistance and backward compatibility, ECDSA and PQC signatures are combined [8, 12, 30].

These solutions demonstrate viable paths to integrating PQC within the strict bandwidth, latency, and compliance requirements of V2V communication.

3 Methodology

This survey follows a structured review process to identify and analyse research related to post-quantum digital signature algorithms (PQ-DSA), fragmentation methods, and their applicability to secure electric vehicle (EV) and V2X communication.

3.1 Data Sources

Relevant papers were collected from five widely used scientific databases:

- **IEEE Xplore**
- **ACM Digital Library**
- **SpringerLink**
- **ScienceDirect**
- **Scopus**

These platforms were selected because they publish high-quality, peer-reviewed work in cryptography, embedded systems, and vehicular communication.

3.2 Search Strategy

Searches were performed using keyword combinations such as:

- post-quantum signatures, PQ-DSA, lattice-based signatures
- CRYSTALS-Dilithium, Falcon, SPHINCS+
- V2X security, V2V authentication, EV communication security
- signature fragmentation, lightweight PQC, hardware PQC

Search results were restricted to peer-reviewed papers published between **2017 and 2025**.

3.3 Selection Criteria

To ensure relevance and technical quality, papers were selected based on the following criteria:

Inclusion:

- Peer-reviewed journal or conference papers
- Focus on PQ-DSA, fragmentation, V2X/EV security, or hardware feasibility
- Provide performance metrics such as signature size, latency, or computation cost

Exclusion:

- Non-English papers
- Articles without technical depth (editorials, blogs)
- Papers unrelated to PQ-DSA or V2X security
- Duplicate entries

3.4 Final Paper Set

After applying the selection criteria, **30 papers** were identified as relevant for this survey. These works form the basis of the analysis presented in the later sections and cover algorithmic design, hardware implementation, fragmentation methods, and PQC-based vehicular communication.

4 Literature survey

This section reviews peer-reviewed literature on post- quantum cryptography in vehicular communication systems, focusing on algorithmic approaches, hardware platforms, and protocol-level security mechanisms

Table 1. Comparative summary of recent works (2021–2025) examining hybrid ECDSA–PQC integration, signature fragmentation techniques, and performance analyses toward efficient and secure post-quantum digital signatures in vehicular communication contexts.

S.no	Paper title	Author(s)	Key findings	Advantages	Disadvantages
1	Compact Hybrid Signature for Secure Transition to Post-Quantum Era [8]	H.-Y. Kwon et al.	Hybrid ECDSA+Falcon with selective verification and size reduction.	• Hybrid scheme • compact size • backward compatible.	• Uses Falcon not Dilithium • Complex • still larger than single scheme.
2	Signature Split Method for PQC-DSA Compliant with V2V communication standards [28]	Y. Kim, S.C. Seo	Introduces signature fragmentation for Dilithium/Falcon to fit V2V limits.	• Direct fragmentation • MTU-compliant • early verification possible.	• V2V-specific • adds latency • requires reassembly logic.

3	When Cryptography Needs a Hand: Practical Post- Quantum Authentication for V2V Communications [30]	G. Twardokus et al.	Hybrid classical+PQC authentication using adaptive scheduling.	• Practical hybrid • real-world test • optimized bandwidth use.	• V2V-specific • complex scheduling • limited generalization.
4	A Framework for Migrating to Post- Quantum Cryptography [1]	K.F. Hasan et al.	Outlines hybrid migration paths and dependency analysis for PQC adoption.	• Structured migration plan • hybrid awareness • case studies.	• High-level • no implementation • no fragmentation method.
5	Hybrid Keys in Practice: Combining Classical, Quantum and PQC [13]	S. Ricci et al.	Implements hybrid key combiner for PQ and classical security.	• Demonstrates hybrid design • backward- compatible • efficient.	• Focuses on keys • not digital signatures • hardware prototype.
6	Performance and Applicability of Post-Quantum Digital Signature Algorithms in Resource-Constrained Environments[25]	M. Vidaković, K. Miličević	Benchmarks Dilithium, Falcon, SPHINCS+ in IoT and blockchain contexts.	• Practical comparisons • supports hybrid selection • lightweight insights.	• Survey only • no hybrid composition • limited dataset.
7	Performance Analysis of PQC Algorithms for Digital Signatures	F. Opiłka et al.	Compares Dilithium, Falcon, SPHINCS+ performance using liboqs.	• Comprehensiv e benchmarks • helps overhead estimation • software-level focus.	• No fragmentation study • no hybrid structure • platform- dependent.
8	Energy Efficiency Analysis of PQ Algorithms	C.A. Roma et al.	Profiles Dilithium energy use and optimization targets.	• Energy- efficient insights • guides fragmentation timing • practical relevance.	• Energy-only focus • limited hybrid view • testbed-specific results.

9	Systematization of Shuffling Counter-measures With an Application to CRYSTALS-Dilithium[19]	J. Lee et al.	Proposes side-channel counter-measures with min-imal overhead.	• Enhances Dilith-ium security • ~12% cost • clear taxonomy.	• Not hybrid • adds runtime load • complex imple-mentation.
10	Enabling Quantum-Resistant EDHOC: Design and Performance Evalua-tion [21]	L. Pocero Fraile et al.	PQ EDHOC protocol using Dilithium/Falcon for constrained IoT.	• Protocol-level design • tested on devices • hybrid-ready approach.	• Protocol-specific • minor overhead • no fragmentation concept.
11	Vectorized Implementation of Kyber and Dilithium on 32- bit Cortex-A Series [20]	Y. Kim, S.C. Seo	Software vectorization to speed up Dilithium on ARM cores.	• Efficient software • faster signing • embedded support.	• Platform-limited • no hybrid concept • not fragmentation-focused.
12	A Survey of Post-Quantum Cryptography Migration in Vehicles [15]	N. Lohmiller et al.	Reviews PQC use in vehicles; highlights hybrid and migration needs.	• Vehicular focus • good transition insight — domain relevance.	• Survey-level • no design proposal — lacks fragmentation analysis.
13	Compact Hybrid PQ Authentication for V2V	G. Twardokus et al.	Partial hybrid PQC+classical design for low-latency V2V communication.	• Practical integration • real experiments • scalable authentication.	• Domain-specific • early-stage • no fragmentation model.

5 Findings and Discussion

5.1 Key Trends and Patterns

The literature examined shows a distinct movement from classical cryptography (ECDSA) toward post-quantum cryptography (PQC) within vehicular networks.. ECDSA remains the industry standard due to its efficacy, small key sizes, and demonstrated integration into the IEEE 1609.2 and ETSI ITS frameworks [30].

Nonetheless, the majority of research concurs that ECDSA is not appropriate for long-term use due to its extreme susceptibility to quantum attacks [1]. CRYSTALS-Dilithium and Falcon are emphasized as promising choices among PQC candidates, with Dilithium being favored for security and Falcon for quicker verification [24], [25]. One common theme is that PQ signatures are much bigger than ECDSA, which causes packet fragmentation and bandwidth issues in V2V systems [28]. As transitional solutions, hybrid approaches that combine ECDSA and PQC are frequently suggested, as are techniques like spectrum optimization [30] and signature splitting [28].

5.2 Interpretation of Results

Table 2. Comparison of ECDSA and Hybrid Signatures in V2V

Metric	ECDSA Only	Hybrid (ECDSA + Dilithium, 400B frag, split)
Signature Size	71 B	~2771 B (71 B + 2700 B)
Signing Time	0.028 ms	0.028 ms (ECDSA) + 2.5 ms (Dilithium)
Verification Time	0.094 ms	0.094 ms (ECDSA) + 4.0 ms (Dilithium)
Fragments Needed	1 (fits in a single packet)	7 (Dilithium split across 400B payloads)
Timeto First Trust	~0.36 ms	~0.36 ms (same, because ECDSA in first packet)
Timeto PQ Trust	N/A (no PQC)	~7.9 ms (after all Dilithium fragments verified)
Quantum Resistance	Not secure vs quantum	Secure (PQ-safe due to Dilithium)

The hybrid approach, which incorporates Dilithium, necessitates fragmentation across multiple packets due to its significant increase in signature size (~2771 B). In comparison to ECDSA, this results in extra signing (2.5 ms) and verification (4.0 ms) delays. Since ECDSA is confirmed in the first packet, the time to first trust (~0.36 ms) is unaffected by this overhead. After all Dilithium fragments have been confirmed, it takes about 7.9 ms to establish post- quantum trust. For safety-critical V2V applications, this delay is still within acceptable bounds even though it is greater than ECDSA-only. It should be mentioned that the performance metrics (signing, verification, and trust establishment times) are obtained from simulation, whereas the signature/key sizes are based on real standardized values. The simulations were run on an Intel Core i7 processor running Linux Ubuntu, which offers a useful baseline for assessment but does not accurately represent the constraints of actual automotive hardware. Overall, the results demonstrate that hybrid signatures offer a workable

compromise, combining the advantages of Dilithium's quantum security with the real-time responsiveness of ECDSA.

5.3 Limitations of this Survey

While this survey offers valuable insights, it comes with a number of limitations. To begin with, many of the studies examined depend on simulation-based experiments rather than actual vehicle settings, which may result in findings that do not accurately reflect the effects of high vehicle density, constrained OBU/ECU hardware, and variability in wireless channels [30]. Additionally, the simulated outcomes were generated using a standard Intel Core i7 system, which fails to represent the computational constraints of real automotive devices, yet it still offers useful benchmarks. Furthermore, the lack of broad industry adoption and standardized implementation frameworks raises concerns regarding the long-term viability of hybrid methods, even though they show considerable promise [1]. Finally, this survey primarily focuses on authentication methods that use fragmentation, indicating that further exploration is necessary into other aspects of post-quantum cryptography related to vehicle communication, including resilience against side-channel attacks, lightweight encryption, and key exchange [21], [27].

6 CONCLUSION

The challenges and potential solutions for safeguarding vehicle-to-vehicle (V2V) communication in the impending post-quantum era were examined in this study. ECDSA, which provides effective performance but is not resilient against quantum adversaries, is the foundation of current systems. Despite providing quantum security, post-quantum schemes such as CRYSTALS-Dilithium suffer from fragmentation and latency in vehicular environments because of their lengthy verification times and large signature sizes.

The work showed that a hybrid ECDSA–Dilithium scheme, backed by fragmentation mechanism, can successfully strike a balance between real-time performance and quantum resistance through a comparative simulation study. According to the results, the hybrid approach offers a viable path for a gradual transition to post-quantum security in V2V networks, even though it adds extra overhead in the form of processing time and signature size while maintaining acceptable latency for safety-critical communication.

The study indicates that hybrid signature schemes can act as a link between current vehicular standards and the challenges posed by future quantum threats. To achieve scalability and reliability within practical limitations, upcoming research should focus on enhancing fragmentation methods, exploring hardware acceleration for post-quantum processes, and testing these approaches in real vehicular settings.

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