

Event-triggered V2X communication and control co-design for intelligent electrified transportation systems

Ziming Wang¹, Xiaohua Ge², Qing-Long Han^{2,✉}

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1 Introduction

The past decade has witnessed remarkable progress in intelligent electrified transportation systems (IETSs), largely driven by the rapid proliferation of electric vehicles (EVs). Compared with conventional internal combustion engine vehicles, EVs offer substantial advantages, including reduced carbon emissions and improved energy efficiency. This transition has been further accelerated by strong governmental policies promoting new energy adoption, thereby creating a favorable ecosystem for large-scale EV deployment. In parallel, the evolution of vehicle-to-everything (V2X) communication technologies has emerged as a key enabler, facilitating deep integration between vehicular control systems and communication networks. As a result, communication-control co-design has progressed from a desirable capability to a fundamental requirement for next-generation transportation infrastructures. Realizing this paradigm requires a clear understanding of the interactions between various V2X communication modalities (Li et al., 2025) and vehicular control system design.

Within V2X architectures, vehicle-to-vehicle (V2V) communication enables direct real-time exchange of state information among automated EVs, supporting cooperative perception and coordinated trajectory planning. Vehicle-to-infrastructure (V2I) communication provides access to traffic signal timing, roadside sensing, and digital twin services, thereby facilitating optimized routing and cooperative maneuvering. Meanwhile, vehicle-to-grid (V2G) communication allows EV aggregators to receive grid regulation signals, enabling EV participation in ancillary grid services and enhancing power system stability. A communication-control co-design strategy explicitly ensures that vehicular control performance requirements inform communication protocol design, while practical network constraints, including bandwidth limitations, latency, and packet loss, are incorporated into controller synthesis. The overarching objective is to guarantee stability, safety, efficiency, and performance under realistic resource-constrained communication environments. Despite its promise, traditional V2X communication assumptions based on dedicated high-bandwidth links are inadequate for supporting such integration in large-scale practical EV deployments.

Conventional vehicular control strategies that assume a periodic data sampling and communication paradigm for each connected vehicle are

inherently impractical in large-scale networked environments. Such strategies further fail to address a scalability challenge associated with dense vehicular populations and neglect the bursty and context-dependent nature of vehicular data generation. Continuous high-frequency sampling and transmission of sensing and state information, regardless of necessity, inevitably leads to network congestion, increased latency, packet collisions, and ultimately degraded closed-loop system performance. This mismatch directly undermines the communication-control co-design principle due to inefficient utilization of limited communication resources. A transition from periodic sampling and communication toward event-triggered scheduling (Tabuada, 2007) is essential.

A representative event-triggered scheduling mechanism (ESM) configuration and a schematic illustration of event-triggered V2X communication are presented in Fig. 1. Specifically, an ESM activates sampling and/or transmission only when a predefined event condition is violated, thereby allocating computation/communication resources to information updates that are truly necessary and informative. Despite their effectiveness, existing ESM designs still suffer from several inherent limitations. For example, static ESMs employ fixed triggering thresholds that, while computationally simple, often lead to conservative operation and unnecessary samplings and/or transmissions. Dynamic ESMs, on the other hand, typically adjust triggering thresholds according to system (or vehicle) state variations, yet they frequently neglect real-time communication-network conditions such as bandwidth availability, channel congestion, and transmission quality (Ge et al., 2025). Consequently, data samplings and/or transmissions may be unnecessarily suppressed even when network resources are underutilized, potentially degrading closed-loop control performance and overall system responsiveness.

In our view, next-generation ESMs should be explicitly co-designed with control objectives in V2X-enabled IETSs. One particularly promising direction lies in the development of bandwidth-aware dynamic ESMs, where triggering thresholds are adaptively regulated by jointly accounting for vehicle dynamical behavior and instantaneous network bandwidth conditions. Another important direction is the design of intelligent ESMs capable of integrating multiple contextual factors, including state regulation errors, communication constraints,

¹ Trust of Artificial Intelligence, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou 511453, China. ² School of Engineering, Swinburne University of Technology, Melbourne VIC 3122, Australia.

✉ Corresponding author. E-mail: gihan@swin.edu.au

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channel quality indicators, traffic environments, and safety-related metrics, to support more informed and adaptive sampling and/or transmission decisions. Such mechanisms constitute a crucial step toward resource-aware and control-oriented communication scheduling, enabling a more effective balance between V2X communication efficiency and closed-loop control performance in next-generation IETs.

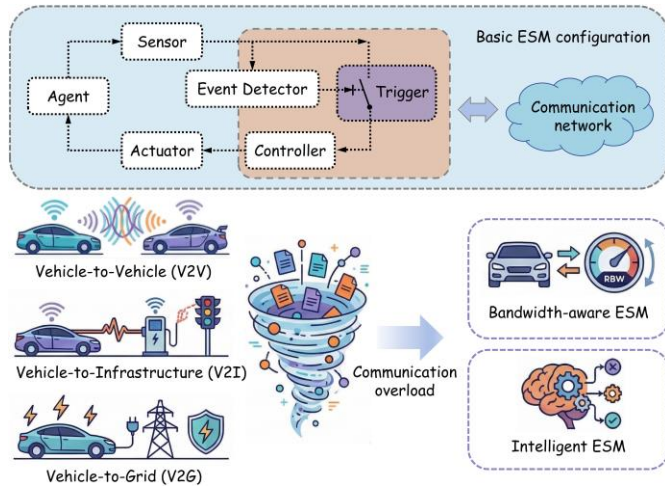


Fig. 1. Basic ESM configuration and event-triggered V2X communication scheduling.

More importantly, in EV-centric IETs, the co-design of event-triggered V2X communication and control should be viewed beyond the conventional communication-control trade-off paradigm. Automated/autonomous EVs are inherently battery-powered, software-defined, and increasingly grid-interactive platforms, meaning that communication behaviors are closely intertwined with control execution and energy-management processes. The frequency and timing of V2X message exchanges influence not only network occupancy and control accuracy, but also auxiliary energy consumption, battery thermal loading, regenerative braking coordination, and the responsiveness and accuracy of V2G services. This observation motivates a broader *tri-coupled design* perspective that simultaneously considers communication, control, and energy management within the event-triggered V2X co-design framework. Such a perspective is expected to play a pivotal role in achieving energy-efficient, communication-aware, and control-resilient operation for future IETs.

2 Event-triggered Scheduling Mechanisms

Although modern wireless communication technologies enable high-rate data transmission, modeling intelligent connected EVs as agents with effectively unlimited bandwidth is unrealistic in large-scale IETS deployments. The massive population of EVs and the shared nature of wireless channels impose stringent communication constraints. Furthermore, periodic high-frequency transmission is often redundant because consecutive packets frequently contain highly correlated information. These observations motivate the development of ESMs, which aim to reduce communication burden while preserving closed-loop stability and control performance, thereby facilitating event-triggered V2X communication and control co-design.

2.1. Bandwidth-aware Event-triggered Scheduling Mechanism

To overcome the conservatism inherent in static ESMs and the network-unaware nature of conventional dynamic ESMs, bandwidth-aware dynamic ESMs (Ge et al., 2025) have recently emerged as a promising direction. The defining feature of such mechanisms is a dynamically adjustable triggering threshold that jointly reflects vehicle regulation errors and real-time communication bandwidth availability within a unified scheduling framework. By explicitly incorporating a bandwidth acknowledgement parameter, the triggering logic can adaptively switch between a performance-oriented mode, permitting more frequent transmissions when channel capacity is ample, and a resource-efficient mode, in which non-essential updates are suppressed under network congestion. In this way, communication resources are utilized only when both control-performance demands and network feasibility conditions are satisfied. Existing results indicate that bandwidth-aware ESMs can substantially improve the trade-off between closed-loop stability guarantees and communication efficiency, offering a responsive and context-aware scheduling paradigm for bandwidth-constrained V2X environments.

Despite these advances, several open challenges remain. In practice, bandwidth acknowledgement information may be noisy, delayed, or partially observable, which motivates the incorporation of uncertainty-aware filtering, confidence-based triggering rules, and short-horizon bandwidth prediction to improve robustness and reliability. In heterogeneous V2X networks featuring multiple communication technologies and links, multi-link ESM architectures that jointly optimize triggering decisions and path selection under latency, reliability, and cost constraints are highly desirable. In addition, in dense traffic scenarios, synchronized triggering across large vehicle populations may lead to network-level oscillations or unfair resource usage, highlighting the need for congestion-aware coordination mechanisms such as mean-field regulation, randomized triggering, or fairness-constrained scheduling policies. Finally, as V2X systems become increasingly exposed to cyber-physical threats, resilient ESM designs that integrate anomaly detection and attack-aware adaptation will be essential to mitigate spoofed acknowledgements and jamming attacks, while preserving both closed-loop stability and communication efficiency.

2.2. Intelligent Event-triggered Scheduling Mechanism

To further enhance adaptability, contextual awareness, and system-level coordination, intelligent ESMs extend conventional event-triggered paradigms by jointly incorporating multiple V2X-related factors into the triggering process. Unlike traditional threshold-based schemes that primarily rely on regulation-error information, intelligent ESMs employ integrated decision mechanisms capable of dynamically adapting to variations in vehicle dynamics, communication-network conditions, traffic environments, and safety requirements. Typical real-time inputs may include vehicle state regulation errors, bandwidth availability, channel quality indicators such as packet loss and latency, surrounding traffic conditions, and safety-critical contextual metrics. By continuously updating triggering policies using historical observations, predictive information, and contextual awareness, intelligent ESMs enable a more refined assessment of transmission necessity. This facilitates

adaptive scheduling behaviors, such as prioritizing transmissions under elevated collision risk despite moderate regulation errors, or intentionally delaying updates when severe network congestion is detected.

More importantly, from the perspective advocated in this article, intelligent ESM design for future EV-centric IETs should move beyond the conventional communication-control co-design paradigm toward a deeper tri-coupled integration of communication, control, and energy management. Since automated EVs are simultaneously mobile cyber-physical systems and distributed energy nodes, communication scheduling decisions inevitably influence not only control performance and network utilization, but also battery operation and energy-management efficiency. Consequently, triggering policies should explicitly incorporate energy-related factors, including battery state of charge, battery thermal conditions, estimated auxiliary communication and computation energy consumption, charging/discharging requests, and grid-support demands associated with V2G services. Such integration enables the scheduling mechanism to evaluate the marginal value of each transmission from multiple interconnected dimensions, including its expected contribution to closed-loop control performance, communication burden, operational safety, and energy-management objectives. In this context, integrated decision models that fuse heterogeneous contextual information may naturally benefit from intelligent control methodologies, such as fuzzy-system-based reasoning (Hoffmann, 2001), adaptive weighting strategies, and learning-assisted inference mechanisms, thereby enabling flexible and situation-aware triggering policies tailored to highly dynamic V2X environments. As a result, intelligent ESMs offer a promising framework for achieving a balanced and coordinated trade-off among communication efficiency, control performance, operational safety, and energy sustainability in next-generation IETs.

Nevertheless, the development of deployable intelligent ESMs with rigorous theoretical guarantees remains largely open. One fundamental challenge arises from the partial observability, uncertainty, and non-stationarity inherent in wireless communication environments, traffic evolution, and driving behaviors, all of which may destabilize or bias learned triggering policies. The incorporation of learning-based or data-driven decision mechanisms further complicates formal analysis and verification, particularly in guaranteeing the exclusion of Zeno-like triggering behavior and ensuring closed-loop stability under random packet losses, variable transmission delays, asynchronous updates, and dynamically changing network topologies. Moreover, multi-source information fusion and online inference inevitably introduce additional computational overhead and latency, which may conflict with the stringent real-time requirements of safety-critical transportation systems. Rare but safety-critical corner cases also remain difficult to capture during training and validation, creating major challenges for robustness assessment, certification, and regulatory approval. Addressing these issues will require new theoretical frameworks that integrate intelligent decision-making, communication-aware control, energy-aware scheduling, and safety verification into a unified and mathematically rigorous co-design methodology for future V2X-enabled IETs.

3 Conclusions and Future Research Directions

This editorial emphasizes the critical role of event-triggered V2X communication and control co-design in IETs. Two representative ESMs are discussed. The first is a bandwidth-aware dynamic ESM that adjusts triggering thresholds according to real-time network capacity, thereby explicitly coupling control performance with communication feasibility. The second is an intelligent ESM that incorporates multi-source contextual information to enable adaptive and situation-aware transmission decisions. Together, these approaches provide a principled pathway toward balancing communication efficiency and control performance in large-scale V2X-enabled systems.

Despite their promise, several research directions remain open for further investigation. From a system-level perspective, the integration of digital twin technology with edge artificial intelligence can enable virtual-physical interactive environments for real-time performance monitoring, predictive analysis, and adaptive scheduling reconfiguration. Such platforms would support rapid validation of triggering policies under diverse traffic densities, communication disturbances, and cyber-physical uncertainties.

From a communication-network integration standpoint, emerging paradigms such as 5G/6G connectivity and vehicle-road-cloud collaborative architectures (Yang et al., 2025) create new opportunities for ESM enhancement. In particular, incorporating network slicing, mobile edge computing, and cross-layer resource orchestration can enable latency-aware and reliability-aware triggering strategies with finer-grained communication resource allocation. These developments are especially relevant for safety-critical cooperative driving applications requiring stringent delay and reliability guarantees.

Furthermore, security and privacy considerations must become intrinsic components of communication and control co-design. ESMs are inherently vulnerable to adversarial manipulation of triggering conditions, bandwidth feedback, and contextual information. Consequently, resilient ESMs that integrate attack detection, privacy-preserving information exchange, and robustness against spoofing and jamming are essential to address escalating cybersecurity threats in V2X environments (Li et al., 2025).

Finally, the transition toward EV-dominated transportation systems introduces a fundamentally stronger coupling between communication, control, and energy management than that encountered in conventional connected-vehicle settings. Communication frequency not only affects vehicular control performance but also influences auxiliary energy consumption, battery degradation, regenerative braking efficiency, and even grid-support accuracy. Consequently, event-triggered V2X co-design becomes an essential mechanism for balancing safety, scalability, and energy sustainability in EV-centric IETs. This challenge is particularly urgent given the rapid increase in EV penetration, the emergence of vehicle-grid integration, and the growing heterogeneity of V2X technologies with distinct latency-energy trade-offs. These developments elevate optimized event-triggered scheduling from a communication-efficiency enhancement to a foundational enabler of large-scale energy-aware cooperative autonomy.

Author contributions

Ziming Wang: Writing – original draft, Methodology, Formal analysis, Software, Conceptualization. **Xiaohua Ge:** Writing –

review & editing, Validation, Methodology. **Qing-Long Han:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Ziming Wang received the B.Eng. degree in Electronic Information Engineering from Southwest University in 2023 and the M.Phil. degree in the Trust of Robotics and Autonomous Systems from the Hong Kong University of Science and Technology (Guangzhou) in 2025. He was a visiting scholar at the School of Vehicle and Mobility, Tsinghua University. He is currently a PhD student in the Trust of Artificial Intelligence from the HKUST GZ. He is a senior reviewer of the IEEE TITS, IEEE TSMC, IEEE TMC and IEEE/CAA JAS. His research interests include control theory, optimization, multi-agent systems, reinforcement learning, and their applications in intelligent transportation systems.



Xiaohua Ge received the Ph.D. degree in Computer Engineering from Central Queensland University, Rockhampton, QLD, Australia, in 2014. From 2015 to 2017, he was a Research Fellow with the Griffith School of Engineering, Griffith University, Gold Coast, QLD, Australia. He is currently an Associate Professor with the School of Engineering, Swinburne University of Technology, Melbourne, VIC, Australia. His research interests include networked control, cooperative autonomy, swarm/collective intelligence, and cyber-physical security and resilience, and their applications in robotics, autonomous/connecting/electric vehicles, intelligent

transportation systems, energy management systems, etc. Dr. Ge serves/served as an Associate Editor of IEEE Transactions on Systems, Man, and Cybernetics: Systems, IEEE Transactions on Intelligent Vehicles, IEEE/CAA Journal of Automatica Sinica, IEEE Transactions on Industrial Informatics, and IEEE Transactions on Circuits and Systems II: Express Briefs, and a Guest Editor of 10+ prestigious journals, including Vehicle System Dynamics, Control Engineering Practice, Information Sciences, and Neurocomputing.



Qing-Long Han received the B.Sc. degree in mathematics from Shandong Normal University, Jinan, China, in 1983, and the M.Sc. and Ph.D. degrees in control engineering from the East China University of Science and Technology, Shanghai, China, in 1992 and 1997, respectively.

He is Pro Vice-Chancellor (Research Quality) and a Distinguished Professor with the Swinburne University of Technology, Melbourne, VIC, Australia. He held various academic and management positions with Griffith University, Nathan QLD, Australia, and Central Queensland University, Melbourne VIC, Australia. His research interests include networked control systems, multiagent systems, time delay systems, smart grids, unmanned surface vehicles, and neural networks.

Professor Han was the recipient of the 2024 IEEE Dr.-Ing. Eugene Mittelmann Achievement Award, the 2024 Chinese Association of Automation Science and Technology Achievement Award, the 2021 Norbert Wiener Award, the 2021 M. A. Sargent Medal, the IEEE Systems, Man, and Cybernetics Society Andrew P. Sage Best Transactions Paper Award in 2019, 2020, and 2022, the IEEE/CAA Journal of Automatica Sinica Norbert Wiener Review Award in 2020, and the IEEE Transactions on Industrial Informatics Outstanding Paper Award in 2020. He is a Member of the Academia Europaea and a Fellow of the International Federation of Automatic Control, the Asian Control Association, and the Chinese Association of Automation. He is also an Honorary Fellow of the Institution of Engineers Australia and a Clarivate Highly Cited Researcher in both Engineering and Computer Science. He was an AdCom Member of IEEE Industrial Electronics Society (IES), a Member of the IEEE IES Fellows Committee and Publications Committee, Chair of the IEEE IES Technical Committee on Network-Based Control Systems and Applications, and Co-Editor-in-Chief of IEEE Transactions on Industrial Informatics. He is currently President-Elect, an Executive Board Member, and a Steering Committee Member of the Asian Control Association, Vice-President of the Chinese Association of Automation, Editor-in-Chief of IEEE/CAA Journal of Automatica Sinica, and Co-Editor of Australian Journal of Electrical and Electronic Engineering.