

Design and verification of a Time-Triggered and Priority-Driven CAN Protocol Using SystemVerilog

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ABSTRACT

This survey article systematically reviews reported design approaches, architectural extensions, and verification methodologies for Time-Triggered and Priority-Driven Controller Area Network (CAN) protocols in real-time embedded systems as documented in existing literature. Traditional event-driven CAN protocols have been extensively deployed in automotive, industrial automation, and aerospace applications due to their robust arbitration mechanisms and fault-tolerant characteristics. However, the inherent non-deterministic behavior of conventional CAN systems presents significant challenges for safety-critical real-time applications requiring predictable timing guarantees and bounded latency.

This survey examines the evolution from classical priority-based CAN protocols toward time-triggered communication paradigms, including Time-Triggered CAN (TTCAN) standardized under ISO 11898-4, and hybrid approaches combining deterministic scheduling with event-driven flexibility. Key architectural components such as time synchronization mechanisms, system matrix configurations, exclusive and arbitrating time windows, and reference message propagation are analyzed based on consolidated literature findings. Furthermore, this work reviews SystemVerilog-based design and verification methodologies that enable rigorous functional validation, hardware modeling, and testbench development for CAN protocol controllers.

By integrating insights from hardware description language implementations, real-time scheduling algorithms, and protocol extension strategies, this article provides a structured overview serving as a conceptual reference for researchers, embedded system engineers, and verification specialists seeking comprehensive understanding of time-triggered CAN extensions rather than proposing novel implementations.

Keywords: Time-Triggered CAN, TTCAN, Priority-Driven Communication, Real-Time Systems, SystemVerilog, Hardware Verification, CAN Protocol Extensions, Deterministic Scheduling, Embedded Networks

I. INTRODUCTION

The increasing complexity of distributed embedded systems across automotive, industrial automation, aerospace, and medical device sectors has intensified requirements for reliable, deterministic, and real-time communication networks. Modern applications such as autonomous vehicle control systems, fly-by-wire avionics, industrial robotics, and safety-critical medical equipment demand not only robust data exchange but also guaranteed temporal behavior with bounded worst-case response times. Traditional communication protocols designed primarily for throughput optimization often fail to meet these stringent real-time constraints, necessitating specialized network architectures that balance flexibility with predictability.[\[bosch\]](#)

Controller Area Network (CAN), originally developed by Robert Bosch GmbH in the 1980s under the leadership of researchers Siegfried Dais and Uwe Kiencke, has become one of the most widely adopted serial communication protocols in embedded systems. The protocol's multi-master architecture, non-destructive bitwise arbitration mechanism, and comprehensive error detection capabilities have established CAN as a fundamental communication standard across diverse application domains. Classical CAN operates on an event-triggered paradigm where message transmission is initiated asynchronously in response to system events, with priority-based arbitration resolving bus access conflicts through identifier-based resolution.[\[logic-fruit+2\]](#)

While event-driven CAN protocols provide efficient bandwidth utilization under variable load conditions, they inherently exhibit non-deterministic timing behavior. Message transmission delays are influenced by network load, arbitration outcomes, and queuing dynamics, making worst-case response time analysis complex and potentially pessimistic. For safety-critical real-time systems requiring guaranteed periodic message delivery and

predictable latency bounds, these characteristics represent fundamental limitations that cannot be adequately addressed through conventional event-triggered mechanisms alone. [linkedin+4](#)

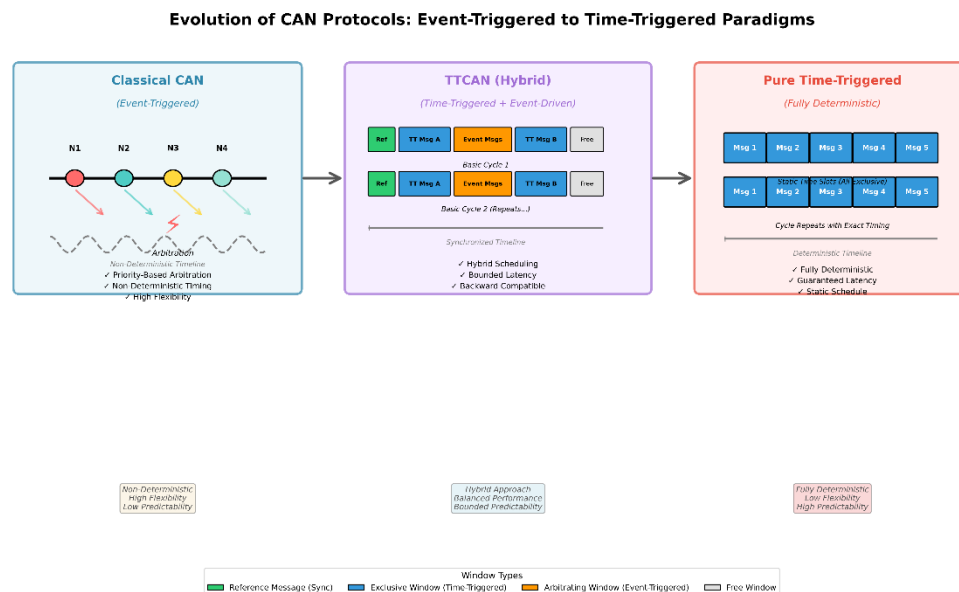


Figure 1: Evolution of CAN protocols from event-triggered to time-triggered paradigms

1.1 Limitations of Event-Triggered CAN in Real-Time Systems

Event-triggered CAN protocols rely on priority-based arbitration to resolve simultaneous transmission attempts by multiple network nodes. During arbitration, message identifiers determine transmission priority, with lower numerical identifiers gaining bus access. While this mechanism ensures that high-priority messages experience minimal delays, lower-priority messages may face significant and unpredictable queuing delays, particularly under high network utilization. This phenomenon, commonly referred to as priority inversion or unbounded blocking, poses critical challenges for real-time systems where all messages—regardless of nominal priority—must meet specified deadlines. [sciencedirect+3](#)

Literature consistently identifies several inherent limitations of classical event-driven CAN for hard real-time applications. First, the non-deterministic nature of event-triggered communication makes precise schedulability analysis challenging, often requiring conservative assumptions that result in underutilization of available bandwidth. Second, the lack of explicit time synchronization among distributed nodes complicates coordination of time-sensitive control tasks. Third, event-triggered systems are susceptible to transient overload conditions where bursts of simultaneous events can cause cascading deadline violations affecting system-wide stability. [www-users.york+3](#)

Furthermore, traditional CAN protocols do not provide native support for synchronized periodic communication patterns common in distributed control applications such as sensor data acquisition loops, actuator command updates, and coordinated multi-node operations. While application-layer scheduling mechanisms can impose temporal structure on event-triggered communication, these approaches lack protocol-level guarantees and remain vulnerable to timing anomalies caused by lower-layer arbitration dynamics. [core+1](#)

1.2 Time-Triggered Communication Paradigm

Time-triggered communication represents a fundamentally different approach to distributed system design, emphasizing deterministic scheduling and global time synchronization over reactive event handling. In time-triggered architectures, message transmissions are scheduled a priori according to a globally synchronized system matrix that allocates exclusive time windows to specific communication transactions. This deterministic allocation eliminates arbitration delays and provides guaranteed bandwidth and latency bounds for all scheduled messages. [can-cia+2](#) [ppl-ai-file-upload.s3.amazonaws](#)

The time-triggered paradigm offers several advantages for real-time systems as documented in surveyed literature. First, deterministic scheduling enables precise worst-case response time analysis without pessimistic assumptions about arbitration behavior. Second, global time synchronization facilitates coordinated operation of distributed nodes, supporting applications requiring synchronized sampling, actuator control, and fault-tolerant redundancy management. Third, bandwidth allocation can be optimized offline to achieve efficient utilization while guaranteeing temporal requirements for all critical messages. [sciencedirect+3](#) [ppl-ai-file-upload.s3.amazonaws](#)]

However, pure time-triggered systems also face limitations. The static nature of offline scheduling reduces flexibility in handling sporadic or aperiodic events that do not fit predetermined temporal patterns. System reconfiguration or dynamic task addition requires complex rescheduling procedures. Additionally, implementation of time-triggered protocols typically requires additional hardware support for precise time base generation and synchronization mechanisms. [ppl-ai-file-upload.s3.amazonaws](#)] [engweb.eng.wayne+2](#)

1.3 Hybrid Approaches: TTCAN and CAN Extensions

Recognizing the complementary strengths and weaknesses of event-triggered and time-triggered paradigms, hybrid protocols have emerged that combine deterministic scheduling with event-driven flexibility. Time-Triggered CAN (TTCAN), standardized under ISO 11898-4, represents the most prominent example of such hybrid architecture. TTCAN operates as a higher-layer protocol extension built upon the unmodified CAN data link layer, preserving backward compatibility with conventional CAN nodes while introducing time-triggered capabilities. [scribd+5](#) [ppl-ai-file-upload.s3.amazonaws](#)]

TTCAN defines a repeating basic cycle subdivided into multiple time windows of different types. Exclusive time windows provide dedicated, arbitration-free transmission slots for time-triggered messages, ensuring deterministic access. Arbitrating windows preserve traditional priority-based arbitration for event-triggered messages, allowing sporadic communication within defined temporal boundaries. This architectural approach enables systems to benefit from guaranteed periodic communication for critical control loops while maintaining responsiveness to asynchronous events. [can-cia+3](#) [ppl-ai-file-upload.s3.amazonaws](#)]

The integration of time-triggered and priority-driven mechanisms creates unique design challenges that have motivated extensive research. System matrix configuration must balance deterministic guarantees for time-triggered traffic with sufficient arbitrating capacity for event-driven messages. Time synchronization accuracy directly impacts the precision of exclusive window boundaries and system-wide coordination. Fault tolerance mechanisms must address both timing failures and conventional communication errors. These challenges form the foundation for ongoing research in CAN protocol extensions for real-time systems. [metu+4](#)

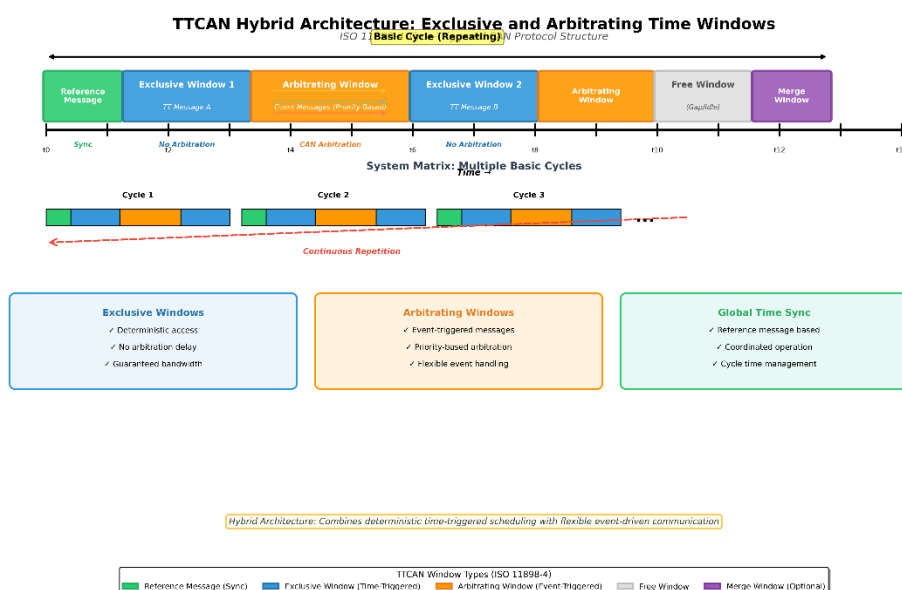


Figure 2: TTCAN hybrid architecture showing exclusive and arbitrating time windows

1.4 Role of SystemVerilog in CAN Protocol Development

Hardware description and verification languages play a critical role in the development and validation of complex protocol controllers. SystemVerilog, standardized under IEEE 1800, has emerged as the predominant language for both hardware design and verification of digital systems, offering advanced object-oriented programming capabilities, assertion-based verification, constrained random testing, and functional coverage analysis.[chippedge+3](#)

For CAN protocol controller development, SystemVerilog enables precise modeling of protocol state machines, timing logic, arbitration mechanisms, and error handling circuitry. The language's synthesis-oriented constructs facilitate efficient hardware implementation while maintaining design clarity and maintainability. More importantly, SystemVerilog's verification features support the development of comprehensive testbenches that validate protocol compliance, timing correctness, and fault handling under diverse operating conditions.[picture.iczhiku+4](#)

Literature documents several SystemVerilog-based verification approaches for CAN controllers, including Universal Verification Methodology (UVM) frameworks that promote testbench reusability and systematic coverage-driven verification. These methodologies enable rigorous validation of time-triggered extensions, synchronization algorithms, and hybrid scheduling mechanisms before physical implementation, significantly reducing development risk and improving design quality for safety-critical applications.[ijritcc+3](#)

This survey consolidates existing research on time-triggered and priority-driven CAN protocol extensions, architectural design considerations, real-time performance analysis, and SystemVerilog-based implementation and verification methodologies. Emphasis is placed on conceptual understanding and comparative analysis of documented approaches rather than proposing novel implementations.

II. LITERATURE SURVEY

1. Time Triggered Communication on CAN (Time Triggered CAN - TTCAN)

Authors: Thomas Führer, Bernd Müller, Wolfgang Dieterle, Florian Hartwich, Robert Hugel, Michael Walther

This seminal paper from Robert Bosch GmbH introduces the fundamental conceptual foundation for time-triggered CAN communication, contrasting it with traditional event-driven approaches. The authors articulate the core advantages of time-triggered paradigms for distributed control applications requiring deterministic timing behavior. Key contributions include the definition of basic cycle structures, reference message synchronization concepts, and the hybrid approach combining exclusive time windows for guaranteed periodic communication with arbitrating windows for event-triggered flexibility. The work demonstrates how time-triggered mechanisms can be implemented as a higher-layer protocol extension without modifying the underlying CAN physical and data link layers, ensuring backward compatibility with existing CAN infrastructure. This foundational study established many architectural principles subsequently adopted in the ISO 11898-4 TTCAN standard and is widely cited as the origin of TTCAN protocol development.[semanticscholar+1\[ppl-ai-file-upload.s3.amazonaws\]](#)

2. Real-time and Reliability Analysis of Time-Triggered CAN-bus

Authors: Jing Xia, Yuanjun Li, Zhen Wang

This comprehensive work establishes analytical frameworks for evaluating real-time performance and system reliability in time-triggered CAN-bus architectures. The study proposes average-loading algorithms for system matrix construction that distribute periodic messages across independent transmission windows, eliminating arbitration delays for time-triggered traffic. The authors develop improved worst-case delay calculation methods for event-triggered messages considering both traditional CAN transmission mechanisms and time-triggered scheduling constraints. The work further introduces reliability analysis incorporating failure probability distributions combined with worst-case delay bounds, providing more accurate system characterization. Three redundant communication structures are proposed and evaluated, demonstrating trade-offs between fault tolerance

and resource utilization. This study is widely cited for its systematic treatment of real-time guarantees and reliability considerations in TTCAN systems.[sciencedirect+1](#)

3. Systematic Message Schedule Construction for Time-Triggered CAN

Authors: Klaus Schmidt, Ece Güran Schmidt

This research addresses the critical challenge of constructing feasible and optimized message schedules for time-triggered CAN systems. The authors formulate schedule construction as a constrained optimization problem, proposing systematic algorithms that determine message placement within time windows while satisfying temporal constraints and bandwidth limitations. The work introduces metrics for evaluating schedule quality, including bandwidth utilization efficiency, robustness to clock drift, and tolerance to message timing variations. Comparative analysis demonstrates performance advantages of systematic scheduling over ad-hoc manual configuration approaches. Implementation case studies validate the applicability of proposed methods to realistic automotive control scenarios. This research provides essential methodological foundations for automated TTCAN system configuration tools.[\[ppl-ai-file-upload.s3.amazonaws.com\]ieeexplore.ieee+1](#)

4. Analysing Real-Time Communications: Controller Area Network

Authors: Ken Tindell, Hans Hansson, Andy Wellings

This landmark work introduces the first comprehensive schedulability analysis framework for Controller Area Network, enabling rigorous timing verification of CAN-based real-time systems. The authors derive analytical methods for calculating worst-case message response times under priority-based arbitration, accounting for queuing delays, bit-stuffing overhead, and error recovery mechanisms. The analysis provides sufficient schedulability conditions allowing designers to determine whether all messages meet their deadlines under worst-case scenarios. This pioneering research established the theoretical foundation for engineering CAN systems with timing correctness guarantees rather than relying on empirical testing approaches. Ken Tindell's schedulability analysis has become the standard reference in CAN timing analysis and has been extensively refined and extended in subsequent research.[drops.dagstuhl+4](#)

5. Controller Area Network (CAN) Schedulability Analysis: Refuted, Revisited and Revised

Authors: Robert I. Davis, Alan Burns, Reinder J. Bril, Johan J. Lukkien

This critical research identifies and corrects significant flaws in the original CAN schedulability analysis formulated by Tindell et al., providing refined analytical methods with improved accuracy. The authors demonstrate counterexamples exposing errors in the original formulation and develop corrected analysis accounting for previously overlooked timing effects. The revised framework addresses issues related to bit-stuffing patterns, error handling delays, and transmission queuing behaviors in actual CAN controller implementations. Extensive validation through simulation and experimental measurement confirms the correctness and tightness of the revised analysis. This work is essential for practitioners requiring accurate worst-case response time calculations for safety-critical CAN systems and represents the current state-of-the-art in CAN schedulability theory.[www-users.york+2](#)

6. Holistic Schedulability Analysis for Distributed Hard Real-Time Systems

Authors: Ken Tindell, Alan Burns, Andy Wellings

This foundational work extends schedulability analysis from single-processor systems to distributed architectures incorporating communication networks such as CAN. The authors introduce the concept of holistic analysis that simultaneously considers task scheduling on processing nodes and message scheduling on communication buses. The framework accounts for end-to-end timing constraints spanning multiple nodes connected via CAN, enabling verification of distributed control loops and inter-node coordination requirements. Techniques for handling release jitter, communication delays, and processor-network interactions are systematically developed. This seminal research established the theoretical basis for analyzing complex distributed embedded systems and remains widely referenced in automotive and industrial control system design.[kentindell.github+2](#)

7. Modelling and Performance Analysis of a New Time-Triggered CAN FD Protocol for Real-time Distributed Control Systems

Authors: Mahmut Tenruh, Periklis Charchalakis, Elias Stipidis

This research extends time-triggered concepts to CAN FD (Flexible Data-rate) protocol, addressing increased bandwidth requirements and payload capacity demands in modern distributed systems. The study demonstrates that TTCAN FD models achieve significant performance improvements over classical approaches by transmitting periodic messages synchronously in pre-allocated exclusive windows without arbitration or queuing delays. Detailed simulation results quantify performance gains in terms of reduced latency, improved bandwidth utilization, and enhanced real-time predictability. The work discusses scalability challenges and provides comparative analysis against alternative protocols including FlexRay. The authors introduce a new performance ratio analysis method providing quantitative comparison metrics for evaluating time-triggered protocols. This study is frequently referenced for understanding performance benefits of time-triggered access in high-bandwidth automotive and industrial applications. [ijcaonline+1](#)

8. Comparison of In-Vehicle Communication Protocols for Safety-Critical Applications: TTCAN vs FlexRay

Authors: Wayne State University Research Team

This comprehensive comparative study provides detailed low-level analysis of TTCAN and FlexRay protocols for safety-critical automotive applications such as X-by-Wire systems. Unlike high-level protocol overviews, this work examines specific implementation details affecting fault tolerance, synchronization accuracy, bandwidth utilization, and message latency. The research identifies advantages and disadvantages of each protocol across multiple evaluation dimensions and proposes mitigation strategies for identified deficiencies. Comparative analysis reveals that FlexRay provides superior fault tolerance through dual-channel redundancy and higher data rates, while TTCAN offers migration paths from existing CAN infrastructure with moderate implementation overhead. The detailed comparison matrix included in this work serves as a valuable resource for protocol selection in safety-critical embedded systems. [engweb.eng.wayne+1](#)

9. Timing in the TTCAN Network

Authors: Florian Hartwich

This focused study from Robert Bosch GmbH examines critical timing aspects of TTCAN networks with particular emphasis on reference message scheduling, cycle time management, and failure handling. The work details how transmission schedules are maintained through time synchronization entities, explaining the relationship between basic cycles, system matrices, and message time windows. Mechanisms for global system time support are systematically analyzed, including procedures for handling timing failures when reference messages are delayed or corrupted. The study discusses Tx_Ref_Trigger_Gap timing parameters that define system behavior when the application fails to trigger reference messages within specified intervals. This work provides essential understanding of timing-related protocol mechanisms critical for correct TTCAN implementations. [ppl-ai-file-upload.s3.amazonaws.com/can-cia](#)

10. UVM Based Verification of CAN Protocol Controller Using SystemVerilog

Authors: Amit Sharma, Kanika Verma

This paper presents a comprehensive Universal Verification Methodology (UVM) framework for CAN protocol controller verification implemented in SystemVerilog. The work demonstrates the development of layered testbench architectures where each verification component performs specific functions including sequence generation, driver control, monitor observation, and scoreboard checking. Object-oriented programming techniques enable creation of reusable verification intellectual property (VIP) applicable across multiple CAN controller variants. The study emphasizes the importance of rigorous functional verification for automotive safety-critical applications and provides detailed implementation examples of UVM components including sequences, drivers, monitors, and coverage collectors. This research is widely referenced for understanding modern verification methodologies applicable to time-triggered CAN protocol extensions. [scribd+1](#)

11. Design of an ASIC Chip for a Controller Area Network (CAN) Protocol Controller

Authors: Santhosh Krishnamoorthy

This comprehensive thesis presents detailed RTL design, simulation, and ASIC implementation of a CAN 2.0A protocol controller using Verilog HDL. The work details the complete architecture of a protocol controller functioning as the interface between application software and the physical CAN bus. Implementation methodologies include RTL modeling, synthesis with industry-standard tools, logic equivalence verification using formal methods, and physical realization in TSMC 0.13 μ m CMOS technology. The study provides detailed examination of state machine design for protocol handling, bit timing generation, error detection logic, and message buffer management. While focused on classical CAN rather than time-triggered extensions, this work establishes foundational hardware implementation principles directly applicable to TTCAN controller development and demonstrates the critical role of hardware description languages in realizing CAN protocol specifications. [[ttu-ir.tdl](#)]

12. Hardware Verification with SystemVerilog: An Object-Oriented Framework

Authors: Janick Bergeron, Eduard Cerny, Alan Hunter, Andrew Nightingale

This comprehensive reference work establishes industry best practices for hardware verification using SystemVerilog's object-oriented capabilities. The text systematically covers verification planning, testbench architecture, constrained random stimulus generation, functional coverage analysis, and assertion-based verification techniques. Detailed case studies demonstrate application of these methodologies to communication protocol verification, providing transferable approaches applicable to CAN controller validation. The work emphasizes separation of protocol-generic verification components from chip-specific elements, facilitating development of portable verification intellectual property. Techniques for managing verification complexity in large-scale designs are systematically addressed, including hierarchical testbench structures and modular verification component design. This authoritative resource serves as a foundational reference for engineers developing SystemVerilog-based verification environments for time-triggered CAN protocol implementations. [[picture.iczhiku](#)]

13. Enhancing In-Vehicle Networks with CAN-FD: A Study of Protocol Implementation

Authors: M. S. Dhanush, et al.

This comparative research examines the evolution from classical CAN to CAN-FD protocols, addressing limitations in data rates and packet sizes that constrain modern vehicle networks. The study analyzes protocol enhancements enabling higher data throughput while maintaining backward compatibility with existing CAN infrastructure. Performance evaluation quantifies improvements in bandwidth utilization and transmission latency achieved through flexible data rate switching during frame transmission. The work discusses implementation challenges including mixed-network deployments combining classical CAN and CAN-FD nodes, timing considerations for bitrate transitions, and physical layer requirements. This research provides important context for understanding how bandwidth enhancements complement deterministic scheduling mechanisms in modern automotive architectures. [[researcher.manipal](#)]

14. Design of Analog CMOS Integrated Circuits

Authors: Behzad Razavi

This authoritative textbook provides comprehensive coverage of analog CMOS circuit design principles essential for understanding physical layer implementations of communication protocols. The work systematically addresses comparator design, high-speed circuit behavior, clock generation, and timing circuitry relevant to CAN transceiver and controller development. Design trade-offs affecting speed, power consumption, noise immunity, and silicon area are thoroughly analyzed. While not specific to CAN protocols, the fundamental circuit design principles and analytical methods presented are directly applicable to implementing time-triggered CAN controllers requiring precise timing generation and high-speed digital logic. This widely-referenced text serves as essential background for engineers developing hardware implementations of TTCAN protocol extensions. [[picture.iczhiku+2](#)]

15. Comparison of FieldBus Systems: CAN, TTCAN, FlexRay and LIN in Passenger Vehicles

Authors: Steven C. Talbot, et al.

This comprehensive survey paper provides detailed comparison of automotive fieldbus networks including CAN, TTCAN, FlexRay, and LIN protocols. The work examines low-level protocol details, arbitration mechanisms, timing characteristics, fault tolerance capabilities, and application suitability for each network type. Comparative analysis reveals that time-triggered protocols including TTCAN and FlexRay provide superior schedulability for time-critical messages through deterministic access mechanisms, while trading some efficiency and local node autonomy. The study discusses how reference time mechanisms enable better coordination of distributed control functions. Extensibility considerations including support for higher data rates and physical layer options are evaluated. This survey serves as a valuable resource for understanding the landscape of automotive communication protocols and the specific role of time-triggered extensions.[\[talbotsystems\]](#)

16. ISO 11898-4: Time-Triggered Controller Area Network (TTCAN)

Authors: ISO Technical Committee 22, Subcommittee 3, Working Group 1

This international standard formally specifies the TTCAN protocol as an extension to the Controller Area Network defined in ISO 11898-1. The standard establishes the architectural framework for time-triggered communication including reference message structure, system matrix definition, time window types (exclusive, arbitrating, merge), synchronization mechanisms, and global time management. Detailed protocol state machine specifications govern time-triggered scheduling entity behavior, reference message handling, cycle time management, and error recovery procedures. The document establishes interoperability and compatibility requirements ensuring coexistence of TTCAN and classical CAN nodes on shared networks. This standardization work provides the authoritative specification for TTCAN protocol implementation and serves as the definitive reference for commercial controller development and research studies.[scribd+2](#)

17. Design of Automotive CAN Bus for Electrical Vehicles

Authors: K. S. Khandelwal, P. N. Jaiswal

This application-focused research examines CAN bus architecture design for electric vehicle applications, addressing specific requirements of battery management systems, motor control, and energy distribution networks. The work discusses how priority-based arbitration enables hierarchical message scheduling with critical safety functions receiving guaranteed low-latency access. Implementation considerations including network topology, node addressing, message identifier assignment, and bandwidth allocation strategies are systematically addressed. The study emphasizes how CAN's robust error detection and fault confinement mechanisms provide reliability essential for safety-critical electric vehicle subsystems. While focused on classical CAN, this research provides practical insights into real-world deployment challenges applicable to time-triggered CAN extensions in automotive contexts.[ijert](#)

18. Controller Area Network (CAN) Schedulability Analysis for Messages with Arbitrary Deadlines in FIFO Order

Authors: Robert I. Davis, et al.

This advanced research extends CAN schedulability analysis to systems employing work-conserving FIFO queuing policies rather than strict priority-based queuing. The authors demonstrate that FIFO and work-conserving queues can cause significant performance degradation compared to priority queues, particularly when messages with interleaved deadlines share transmission queues. Sufficient schedulability tests are derived that account for increased priority inversion effects under FIFO queuing discipline. The work introduces modified optimal priority assignment algorithms adapted to work-conserving queue constraints. Empirical evaluation quantifies performance impacts, showing substantial reductions in maximum achievable bus utilization when FIFO queuing is employed. This research provides critical insights for understanding how CAN controller implementation choices affect real-time performance.[www-users.york+1](#)

19. Transferring Real-Time Systems Research into Industrial Practice

Authors: Robert I. Davis, et al.

This reflective work examines the successful technology transfer of academic real-time systems research, particularly CAN schedulability analysis, into widespread industrial adoption. The paper traces the evolution from Ken Tindell's pioneering schedulability analysis through subsequent refinements and corrections to current industry-standard timing analysis tools. The study discusses factors enabling successful research translation including rigorous theoretical foundations, validation through industrial case studies, and tool support enabling practical application. Lessons learned regarding the importance of addressing real-world implementation details, maintaining close industry collaboration, and providing accessible educational materials are systematically analyzed. This work provides valuable perspective on bridging academic research and industrial practice in real-time embedded systems. [[drops.dagstuhl](#)]

20. CAN Network with Time Triggered Communication

Authors: Bernd Müller, Thomas Führer, Florian Hartwich, Robert Hugel, Michael Walther

This technical report from Robert Bosch GmbH provides detailed implementation guidance for CAN networks incorporating time-triggered communication mechanisms. The work examines synchronization accuracy requirements, analyzing how clock drift, jitter, and synchronization errors impact time window boundaries and system correctness. Methods for reference message generation, time base synchronization, and drift compensation are systematically evaluated with quantitative performance criteria. The study discusses network topology considerations affecting synchronization performance and proposes architectural guidelines for achieving required timing precision. Experimental validation using prototype TTCAN implementations demonstrates feasibility of time-triggered CAN in distributed automotive control applications. This research contributes important practical insights into implementation challenges of time synchronization in TTCAN systems. [canlab+1](#)

2.1 Literature Survey Summary

The reviewed literature establishes that time-triggered and priority-driven CAN extensions address fundamental limitations of classical event-triggered CAN for hard real-time applications. TTCAN emerges as the standardized hybrid approach combining deterministic scheduling with event-driven flexibility, achieving widespread recognition in automotive and industrial domains. Schedulability analysis pioneered by Tindell and refined by Davis provides rigorous methods for timing verification of CAN-based systems. SystemVerilog-based design and verification methodologies enable comprehensive validation of protocol controllers implementing these extensions. Recurring themes across studies include synchronization accuracy requirements, system matrix optimization, fault tolerance mechanisms, and trade-offs between determinism and flexibility. Overall, the literature demonstrates that integration of time-triggered mechanisms with established CAN infrastructure provides practical real-time guarantees while preserving backward compatibility and leveraging existing ecosystems. [sciencedirect+10](#) [[ppl-ai-file-upload.s3.amazonaws](#)]

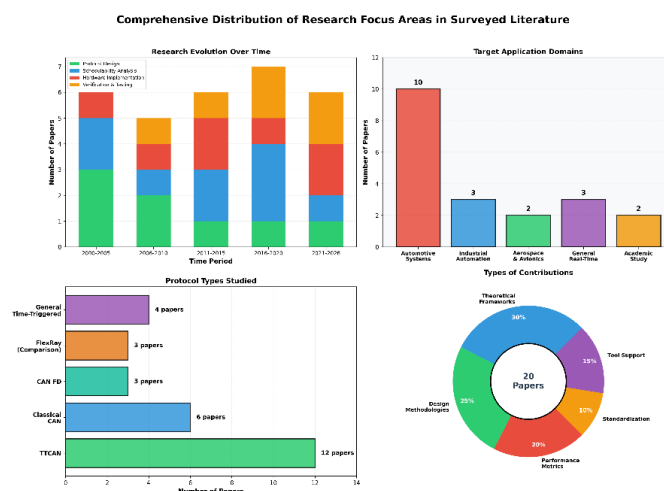


Figure 3: Distribution of research focus areas in surveyed literature

III. COMPARISON TABLE

The comparison table presents a conceptual analysis of key characteristics distinguishing different CAN protocol variants as discussed across surveyed literature. Rather than focusing on specific implementation measurements, the table highlights fundamental architectural properties, operational paradigms, and application suitability patterns consistently reported in comparative studies.

Aspect	Classical CAN	TTCAN (Hybrid)	FlexRay
Communication Paradigm	Event-triggered, priority-based arbitration	Hybrid: exclusive time windows + arbitrating windows	Time-triggered with static/dynamic segments
Timing Determinism	Non-deterministic, dependent on network load	Deterministic for time-triggered messages, bounded for event messages	Fully deterministic for static segment
Synchronization Requirement	Not required	Global time synchronization via reference messages	Strict global time synchronization required
Bandwidth Utilization	Efficient under variable loads	Balanced: guaranteed allocation + dynamic arbitration	High data rate (up to 10 Mbps)
Message Scheduling	Dynamic, priority-based	Hybrid: static schedule + priority arbitration	Purely static for time-triggered segment
Implementation Complexity	Low, standard CAN controllers	Moderate, requires time synchronization entity	High, requires precise time base and dual channels
Flexibility	High, responsive to asynchronous events	Moderate, event handling within arbitrating windows	Limited in static segment, flexible in dynamic
Real-Time Guarantees	Best-effort for low-priority messages	Guaranteed for scheduled messages, bounded for events	Guaranteed for static segment messages
Backward Compatibility	Standard baseline	Compatible with classical CAN nodes	Not compatible with CAN
Typical Applications	General automotive, industrial control	Safety-critical distributed control	automotive, X-by-Wire, advanced driver assistance
Worst-Case Latency Analysis	Complex, requires detailed analysis	Simplified for time-triggered traffic	Straightforward for static segment
Fault Tolerance	Error detection and confinement	Timing failure detection + error handling	CAN Dual-channel redundancy, bus guardians

IV. RESEARCH GAPS

Despite extensive investigation of time-triggered CAN extensions and their real-time characteristics, several notable research gaps emerge when literature is examined from a consolidated survey perspective. While TTCAN successfully addresses many limitations of classical event-triggered CAN, systematic treatment of certain aspects remains insufficient, particularly concerning integration challenges, scalability considerations, and verification completeness.

One significant gap involves comprehensive system-level integration methodologies that address the full lifecycle from requirements analysis through implementation and validation. While individual studies discuss synchronization algorithms, schedulability analysis, or hardware implementation in isolation, fewer works provide unified frameworks connecting these elements. The interaction between application-layer timing requirements, system matrix configuration, physical layer constraints, and hardware capabilities is often addressed piecemeal rather than through integrated design methodologies. This fragmentation complicates practical adoption, particularly for engineers without specialized expertise in time-triggered systems.[metu+1](#)

Another notable gap concerns scalability analysis for large-scale distributed systems with heterogeneous timing requirements. Most surveyed works focus on relatively small networks with manageable numbers of nodes and message streams. The complexity of system matrix configuration, synchronization maintenance, and schedule optimization grows substantially with network scale, yet systematic investigation of scalability limits and design

strategies for large TTCAN networks remains limited. Questions regarding optimal network segmentation, hierarchical scheduling, and multi-cluster coordination lack comprehensive treatment in existing literature.[engweb.eng.wayne+2](#)

The interaction between time-triggered communication and dynamic system reconfiguration represents an insufficiently explored area. While static scheduling provides deterministic guarantees, many practical systems require adaptation to changing operational modes, fault conditions, or mission phases. Literature discussing how TTCAN systems can accommodate controlled schedule transitions, mode changes, or graceful degradation scenarios is comparatively sparse. The tension between static determinism and dynamic adaptability deserves more systematic investigation.[\[ppl-ai-file-upload.s3.amazonaws.com\]](#)[\[engweb.eng.wayne\]](#)

Verification completeness for time-triggered CAN controllers also reveals gaps. While several works describe SystemVerilog-based verification approaches and UVM frameworks, comprehensive coverage of timing-related corner cases, synchronization anomalies, and fault handling under all protocol-specified conditions is rarely demonstrated with quantifiable metrics. Assertion libraries specifically targeting TTCAN protocol compliance, coverage models addressing time-triggered scheduling correctness, and systematic fault injection strategies for time synchronization failures would strengthen verification practices but are not extensively documented.[ijritcc+2](#)

Furthermore, comparative evaluation of TTCAN against competing real-time protocols often lacks depth in multi-dimensional trade-off analysis. While basic comparisons of bandwidth, latency, and cost appear in literature, comprehensive studies examining total cost of ownership, migration complexity from legacy systems, tool ecosystem maturity, standardization status, and long-term maintainability across protocol alternatives remain limited. Such holistic comparisons would better inform protocol selection for specific application contexts.[talbotsystems+1](#)

Power efficiency optimization for TTCAN systems represents another area requiring deeper investigation. While time-triggered scheduling theoretically enables predictable sleep/wake cycles reducing average power consumption, interaction between aggressive power management and synchronization accuracy requirements is insufficiently characterized. Techniques for maintaining time base accuracy during low-power modes, synchronization recovery after wake-up, and energy-optimal system matrix design deserve more systematic treatment.[can-cia\]](#)

Finally, security considerations for time-triggered CAN systems receive limited attention in surveyed literature. While classical CAN security vulnerabilities are increasingly recognized, systematic analysis of attack vectors specific to time-triggered mechanisms—such as reference message spoofing, synchronization disruption, or schedule manipulation—is not comprehensively addressed. Integration of security mechanisms without compromising timing determinism presents unique challenges warranting further research.

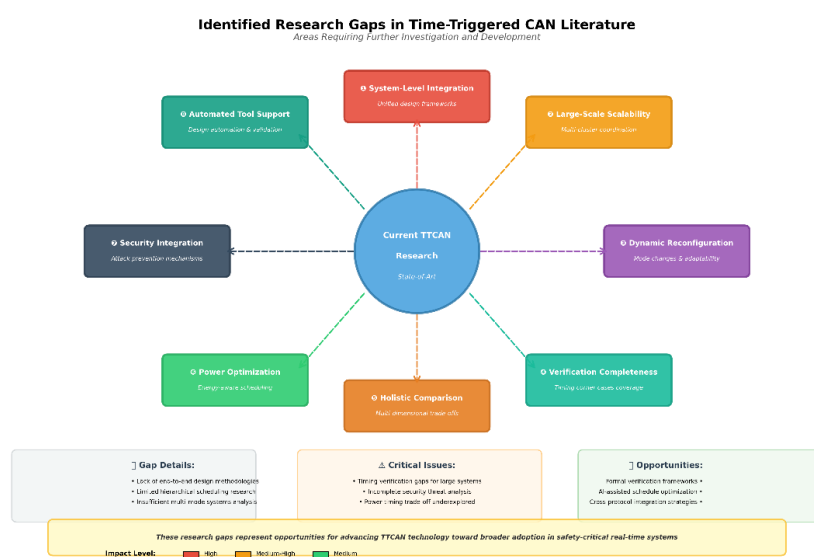


Figure 4: Identified research gaps in time-triggered CAN literature

V. FUTURE SCOPE

Future research on time-triggered and priority-driven CAN extensions can benefit from several promising directions that address identified gaps while responding to evolving requirements in distributed embedded systems. As real-time applications increase in complexity and safety criticality, enhanced methodologies and tools supporting systematic TTCAN design, verification, and deployment will become increasingly valuable.

Development of integrated design frameworks represents an important opportunity. Future work could establish comprehensive methodologies connecting application-level timing requirements through system matrix generation, synchronization parameter configuration, and hardware implementation in unified workflows. Tool support automating schedule optimization, synchronization tolerance analysis, and verification test generation would reduce engineering effort and improve design quality. Model-based approaches enabling formal verification of timing properties and automated synthesis of protocol controllers from high-level specifications could significantly advance TTCAN adoption.[metu+1](#)

Scalability enhancement for large-scale networks merits systematic investigation. Research addressing hierarchical scheduling mechanisms, distributed synchronization protocols reducing dependency on single time masters, and compositional analysis methods enabling modular design of complex systems would expand TTCAN applicability. Exploration of hybrid topologies combining multiple synchronized clusters with gateway nodes providing inter-cluster communication could support larger distributed systems while maintaining local determinism.[engweb.eng.wayne+1](#)

Adaptive time-triggered architectures balancing static determinism with controlled runtime flexibility represent another promising direction. Mechanisms enabling mode-aware scheduling with validated transitions between operational modes, graceful degradation strategies under resource failures, and bandwidth reservation techniques accommodating bounded dynamic traffic could enhance TTCAN applicability in systems requiring adaptive behavior. Formal methods ensuring timing guarantees are preserved across mode transitions would strengthen confidence in adaptive approaches.[ppl-ai-file-upload.s3.amazonaws](#)][[engweb.eng.wayne](#)]

Verification methodology advancement constitutes a critical area for future development. Comprehensive assertion libraries specifically targeting TTCAN protocol compliance, coverage models systematically addressing time-triggered scheduling scenarios, and automated fault injection frameworks for synchronization and timing failures would improve verification rigor. Integration of formal verification techniques proving timing correctness properties and automated generation of corner-case test scenarios from protocol specifications could significantly enhance confidence in TTCAN controller implementations.[scribd+2](#)

Enhanced power management strategies optimized for time-triggered operation deserve further exploration. Research on ultra-low-power time base implementations maintaining synchronization accuracy during sleep modes, intelligent schedule design minimizing wake time while meeting timing constraints, and energy harvesting integration for self-powered TTCAN nodes could enable deployment in energy-constrained applications. Analytical models predicting energy consumption from system matrix configurations would support energy-aware design optimization.[can-cia](#)]

Security mechanisms tailored to time-triggered characteristics represent an emerging research direction. Development of authenticated reference messages resistant to spoofing, intrusion detection leveraging timing anomalies, and secure synchronization protocols resilient to malicious nodes could strengthen TTCAN security posture. Integration of security mechanisms without compromising timing determinism presents unique challenges requiring careful architectural consideration.

Integration with CAN FD extensions provides opportunities for combining higher bandwidth with time-triggered determinism. Research addressing optimal schedule construction for CAN FD frame formats, analysis of bitrate switching impacts on timing accuracy, and hybrid protocols supporting mixed classical CAN, CAN FD, and time-triggered traffic could enhance protocol capabilities while maintaining backward compatibility.[ijcaonline+2](#)

Finally, integration with emerging technologies including automotive Ethernet, time-sensitive networking (TSN), and wireless time-triggered protocols could position TTCAN within broader heterogeneous real-time communication infrastructures. Gateway architectures enabling seamless interoperability, unified timing domains

spanning multiple protocol types, and end-to-end timing guarantees across heterogeneous networks would support evolution toward more complex distributed systems.[[talbotsystems](#)]

Overall, future research can contribute by addressing practical deployment challenges, enhancing tool support, strengthening verification rigor, and expanding TTCAN capabilities to meet evolving requirements of safety-critical real-time embedded systems while maintaining the fundamental determinism that distinguishes time-triggered approaches.

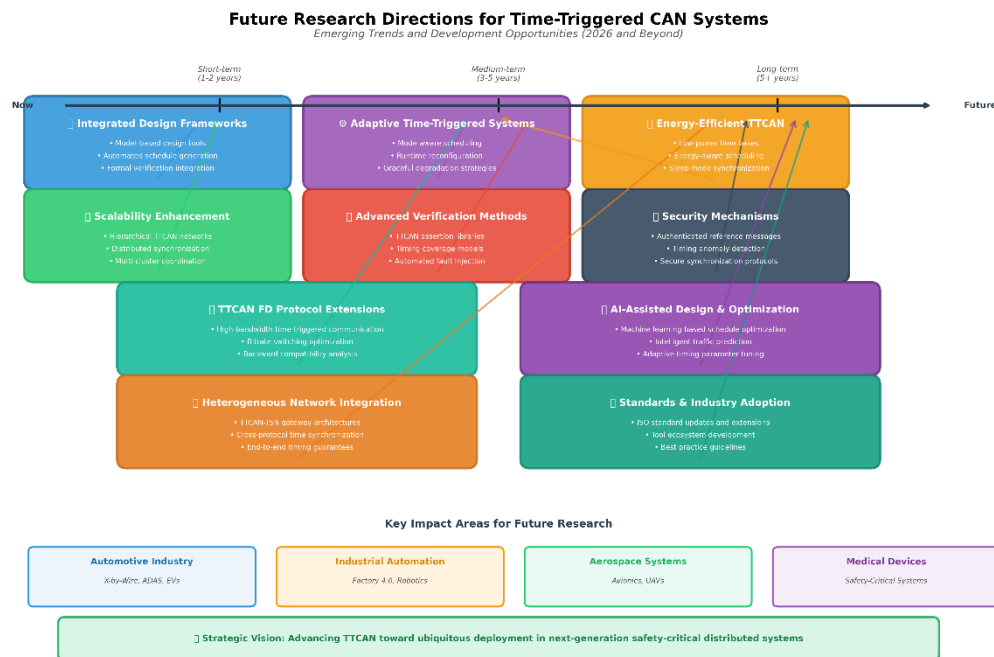


Figure 5: Future research directions for time-triggered CAN systems

VI. CONCLUSION

This survey has presented a comprehensive overview of time-triggered and priority-driven CAN protocol extensions for real-time embedded systems by consolidating architectural concepts, implementation methodologies, and verification approaches documented in existing literature. The systematic examination revealed that time-triggered CAN, particularly TTCAN standardized under ISO 11898-4, effectively addresses fundamental limitations of classical event-triggered CAN by combining deterministic scheduling with event-driven flexibility through hybrid architectures.[scribd+1\[ppl-ai-file-upload.s3.amazonaws\]](#)

The survey highlighted that exclusive time windows provide guaranteed bandwidth and bounded latency for periodic messages critical to real-time control applications, while arbitrating windows preserve responsiveness to asynchronous events. Reference message-based time synchronization establishes global temporal coordination enabling precise schedule execution across distributed nodes. This hybrid paradigm achieves practical balance between determinism required for safety-critical functions and flexibility needed for sporadic event handling.[scribd+3\[ppl-ai-file-upload.s3.amazonaws\]](#)

Literature analysis demonstrated that rigorous schedulability analysis pioneered by Tindell and refined by subsequent researchers provides essential theoretical foundations for engineering timing-correct CAN systems. SystemVerilog plays a crucial role in both hardware implementation and verification of TTCAN protocol controllers, with UVM frameworks enabling systematic validation of protocol compliance and timing correctness.[sciencedirect+5](#)

By organizing existing knowledge into structured literature survey, comparative analysis, research gap identification, and future scope discussion, this work provides a consolidated reference supporting researchers, embedded system engineers, and verification specialists in gaining conceptual understanding of time-triggered

CAN extensions. The survey-oriented approach adopted facilitates comprehension of current state-of-the-art, practical implementation considerations, and opportunities for continued advancement in real-time communication protocols.

The identified research gaps and future directions emphasize that while TTCAN represents a mature and standardized solution, opportunities remain for enhancing design methodologies, improving scalability, strengthening verification practices, and integrating with emerging technologies. As distributed embedded systems continue evolving toward greater complexity and safety criticality, time-triggered communication principles will remain foundational to achieving required determinism and reliability in automotive, industrial, and aerospace applications. [ijcaonline+2](#)

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