OPTIMIZING WIRELESS INTER-PROCESSOR COMMUNICATION FOR LOW-LATENCY MULTI-SENSOR FUSION IN VEHICULAR SAFETY APPLICATIONS

Mr. G.P. Gawali
Research Scholar, P.G. Dept. of Computer Science, Sant Gadge Baba Amravati University, Amravati, India
gg020988@gmail.com

Dr.V. M. Patil
Research Guide, P.G. Dept. of Computer Science, Sant Gadge Baba Amravati University, Amravati, India
vinmpatil21@yahoo.co.in

Abstract
Real-time vehicular safety systems that use low-latency inter-processor communication (IPC) via wireless are essentially powered by multi-sensor fusion. Heterogeneous-processor distributed architectures are being deployed widely and rely as much as on wireless IPC to correspond to any reaction time. This paper also discusses the optimization techniques of wireless IPC on vehicle safety, discusses the protocols including Wi-Fi, Bluetooth, UWB, and 5G-V2X, and also the data management schemes. We call attention to the difficulties of maintaining synchronization and effective data exchange between processors in cars, the local ones, and cloud computing facilities. Adaptive modulation, intelligent channel access, and event- driven messaging approaches are some strategies suggested to make secure, pre-emptive interventions in connected and autonomous vehicles reliable.

Keywords: *Wireless Inter-Processor Communication (WIPC), Multi-Sensor Fusion, Vehicular Safety, Real-time Sys- tems, Sensor Networks, Ultra-Wideband (UWB).*

I. Introduction

The rapid evolution of intelligent transportation systems and the rise of autonomous vehicles have placed unprecedented emphasis on road safety. At the core of this transformation is the ability to pre-emptively detect human-factor risks such as driver drowsiness, distraction, and impairment [1]. Achieving this requires advanced cross-sensor perception, where diverse modalities—visual inputs from cameras, physiological data (e.g., EEG, ECG), and environmental signals (e.g., alcohol sensors, radar)—are intelligently integrated to build a holistic picture of both the driver's state and surrounding conditions [2].

While these systems enhance safety, their design often introduces a critical challenge: inter-processor communication (IPC) latency. Wired IPC inside a single Electronic Control Unit (ECU) has been optimized for years. However, modern safety architectures increasingly depend on distributed modules, external sen- sors, and even vehicle-to-vehicle or vehicle-to-infrastructure exchanges, which frequently require wireless links. The growing reliance on wireless IPC amplifies concerns about real-time reliability.

Current vehicular safety frameworks often adopt mixed architectures: inertial measurement units (IMUs) and basic sensors feed microcontrollers, while advanced single-board computers (SBCs) or embedded GPUs handle computationally heavy AI algorithms for data fusion and decision-making [3].

In such cases, low-latency wireless communication becomes indispensable. Any slowdown across these links risks converting a pre-emptive alert into a delayed response—or worse, missing an intervention entirely.

This paper examines strategies to optimize wireless IPC specifically for multi-sensor fusion in vehicular safety. We evaluate communication protocols suited for mobile embedded automotive systems, identify conditions that trigger latency in wireless transmissions, and propose architectural as well as algorithmic methods to mitigate delays. By emphasizing physical and data link layer considerations, we argue that robust wireless IPC is not simply an advantage but a necessity for the next generation of connected and autonomous vehicles.

The contributions of this paper are threefold: (i) A structured analysis of Wireless Inter-Processor Communication latency bottlenecks in vehicular safety systems. (ii) A comparision review of wireless and wired IPC considerations in multi-sensor fusion architectures. (iii) A set of theoretically levelled optimization strategies tailored to dynamic vehicular environments, emphasizing real-time responsiveness.

II. Multi-Sensor Fusion in Vehicular Safety

Multi-sensor fusion stands as a fundamental paradigm in modern vehicular safety systems, driven by the inherent limitations that plague single-sensor approaches. It's simply impossible for any lone sensor to provide a complete or unambiguous understanding of complex driving scenarios or the nuanced states of a driver [4]. For example, while the camera sensor might detect signs of drowsiness and its effectiveness can be severely inhibited by poor lighting or physical obstructions. Similarly, a physiological sensor, though precise, often comes with the drawback of being intrusive. By intelligently combining data from the multiple, complementary sensors and a system can achieve far greater accuracy, robustness, and overall reliability, effectively cutting down on frustrating false positives and dangerous false negatives [5]. In the specific context of driver safety, multi-sensor fusion involves bringing together inputs from a variety of sources: Visual Sensors: Cameras are indispensable here, used for tasks like facial landmark detection (from which we derive metrics such as Eye Aspect Ratio, EAR, and Mouth Aspect Ratio, MAR), head pose estimation, and even gaze tracking [6]. These provide direct behavioral cues. Chemical or environmental sensors: These types of sensors include, among others, the MQ-3 alcohol sensor that can be used in the analysis of the breath sample [7] or CO2 sensors to monitor the cabin air atmosphere. Sensors like these will provide information about the direct surroundings of the driver and any impairments. Biometric Sensors: Biometric sensing technologies involving the use of fingerprint scanners or advanced facial recognition technology would be very helpful in driver verification and ID authentication [8] [18], where only approved drivers can take control and operate the wheel. Vehicle Telemetry: In this method information is tapped into the internal network of the vehicle, usually the Controller Area Network (CAN) bus. Information like steering wheel angle, current vehicle speed, and braking patterns can provide subtle, indirect cues about driver behavior and vehicle control [9]. The process of fusion itself can happen at different levels: Data-level fusion: This is where raw data from multiple sensors is combined before any feature extraction takes place. It’s about blending the most fundamental information. Feature-level fusion: Here, individual features are extracted from each sensor’s data first, and then these extracted features are combined before being fed into a classification algorithm. Decision-level fusion: This is a higher-level approach where individual sensor-based classifiers each make their own decisions (e.g., ”drowsy” or ”not drowsy”), and a higher-level fusion algorithm then combines these independent decisions to reach a final, more confident conclusion [10]. Regardless of how the fusion is structured, the ultimate effectiveness of the entire safety system hinges critically on the timely and accurate transfer of data. This applies not just to data moving within a single processing unit, but especially to data exchanged between distinct processing units responsible for individual sensor streams and the central fusion logic. This reality emphasizes the sever need of optimizing wireless inter-processor communication, as multiple sensors or processing units might be physically separated or require flexible connectivity.

III. Inter-Processor Communication Architectures

Most current embedded systems, especially those highly incorporated into automobiles, have started using distributed processing architectures. The strategic move to this design follows the increase of computational requirements, the requirement to improve fault tolerance, and the requirement to optimize the real-time performance in complex vehicular environments [11]. The very definition of such distributed arrangements implies a strong IPC mechanism that enables a standout amongst the most low-latency and smooth exchange of information with a heterogeneous processor, commonly over a physical distance.

A. Embedded Inter process Communication protocols

Although the main practical application of this paper is wireless IPC, it would be best to comprehend the basis of the wired protocols which are usually utilized in remote data collection or a precursor to wireless implementation. The two protocols provide different features in terms of speed, complexity and appropriateness to various data volumes and latency demands: UART (Universal Asynchronous Receiver-Transmitter: A simple, widely used asynchronous serial protocol for point-to-point communica- tion, favoured for its low hardware overhead and ease of implementation [12]. SPI (Serial Peripheral Inter- face): This is a synchronous serial communication interface commonly used in master-slave configurations for short-distance, high-speed data transfer, ideal for continuous data streams [13]. I2C (Inter-Integrated Circuit): A synchronous, multi-master, multi-slave serial bus, I2C is ideal for connecting multiple low-speed peripheral devices over short distances with minimal wiring [14]. CAN (Controller Area Network): A robust vehicle bus standard, CAN is specifically designed to allow microcontrollers, and the devices to communicate with each other in applications without the host computer. It is a message-based protocol, highly resilient to electrical interference, and widely adopted in automotive applications for inter-ECU communication and safety-critical data [15]. Ethernet: While more complex to implement in embedded systems, Ethernet (and its automotive variants like BroadR-Reach) offers very high bandwidth and is increasingly used for high-data-rate applications like raw camera data streaming, complex sensor fusion, infotainment, and inter-domain controller communication in advanced driver-assistance systems [16].

B. Hybrid Processing Models

Today's advanced vehicular safety mechanisms increasingly adopt hybrid processing models to optimize performance, as example by architectures combining a microcontroller and a single-board computer. This distributed approach allows for specialization and efficient resource utilization. Microcontroller (e.g., Arduino Mega): These are ideal for deterministic, low-latency control tasks, direct sensor interfacing (e.g., analog MQ-3 for alcohol detection, digital fingerprint readers for authentication), and immediate actuator control (e.g., engine immobilization, buzzer activation). Their minimal operating system overhead ensures predictable real-time responses, making them perfect for safety-critical ”reflex” actions. Single-Board Computer (e.g., Raspberry Pi 5): In contrast, SBCs provide significant computational power for complex, non-deterministic tasks. This includes real-time computer vision (such as facial landmark detection, drowsiness assessment using EAR/MAR), running sophisticated machine learning models, and managing higher-level communication protocols (e.g., Wi-Fi, cellular for SMS alerts, or even direct V2X communication). They handle the ”cognitive” load of the system. In such hybrid systems, IPC becomes a critical bridge. For instance, the SBC might process a high-resolution video stream to detect subtle signs of drowsiness and then send a simple, low-latency trigger signal to the MCU, which then executes the immediate safety intervention. The efficiency of this trigger transmission, whether wired or wireless, is paramount. In addition to internal communication, these hybrid systems often need to wirelessly interact with external entities—such as other vehicles, roadside units, or cloud services—to share critical safety information, making wireless IPC a priority.

C. Wireless IPC Protocols for Vehicular Safety

The growing complexity and distributed nature of modern vehicular safety systems, along with co-operative intelligent transportation systems (C-ITS), necessitate robust and low-latency wireless inter- processor communication (W-IPC). Several protocols have been evaluated for their suitability in vehicular environments. Table I summarizes the candidate protocols in terms of range, data rate, latency, and representative use cases.

Dedicated Short-Range Communications (DSRC, IEEE 802.11p) enables low-latency, reliable V2V/V2I links, making it well-suited for safety-critical alerts. Cellular V2X (C-V2X, including 5G NR-V2X) extends coverage beyond 500 m and supports both direct and network-assisted modes, offering ultra-low latency and high throughput for cooperative driving. Wi-Fi (IEEE 802.11ac) and Bluetooth/BLE are better suited for in-vehicle and wearable sensor connectivity, while Ultra-Wideband (UWB) provides precise ranging for secure access and collision avoidance. Ultimately, protocol choice depends on the urgency and volume of the data: safety-critical alerts require DSRC or 5G NR-V2X, whereas diagnostic and bulk data can leverage Wi-Fi or Bluetooth.

TABLE I: Candidate Wireless Protocols for Vehicular Safety Applications

Protocol	Range	Data Rate	Latency	Use Case
DSRC (802.11p)	300 m	3–27 Mbps	<10 ms	Safety-critical V2V/V2I
C-V2X (5G NR)	500+ m	>100 Mbps	<1 ms	Cooperative driving, sensor sharing
Wi-Fi (802.11ac)	50 m	100s Mbps–Gbps	10–50 ms	In-vehicle data, diagnostics
Bluetooth/BLE	10–30 m	1–3 Mbps	10–100 ms	Wearable sensor connectivity
UWB	10–50 m	27–110 Mbps	<10 ms	Precise ranging, secure access

IV. Influences to W-IPC latency in Multi-Sensor Fusion

To achieve low latency in wireless IPC of multi sensor fusion it is important to understand some of the unique problems of sending data to an IPC in fast changing vehicular environments. But unlike wired systems, wireless communication has to deal with very unpredictable environments at the physical and link layers that may introduce delays and may reduce reliability.

A. Interference and Impairments to the Wireless Channel

One of the largest causes of latency and packet losses lies in itself as a wireless medium. Fading and Multipath: When in an urban area or congested roadways, the signals fail to reach their destination by simply bouncing off buildings, cars and other obstructions. This so-called multipath effect, combined with variations in the signal level (fading), could corrupt data, necessitate retransmissions and consume precious milliseconds on the turnaround time. Interference: Interference on wireless connections occurs with other devices, which includes Wi-Fi routers, Bluetooth systems, and cars in the surrounding area using V2X communication. Such congestion can result in collision of packets, queueing delays or even data loss especially in high-traffic applications where every millisecond is important. Noise: Background electrical and environmental noise further compromises quality of signal. To deal with this, they use error-correction coding in their systems, which enhance reliability at the cost of processing time, therefore, increasing overall latency.

B. Protocol Overhead in Wireless Contexts

While general protocol overhead applies, wireless protocols introduce specific overheads. Medium Access Control (MAC) Overhead: Wireless protocols require complex MAC layers to manage shared channel access (e.g., CSMA/CA in Wi-Fi/DSRC, or scheduled access in C-V2X). This involves contention resolution, acknowledgements, and retransmissions, all contributing to latency. Security Overhead: Wireless communication is inherently vulnerable to eavesdropping and tampering. Implementing robust encryption and authentication mechanisms (e.g., TLS, IPSec) adds computational overhead and packet size, increasing latency, especially for small, frequent safety messages. Handover Latency: As vehicles move, they might hand over connections between different access points or cellular base stations. This handover process can introduce significant, transient delays, which are unacceptable for safety-critical real-time data.

C. Data Volume, Bandwidth, and Wireless Link Capacity

The volume of sensor data must be carefully matched with the wireless link's capacity. High-Resolution Video Streams: Transferring raw, high-resolution video frames wirelessly (e.g., from an external vehicle camera to an internal processing unit, or between vehicles for cooperative perception) demands extremely high bandwidth (several hundreds of Mbps to Gbps), which only advanced technologies like 5G NR-V2X can reliably provide. If bandwidth is insufficient, frames will be dropped, or latency will skyrocket. Sensor Data Rate: While individual sensor data might be small, aggregating data from many sensors (e.g., an array of lidar/radar sensors) and transmitting it wirelessly can quickly saturate lower-bandwidth links [19]. Dynamic Channel Conditions: Wireless channel capacity is not static; it fluctuates with distance, obstacles, and interference. Adaptive modulation and coding schemes are needed, but switching between them adds complexity and potential latency.

D. Synchronization Challenges in Distributed Wireless Systems

Maintaining precise temporal synchronization across physically separated, wirelessly communicating sensors and processors is even more challenging. Time Skew: Wireless transmission delays are variable and difficult to predict. If data from a wirelessly connected sensor (e.g., a smart roadside unit) arrives at the central fusion unit with a different delay than an internal sensor, it can lead to inaccurate temporal correlation and flawed fusion results. Network Time Protocol (NTP) Limitations: While NTP can synchronize clocks over IP networks, its accuracy might be insufficient for very low-latency, safety-critical applications (e.g., requiring microsecond precision). More advanced synchronization mechanisms like IEEE 802.1AS (gPTP) or precise timing protocols over 5G are needed. Event Correlation: Developing algorithms that can intelligently correlate events across wirelessly transmitted data streams based on potentially imprecise timestamps requires robust statistical methods and predictive models to account for variable wireless transmission delays [20]. Time-Sensitive Networking (TSN): Explore the application of TSN standards (IEEE 802.1Qbv, 802.1Qbu, etc.) over automotive Ethernet or other suitable wireless links. TSN provides mechanisms for deterministic data delivery and precise time synchronization, crucial for safety-critical multi-sensor fusion in highly automated driving [22] [23].

V. Conclusion

Real-time multi-sensor fusion in automotive safety requires optimization of wireless inter-processor communication, which is a key, but underestimated challenge in developing such systems. This paper has discussed some of the special aspects causing W-IPC Latency anomalies such as wireless channel degradation and protocol overheads and complicated synchronization problems. We have presented a full optimization package focused on intelligent processing at the edge with event driven wireless messaging, careful selection of hybrid wireless strategies, superior buffering strategies, and powerful sync strategies. These strategies can be used to design highly responsive and reliable systems devoted to safety by prioritising a low latency, general purpose, wireless data exchange between heterogeneous processing units and external vehicular nodes. The theoretical knowledge of the matter described herein will represent a baseline of knowledge on how to reduce the human-factor risk in the context of connected and autonomous vehicles and open the path to more successful iterations of proactive safety measures. In this work we highlight that the potential of multi-sensor fusion in tomorrow's intelligent transportation systems is not realized only by the sensors themselves, though. The potential is realized by the interconnected and optimized wireless communication channel that ties them together in an intelligent (real-time) whole [21].

References

1. Y. Albadawi, M. Takruri, and M. Awad, "A Review of Recent Developments in Driver Drowsiness Detection Systems," *Sensors*, vol. 22, no. 5, p. 2069, 2022.
2. M. Nouri, M. M. Mansour, and A. A. Kherani, "Driver Drowsiness Detection Based on Multi-Sensor Fusion and Deep Learning,"
3. *IEEE Trans. on Intelligent Transportation Systems*, vol. 22, no. 8, pp. 5368–5378, 2021.
4. X. Geng, K. Yang, B. Li, and X. He, "A Deep Learning Based Fingerprint Recognition System for Smart Car," *Applied Sciences*, vol. 12, no. 15, p. 7549, 2022.
5. Z. Ma, B. Xia, X. Li, and X. Liu, "Driver Monitoring System Based on Multi-Sensor Fusion," *Journal of Physics: Conference Series*, vol. 2548, no. 1, 012015, 2023.
6. B. Jadoon and S. Khan, "A Comprehensive Review of Driver Monitoring Systems for Autonomous Vehicles," *Sensors*, vol. 22, no. 19, p. 7483, 2022.
7. X. Li, Y. Ren, Y. Zhang, and X. Wei, "A Review of Driver Fatigue Detection Technologies," *Applied Sciences*, vol. 13, no. 7, p. 4381, 2023.
8. T. Radu, "MQ-3 Alcohol Sensor: A Comprehensive Guide," *Sensors Journal*, vol. 18, no. 4, pp. 56–62, 2021.
9. Y. Sun, C. Wu, H. Zhang, Y. Zhang, S. Li, and H. Feng, "Extraction of Optimal Measurements for Drowsy Driving Detection Considering Driver Fingerprinting Differences," *Journal of Advanced Transportation*, 2021.
10. J. Liu, C. Wang, Z. Liu, Z. Feng, and N. N. Sze, "Drivers' Risk Perception and Risky Driving Behavior under Low Illumination Conditions," *Journal of Advanced Transportation*, 2021.
11. A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.
12. M. N. Ben-Romdhane and R. Cheour, "An IoT-Based Smart Agriculture System Using Arduino and Cloud Platform," in *Proc. 2020 17th Int. Conf. on Smart Technologies (SmarTech)*, pp. 1–6, 2020.
13. H. Wajid and S. Hussain, "Interfacing Raspberry Pi with Arduino: A Review of Communication Protocols," *Int. J. of Computer Science and Network Security*, vol. 22, no. 4, pp. 180–186, 2022.
14. J. Singh and R. Kaur, "A Comprehensive Review on Routing Protocols in Vehicular Ad-Hoc Networks (VANETs)," *Int. J. of Communication Systems*, vol. 33, no. 1, e4204, 2020.
15. M. Goudarzi, A. Rahbari, and M. Bahadori, "A Comprehensive Review on Communication Technologies in Vehicular Ad-Hoc Networks," *Journal of Computer Networks and Communications*, 2020.
16. A. Talukder and M. Hasan, "A Comprehensive Review on Controller Area Network (CAN) Protocol for Automotive Applications,"
17. *Int. J. of Advanced Computer Science and Applications*, vol. 14, no. 1, 2023.
18. J. Ahmad, M. Tahir, and S. A. Hassan, "A Comprehensive Survey on 4G/5G-Based V2X Communication for Smart Transportation,"
19. *IEEE Access*, vol. 10, pp. 43828–43851, 2022.
20. M. A. Al-Hammami, "Driver Drowsiness Detection Systems: A Review," *Journal of Applied Sciences*, vol. 13, no. 2, pp. 527–540, 2023.
21. X. Li, Y. Guo, and Y. Zhang, "Driver Fatigue Detection and Warning System Based on Facial Features," *Optical Engineering*, vol. 60, no. 10, 108201, 2021.
22. S. Mubeen, A. Hasan, and S. S. Ahmad, "Driver Behavior Monitoring Systems: A Review," *Artificial Intelligence Review*, vol. 56, no. 5, pp. 4567–4599, 2023.
23. S. Nanda, M. Subudhi, and R. Kumar, "A Review on Recent Trends in Driver Drowsiness Detection Systems Using Machine Learning,"
24. *Int. J. of Computer Networks and Communications*, vol. 13, no. 2, pp. 1–17, 2021.
25. G. Tsaramirsis et al., "A Modern Approach towards an Industry 4.0 Model: From Driving Technologies to Management," *Journal of Sensors*, 2022.
26. L. Chen, G. Xin, Y. Liu, and J. Huang, "Driver Fatigue Detection Based on Facial Key Points and LSTM," *Security and Communication Networks*, 2021.
27. H. Han, K. Li, and Y. Li, "Monitoring Driving in a Monotonous Environment: Classification and Recognition of Driving Fatigue Based on LSTM Network," *Journal of Advanced Transportation*, 2022.