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Next-Generation V2X: Enabling Intelligent Mobility through 6G V2V2I Architectures

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Abstract

Advances in Vehicle-to-Everything (V2X) communication, 6G networks, and machine learning are transforming vehicles into intelligent, connected, and energy-smart systems. This paper reviews recent progress in V2X architecture, V2V2I models, and emerging technologies such as Visible Light Communication (VLC), Reconfigurable Intelligent Surfaces (RIS), and cooperative computing. It also examines the role of Gridable Electric Vehicles (GEVs) in energy sharing through V2G, V2H, and V2V. Applications in safety, collision avoidance, and traffic optimization are discussed, alongside key challenges in interoperability, security, and adoption. Together, these developments point toward a smarter, cleaner, and more resilient future for transportation.

Keywords: Vehicle-to-Vehicle-to-Infrastructure (V2V2I); 6G networks; Reconfigurable Intelligent Surfaces (RIS); Visible Light Communication (VLC); Cooperative computing; Gridable Electric Vehicles (GEVs); Vehicle-to-Grid (V2G); Mobile Edge Computing (MEC); Intelligent Transportation Systems (ITS)

1. Introduction

Transportation is entering a new era, one where vehicles are no longer just machines that move people and goods. They are becoming intelligent, connected, and active participants in a vast network that links roads, infrastructure, energy systems, and other vehicles. In this future, vehicles will share information in real time, respond instantly to changing conditions, and even supply power when it's needed. The goal is clear: safer travel, cleaner environments, smoother traffic, and smarter use of resources.

At the core of this change is Vehicle-to-Everything (V2X) communication, which is set to grow even stronger with the arrival of 6G networks. Building on what 5G already offers, 6G will bring faster speeds, almost instant response, and the ability to connect huge numbers of vehicles and devices at the same time. This means it's not just about sending data more quickly, but about helping vehicles detect risks, adjust routes immediately, and move together like a single connected system. Adding to this, machine learning will help vehicles recognize patterns on the road, anticipate traffic, and react instantly when it matters most.

Electric mobility is also evolving beyond its role as a cleaner alternative to combustion engines. Gridable electric vehicles (GEVs) are emerging as flexible energy resources. They can power buildings during outages (V2H), share energy with other vehicles (V2V), or return electricity to the grid during peak demand (V2G), supporting renewable energy sources like solar and wind.

Innovative technologies are strengthening this vision. Reconfigurable Intelligent Surfaces (RIS) can shape and direct wireless signals to improve speed and reliability. Visible Light Communication (VLC) allows vehicles to transmit

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information using their lights, avoiding the crowded radio spectrum. Cooperative computing systems enables vehicles and roadside units to share data-processing tasks, ensuring that critical information is handled quickly and accurately.

Of course, there are challenges ahead, different systems will need to work seamlessly together, networks must be protected from cyber threats, large-scale energy sharing will need to be managed efficiently, and there must be clear benefits for users to adopt these systems.

The following research reviews the latest progress in V2X communication, intelligent transportation systems, safety solutions, and energy integration. It explores where research stands today, the challenges we face, and the opportunities on the horizon. This is more than just the evolution of vehicles, it's the foundation for a smarter, cleaner, and more connected future of mobility.

2. General V2X Technologies & Overviews

We're about to witness a major shift in how we move, travel, and even think about transportation. Connected and self-driving vehicles aren't just futuristic concepts anymore, they're shaping up to make our roads safer, our air cleaner, and our journeys smoother and more enjoyable. Imagine cars that can "talk" to each other, avoid accidents before they happen, and adapt to traffic conditions instantly. To make this possible, we'll need Vehicle-to-Everything (V2X) networks that are lightning-fast, ultra-reliable, and capable of handling massive amounts of data in real time without missing a beat [1].

That's where sixth-generation (6G) networks step in. Building on the progress of 5G, 6G will bring jaw-dropping speeds, near-instant responsiveness, and the ability to connect huge numbers of devices all at once. Think of it as the nervous system of a future transport ecosystem sending and receiving information so quickly that vehicles can make decisions almost as fast as humans blink. At the heart of this will be machine learning, enabling vehicles to learn from data, predict hazards, optimize routes, and coordinate with each other for maximum safety and efficiency. In this work, we look at how ML is already being used in 6G-V2X, the breakthroughs so far, the challenges still in the way, and the exciting opportunities ahead.[2]

Meanwhile, electric vehicles (EVs) are stepping up as more than just a cleaner alternative to petrol cars, they're becoming active players in our energy system. Once connected to the power grid, they turn into GEVs, capable of doing far more than charging. With Vehicle-to-Home (V2H), they can power your home during a blackout. With Vehicle-to-Vehicle (V2V), they can share energy with other cars that are running low. And with Vehicle-to-Grid (V2G), they can send electricity back to the grid, helping keep the balance between supply and demand and supporting renewable energy sources like solar and wind [1][2].

We explore the tech that makes all of this possible advanced power electronics for smooth two-way energy flow, smart battery management systems to keep things efficient, secure communication systems to coordinate between vehicles and the grid, and control frameworks to make sure everything runs smoothly. A case study on V2G optimization shows how, with the right planning, GEVs could become a crucial part of a cleaner, smarter, and more resilient energy network.

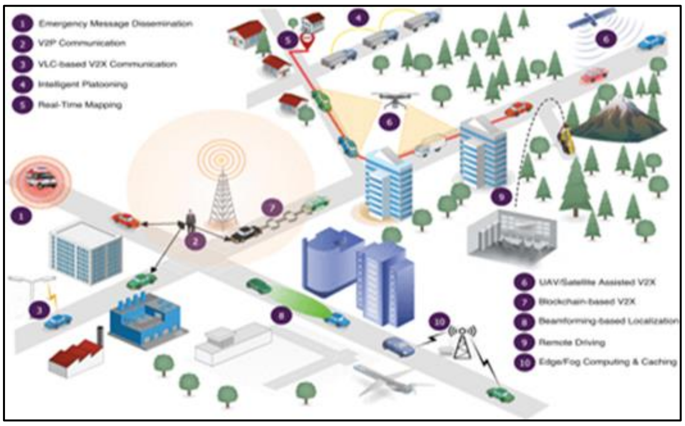

Figure 1 Overview of V2X communications [1]

This issue can be solved by making different manufacturer's systems work together, protecting against cyber threats, managing energy transfers at scale, and giving people clear reasons and rewards for joining in. But if we can tackle these challenges, the future will see vehicles that aren't just for transport they'll be intelligent, connected, and sustainable partners in building a better world [2].

3. V2V2I Architectures & Intelligent Transportation Systems (ITS)

The following research is about making sure vehicles can stay online at all times using IPv6, even while moving at high speeds, and still follow the IEEE WAVE standard. Right now, every car's On-Board Unit (OBU) supports IEEE 802.11p for short-range communication, but the rollout of Road-Side Units (RSUs) which are key for direct Vehicle-to-Infrastructure (V2I) links is happening slowly. That's holding back some of the most advanced intelligent transportation services. Meanwhile, many cars already come with LTE for things like remote diagnostics, emergency assistance, software updates, and entertainment [3].

To fill the gap until RSUs are everywhere, the concept of Vehicle-to-Vehicle-to-Infrastructure (V2V2I) is proposed. In this system, certain "gateway" vehicles use LTE to connect to the Internet and then share that link with nearby cars over 802.11p. In the future, LTE-to-LTE sharing between vehicles could make this even more powerful [3][4].

One of the toughest technical challenges is giving fast-moving vehicles proper IPv6 addresses and routing details quickly and reliably. Traditional DHCPv6 isn't built for such fast-changing conditions it can be slow and create unnecessary network traffic. In solution to this problem, the researchers improved the Neighbor Discovery (ND**)** protocol so it can handle Prefix Delegation (letting a connected vehicle assign part of its address range to others) and Route Exchange (sharing the best routing paths). This speeds up handovers, reduces complexity, and cuts network chatter. The system already works on Linux using RADVD (Router Advertisement Daemon). Next, large-scale simulations will be done to test how well it performs under different driving and traffic conditions [4][5].

The V2V2I design also changes how traffic data is collected and shared. Instead of every vehicle sending data to a central server, the road network is divided into zones each led by a "Super Vehicle" [3].

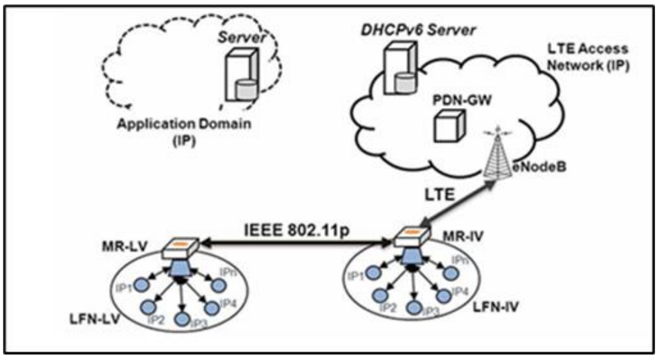

Figure 2 V2V2I reference model [3]

The leader collects speed and location data from cars in its zone, then passes it to the central system or other Super Vehicles. Regular vehicles only talk to their own leader. This massively reduces the load on central servers while keeping the traffic data accurate. Tests using real traffic data from California's District 7 (Greater Los Angeles) showed that as more vehicles are grouped into zones, the bandwidth savings grow without losing precision making it ideal for things like real-time traffic prediction and route optimization.

The study also explored how lane-level traffic data could make routes faster and safer. Using real highway loop detector data and the Free Sim traffic simulator [3].

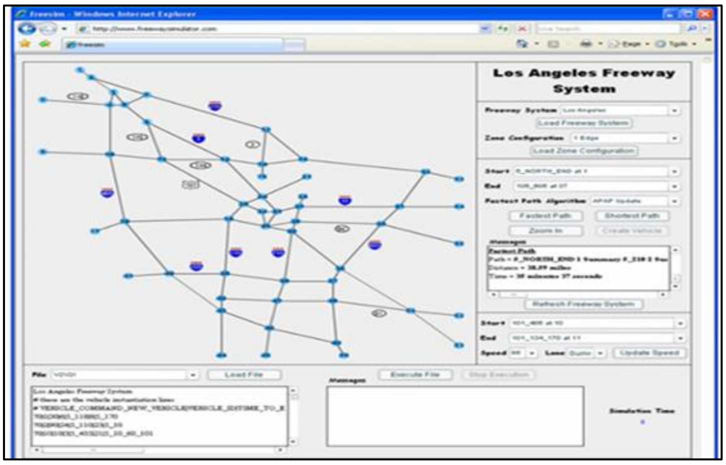

Figure 3 FREESIM screenshot where nodes 1-35 were used for V2V2I analysis [3]

The researchers modelled conditions where travel times for every lane and segment were updated continuously. Routes that included optimal lane changes cut travel times by about 33% compared to using only average road segment data. In low-traffic areas, these routes required fewer lane changes, making driving smoother. On busy highways, more lane changes were needed to keep up speed, but overall trips were still faster. Since lane changes are a leading cause of accidents, optimizing them improves both travel times and safety [3].

Finally, presents a V2V2I system with smart antennas.

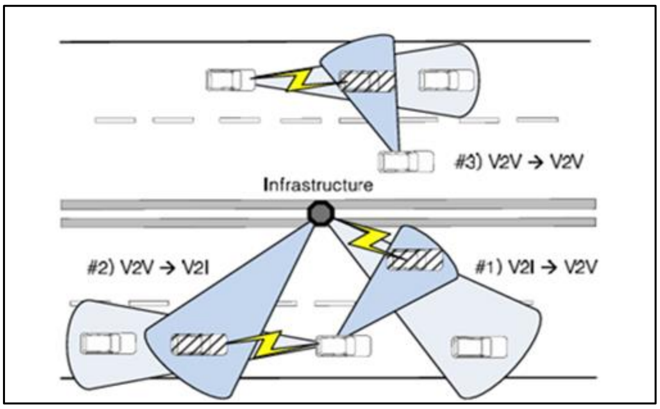

Figure 4 Co-channel interference scenarios in V2V2I communication system [6]

These antennas can create multiple directional beams, allowing vehicles and RSUs to send several data streams at the same time. Since V2V and V2I use the same spectrum, interference can be a big problem. To fix this, the researchers developed a downlink resource allocation method that manages interference while making the most of available bandwidth. Simulations showed that this setup was far faster, more reliable, and more efficient than traditional V2I systems. In short, this work outlines a practical, future-ready way to keep vehicles connected and informed long before RSUs are fully rolled out. By combining V2V and V2I into a flexible V2V2I model, improving IPv6 mobility, organizing data sharing through Super Vehicles, using lane-level insights for better routes, and boosting capacity with smart antennas, the approach promises a future of safer, faster, and smarter travel [6].

4. V2I Communication & Data Offloading

The following two studies dive into creative ways to keep vehicles connected, whether they're far from traditional roadside infrastructure or using entirely new ways to send data [7].

The first study focuses on a common problem: what happens when a connected vehicle moves out of range of a Road Side Unit (RSU). Instead of simply waiting to reconnect, the researchers propose a Vehicle-to-Vehicle-to-Infrastructure (V2V2I) setup powered by Mobile Edge Computing (MEC). Here's how it works: a MEC server keeps an eye on the network, spots potential multi-hop paths between vehicles, and even predicts routes that might open up soon. This means data can start transferring earlier, without waiting for RSU coverage, and sessions can keep running longer [8].

The system uses two clever features:

- Delay-constrained routing, which takes advantage of short-lived paths that would normally be ignored, perfect for time-sensitive messages like accident alerts.
- Path recovery, which quickly repairs broken connections, especially in longer routes where disruptions are more likely [7][8].

The results are impressive. In the best case, an 8-hop route with both delay-constrained routing and path recovery, the system transferred 3.4 times more data than the old approach. Even the simplest version of this method still did better than traditional RSU-only communication. The team's next goal is to make the system choose the very best routes in real time and keep sessions alive during RSU handovers, so data flows smoothly no matter where the vehicle is.

The second study takes a different route, literally shining a light on communication. Instead of using radio signals, it tests a light-based Vehicle-to-Infrastructure (V2I) method where a car's headlights send encoded messages to optical sensors on

traffic light poles [8].

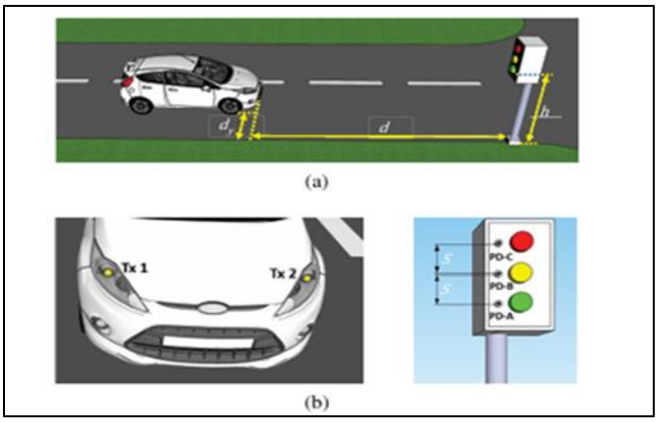

Figure 5 (a) V2I scenario under consideration and **(b)** Location of high-beam headlamps (transmitters) and photodetectors (receivers) [8]

This approach avoids crowded radio frequencies and could be especially useful in busy urban environments.

To see if it would work, the researchers built a simulation that mimics how light behaves in the real world, including reflections and scatter. They tested how a car's position on a two-lane road, whether hugging the curb, centered in the lane, or shifting over, affects signal clarity. They also studied how LED headlights, with their unique beam patterns and brightness levels, influence how well the traffic light's sensors pick up the signal [8].

The findings? Even small changes in a car's position can make a big difference to both signal strength and data speed. That means the system will need smart design tweaks, like adjustable light beams or sensors with a wider detection angle, to stay reliable. If perfected, this technology could help cars talk to traffic lights more smoothly, leading to better traffic flow, quicker responses to changing road conditions, and safer journeys overall [8]

5. V2V Communication & Performance Optimization

We're heading towards the future where vehicles won't just move us, they'll actively talk to each other and to the road around them. This isn't just about self-driving cars; it's about creating a connected ecosystem where every vehicle, traffic light, and roadside sensor works together to keep traffic flowing and make roads safer [9].

One of the approaches explored in this research focuses on V2V2I data offloading. Picture a car driving far from any roadside unit (RSU), the devices that connect vehicles to the wider network. Normally, it would have to wait until it came into range to send its data. But here's the twist: instead of waiting, the system uses multi-hop V2V paths, passing information from car to car until it reaches an RSU [9][10].

A Mobile Edge Computing (MEC) server keeps an eye on the whole network, spotting possible routes in advance and even predicting when new paths might open up. This proactive strategy lets cars start transferring data earlier and hold their connection for longer. It also includes a delay-constrained mode that makes use of short-lived paths most systems would ignore, and a path recovery tool to fix broken links, something especially valuable in multi-hop setups, where there's a lot more that can go wrong [11][12].

The results speak for themselves. In the best-case test, an 8-hop route with delay constraints and path recovery, the system successfully offloaded data 3.4 times more often than the standard method, which only works when a car is directly in range of an RSU. Even the least advanced version of this new method outperformed the traditional approach [12].

Another part of the research turns to be a very different idea: using light for V2I communication. Instead of radio waves, the car's headlights act as transmitters, sending messages to sensors mounted on traffic light poles. Using detailed simulations that mimic how light travels and bounces in real-world conditions, researchers tested how well this works when cars are in different positions on a two-lane road [12].

The researchers also dug deep into headlight design, because the way LEDs behave can have a big impact on how clear the signal is. Measurements of signal strength and data rates revealed that even small shifts in the car's position can change the quality of the connection, an insight that could help engineers fine-tune these systems to make them more reliable [12][13].

Together, these studies show two promising directions for the future of connected transport: smarter, more flexible data routing that doesn't rely solely on RSUs, and innovative communication methods like visible light that could complement or even replace traditional wireless systems in certain situations. The ultimate goal? Vehicles that stay connected no matter where they are, ensuring safer journeys and smoother traffic for everyone [13].

6. Safety & Collision Avoidance

The following research looks at how smart vehicle communication can prevent accidents in different driving scenarios, focusing both on regular cars and heavy trucks.

The first part of the study examined the use of IEEE 802.11p, a wireless standard built for vehicle-to-vehicle communication, to warn drivers about two particularly dangerous situations: head-on collisions and intersection crashes [14].

For these systems to work effectively, nearby vehicles must receive a steady flow of warning messages quickly enough to react in time. The researchers recreated realistic traffic conditions, including effects like the **capture effect**, where stronger signals overpower weaker ones, and measured how many messages per second vehicles could receive and how long they stayed above the safety threshold.

Results showed that for head-on collisions, the system worked well with up to about 150 vehicles in range before performance dropped due to message collisions in dense traffic. In intersection crashes, the system could handle up to around **200 vehicles** before quality declined [14].

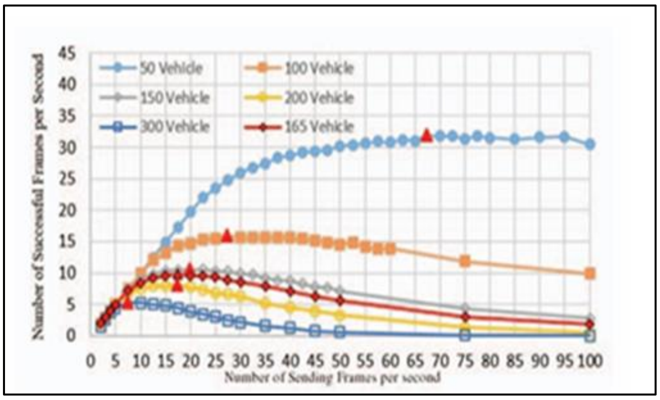

Figure 6 The number of Frames that the Receiving Vehicle Successfully Receives per Second in 2.5 sec – 3.5 sec prior to the Estimated Crash (Head-on Car Crash) [14]

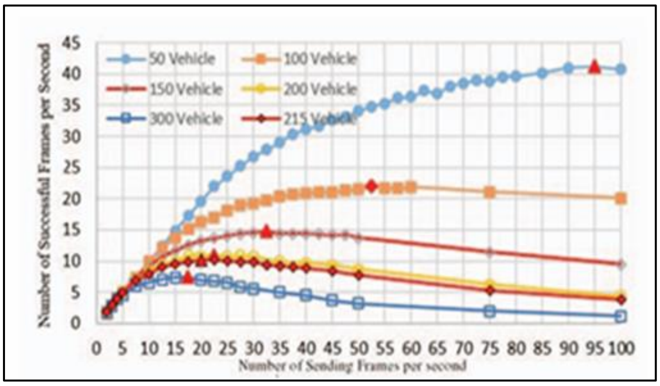

Figure 7 The number of Frames that the Receiving Vehicle Successfully Receives per Second in 2.5 sec – 3.5 sec prior to the Estimated Crash (Intersection Car Crash) [14]

Interestingly, in heavy traffic, intersection scenarios gave drivers up to seven times more warning time than head-on situations. This suggests that while IEEE 802.11p is effective for crash warnings, it's better suited to intersection-type environments and needs further optimization for crowded, head-on conditions [14][15].

The further part of the research turned to heavy truck safety, since large vehicles are involved in more severe accidents due to their mass, slower maneuverability, and longer stopping distances. The team explored a collision avoidance system that uses both V2V and V2I communication, focusing on how latency, the delay in delivering messages affects performance. Using a Hardware-in-the-Loop simulation to mimic real driving, they tested a setup with a 100-millisecond communication delay and 10 updates per second. The findings were encouraging while the delay influenced how closely trucks followed each other and how they adjusted their speeds, it didn't compromise overall safety. The impact of delay depended on vehicle speed, with higher speeds making precise timing more critical. This suggests that adaptive timing algorithms, which adjust based on speed and road conditions, could make collision avoidance systems even more effective for heavy vehicles.

Together, these studies show that advanced communication technologies can significantly improve road safety. IEEE 802.11p offers strong performance, particularly at intersections, while adaptive systems for heavy trucks can maintain safety even when communication isn't perfectly instant. With further refinement, such systems could make roads safer for everyone, from passenger cars to the largest freight haulers [15].

7. Applications & Specialized Communication Technologies:

The future of driving isn't just about faster cars or sleeker designs, it's about creating a whole new way for vehicles, roads, and energy systems to work together. Imagine a world where your car not only talks to other cars and traffic lights but also helps keep the lights on in your home during a power outage. That's the direction we're heading, and recent breakthroughs are making it possible sooner than most people think.

One of the most exciting innovations is something called Reconfigurable Intelligent Surfaces (RIS) with polarization modulation (PM). Think of them as "smart billboards" by the roadside, except instead of showing ads, they bend and shape wireless signals to carry more information. This allows multiple data streams to be sent at once without clogging up the network. In practical terms, it means your car could receive real-time 3D navigation, hazard alerts, and even streaming entertainment, all without missing a beat. In some setups, deep learning algorithms are used so the system can adapt on the fly, picking the best route for data to travel depending on traffic, weather, and network load [16].

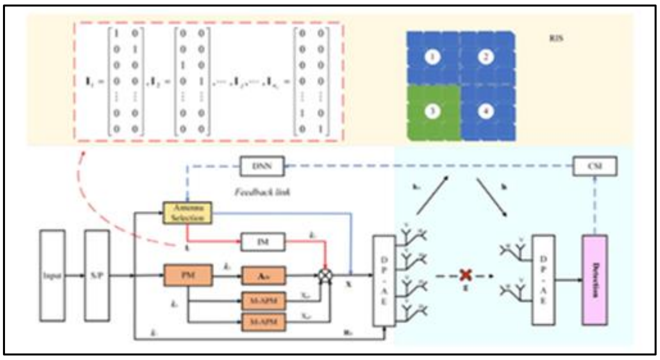

Figure 8 TAS for RIS-aided PM communication system model [16]

Safety is getting a serious boost too. With VLC, your car's headlights and taillights can send coded signals to nearby traffic lights or roadside cameras. These systems, in turn, scan for hazards like a child stepping into the road or another vehicle speeding toward an intersection, then beam a warning straight back to your dashboard. Because it uses light waves instead of radio, VLC avoids interference from other wireless systems, perfect for crowded cities. Tests show that even small details, like how light bounces off wet roads, can affect performance, so engineers are fine-tuning every aspect for maximum reliability [17].

Cars are also becoming key players in our energy networks. With Vehicle-to-Grid (V2G) technology, electric cars can send power back into the grid when demand is high. That means during a heatwave, thousands of parked EVs could help keep the air-conditioning running in homes and hospitals. In Spain, a real-world trial used **Long Range Wide Area Network** (LoRaWAN) technology to keep cars connected to the grid controller even when driving through busy, obstacle-filled streets, and it worked flawlessly, delivering every single data packet without a miss [17][18].

Figure 9 Transmission within a bidirectional VLC safety information system [17].

Then there's RoadEye, a system designed to make roads smarter by linking groups of cars (called "platoons") and roadside hazard detectors. If one car in the group detects black ice or heavy rain, all the others are warned instantly. Using low-power communication standards like IEEE 802.15.4 and ZigBee, RoadEye is especially valuable in areas where poor road conditions and delayed driver reactions often cause serious accidents [16][17].

Finally, cooperative vehicle-infrastructure systems (CVIS) are changing how cars and roads handle complex computing. Instead of each car crunching all the data itself, the workload is shared between vehicles and roadside units. This speeds up processes like 3D mapping, sensor fusion, and traffic prediction, which are crucial for self-driving cars. The system decides in real time where to send the computing tasks, balancing speed, reliability, and network load so that critical information is processed without delay [19][20].

8. Conclusion

The future of transport is about vehicles that think, connect, and share. With V2X communication, 6G networks, and gridable electric vehicles, travel can become safer, cleaner, and more efficient. Innovations like VLC, RIS, and cooperative computing are turning this vision into reality, but we still need to solve issues around compatibility, security, and trust. If we do, vehicles will be more than just transport they'll be active partners in creating a smarter, greener world.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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