Chapter 1

Cooperative Intelligent Transport Systems for Net-Zero

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The global pursuit of achieving Net-Zero emissions has gained significant attention in recent years as a crucial strategy for combating climate change and ensuring a sustainable future for our planet. Net-Zero emissions refer to the balance between greenhouse gas (GHG) emissions and removals. Achieving Net-Zero emissions requires a reduction in GHG emissions to the extent possible, coupled with the removal of the remaining emissions through carbon sequestration or other means [1]. The transportation sector is a significant contributor to CO2 emissions, accounting for approximately 37% of global emissions in 2021 [2]. Achieving Net-Zero emissions in the transportation sector requires a shift towards low-carbon fuels and the adoption of energy-efficient technologies. Intelligent transportation systems (ITSs) are employed to reduce carbon emissions, enhance transportation safety and increase productivity. The advent of wireless technology has played a pivotal role in fostering the advancement of diverse communication networks across various modes of transportation, as illustrated in Fig. 1.1. However, this chapter specifically directs its attention towards the technology of connected vehicles. The connected vehicle technology can drastically change our current transportation system by enabling real-time wireless communications among vehicles, pedestrians, and roadside units (RSUs) deployed on both roadsides [3]. Each vehicle within the vehicular network contains an onboard unit (OBU), a wireless communication device that facilitates secure communication with nearby vehicles and RSUs. Fig. 1.2 illustrates two main categories of connected vehicles: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). The application of this technology has demonstrated significant potential to improve the efficiency and effectiveness of various traffic-related applications, as demonstrated by previous studies [4, 5].

- For environmental applications and Net-Zero emissions, connected vehicles provide a valuable opportunity for mitigating carbon emissions and promoting ecologically responsible transportation alternatives. By establishing direct commu-

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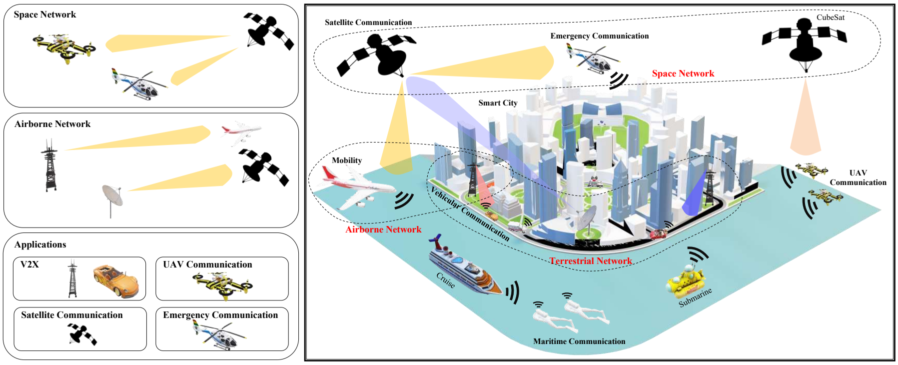

Figure 1.1 Wireless communication technology for different intelligent transportation systems.

nication with intelligent traffic signals, these vehicles possess the capability to minimize idling and eliminate unnecessary stops. Simultaneously, the traffic signals provide essential information regarding their status and timing, enabling vehicles to provide speed recommendations to drivers. Consequently, drivers are empowered to make informed choices to optimize their speed, thereby ensuring they encounter subsequent traffic signals during green intervals or decelerate efficiently for a controlled stop. This approach yields notable advantages, including fuel preservation, emissions reduction, and cost savings for drivers.

- For safety-related applications, connected vehicles empower drivers with an unparalleled level of situational awareness, providing a comprehensive view of other equipped vehicles within a radius of approximately 300 meters. It is imperative to underscore that this system places paramount importance on safeguarding drivers' personal information and adheres to rigorous privacy standards that strictly prevent any form of location tracking. In the interest of en-

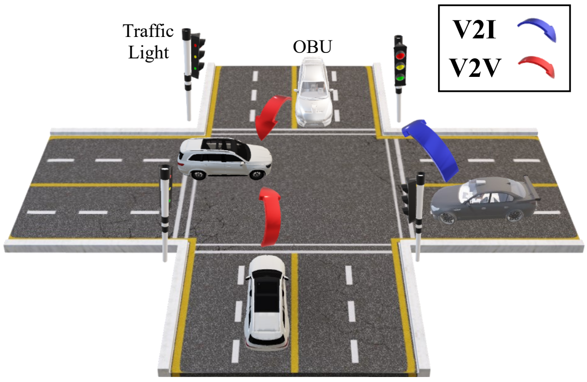

Figure 1.2 Common types of connected vehicles.

hancing safety, drivers receive timely warnings through various sensory channels, including visual displays, seat vibrations, or auditory cues, effectively alerting them to potential road hazards. Importantly, it is essential to emphasize that despite these warnings, drivers maintain full control over their vehicles at all times. Nevertheless, this technology also supports limited automated functionalities, affording drivers the option to temporarily delegate partial control of their vehicles. The provided warnings serve as invaluable aids, enabling drivers to respond promptly and effectively, thereby mitigating the risk of potential collisions. An exemplary application is the intersection movements assist, which actively notifies drivers when it is deemed unsafe to cross an intersection. Additionally, consider the immense value offered by a blind spot warning application, seamlessly enabling drivers to perceive their surroundings within blind spots. Furthermore, connected vehicles establish communication with intelligent roadside infrastructure, including rail grade crossings, ensuring that drivers are promptly alerted to the presence of approaching trains, even in cases of compromised visibility or auditory perception.

- For weather-related applications, connected vehicles play a pivotal role in addressing safety and traffic concerns arising from adverse weather conditions. This becomes particularly crucial in situations like icy roads, where hazards may not be visually apparent but still pose significant risks due to slippery surfaces. By harnessing data collected from numerous connected vehicles, potential dangers such as icy roads can be identified, enabling timely warnings for drivers before they encounter these perilous conditions. Additionally, weather-related traffic data collected by vehicles can be seamlessly transmitted to traffic management centers, equipping them with real-time and detailed insights into prevailing conditions. This enables efficient monitoring and transportation performance management. In response, traffic centers can take necessary actions, including adjusting traffic signal timings, notifying maintenance staff, implementing appropriate speed limits, issuing informative alerts to motorists, and dispatching vehicles for road maintenance. Through in-car displays, motorists can receive up-to-date weather notifications, ensuring they remain well-informed and can make decisions based on real-time conditions.
- For emergency-related applications, harnessing the capabilities of connected vehicle technology offers numerous advantages in improving situational awareness regarding unexpected events on the road, such as vehicular collisions, law enforcement interventions, and the presence of emergency responders attending to accident victims. By providing timely notifications about incidents in specific zones, drivers can quickly become aware of upcoming events, enabling them to adjust their speed and change lanes accurately. Additionally, the utilization of radio signals facilitates the seamless transmission of crucial information to first responders, ensuring they are promptly alerted to potential risks posed by approaching vehicles. Leveraging the potential of connected vehicle technology allows for effective traffic flow regulation and proactive management of congestion at accident sites, effectively preventing the escalation of disorder to unmanageable levels.

- For mobility-related applications, the ability to exchange traffic-related information between connected vehicles, smart infrastructures, and the surrounding environment signifies an ongoing advancement with the potential to optimize traffic flow, enhance transit coordination, and contribute to safer and more livable communities. Furthermore, connected vehicle technology presents a significant opportunity to support pedestrians with disabilities by facilitating their interaction with smart traffic lights through mobile signals. This innovative approach enables drivers to receive prompt alerts concerning the presence of pedestrians with disabilities at crosswalks, thereby fostering increased awareness and ensuring their safe passage.

The benefits presented by interconnected transportation systems arise from their ability to enhance safety and mobility, mitigate potential environmental impacts, enhance the quality of life in our communities, and ultimately foster a safer and more advanced transportation network.

1.1 Overview of ITS worldwide

A vehicular communication network represents a mobile ad-hoc network specific to the domain of vehicles, commonly known as a vehicular ad-hoc network (VANET). This architecture involves three essential entities: the trusted authority (TA), multiple fixed RSUs, and OBUs installed in vehicles [6]. The modernization and digitalization of the transportation system, as well as the utilization of ITS technology, have garnered significant attention from the European Committee (EC). These advancements offer a wide range of benefits, such as improved road safety, reduced traffic congestion and gas emissions, and the creation of employment opportunities and economic growth. In order to address these concerns, the EC introduced decision 2008/671/EC, which designates the frequency band from 5875 to 5905 *MHz* (30 *MHz*) for safety-related ITS applications [7]. Furthermore, the EC adopted the ITS action plan, COM(2008)886, with the aim of accelerating and coordinating the implementation of ITS systems on both roads and vehicles across the European Union [8]. To facilitate the rapid deployment of ITS throughout the EU, Directive 2010/40/EU, enacted in July 2010, established a legal framework emphasizing the importance of V2I communication as a critical component [8].

The advancement of cooperative intelligent transportation systems (C-ITS) in Europe is facilitated through the collaboration of two notable sustainable development observatories (SDOs): the European Telecommunications Standards Institute (ETSI) and the European Committee for Standardization (CEN), including its technical committees, specifically CEN TC 278 - ITSs [10]. CEN, in partnership with the EC and in collaboration with the International Organization for Standardization (ISO), proposes joint specifications to establish a comprehensive set of standards for the implementation of vehicle-to-everything (V2X) communication systems in Europe [11]. ETSI primarily focuses on communication systems and V2V applications, while CEN places emphasis on V2I applications, catering to the two common types of connected vehicles. A significant milestone in the progression of C-ITS occurred in 2013 when automobile manufacturers within the car-to-car communication consortium (C2C-CC) reached an agreement to adopt the V2X system. Subsequently, the Amsterdam Group, a strategic alliance of European stakeholders, formulated additional plans for C-ITS deployment. To address the remaining obstacles hindering the commercial implementation of C-ITS systems in the European Union, the EC initiated a multilateral framework in November 2014. This framework involved active participation from national authorities and various C-ITS stakeholders. During the initial phase of the C-ITS platform (2014-2016), a shared vision was developed for the interoperable deployment of the C-ITS system within the European Union. This involved identifying key legal, technical, and commercial considerations, as well as formulating policy recommendations. In January 2016, a comprehensive technical and strategic report was published [12], accompanied by a thorough cost-benefit analysis and a public consultation process.

In July 2016, the second phase of the C-ITS platform was initiated with the primary objective of advancing the development of a unified vision for the interoperability of C-ITS systems within the European Union (EU). This phase focused on establishing a cohesive technical and legal framework to address critical aspects, including security, data protection, compliance assessment, and hybrid communication issues that were identified during the initial phase. Additionally, it involved exploring the potential benefits of C-ITS in the context of autonomous vehicles. To support these efforts, an expert report was published in September 2017 [13]. Consistent with the objectives outlined in COM(2016)588 [14], the EC proposed the deployment of 5G-based communication along major transport routes as a crucial component of the "5G for Europe: An Action Plan." This proposal aimed to leverage the capabilities of 5G technology to enhance C-ITS systems. In October 2017, the radio spectrum committee, comprising representatives from the EC and EU member states, approved a study to extend the dedicated safety-related ITS frequency band of 5.9 *GHz* from 30 *MHz* to 50 *MHz*. This decision recognized the need for additional bandwidth to support the evolving requirements of C-ITS. Furthermore, it is acknowledged that there is an incompatibility between the communication protocols used by the IEEE 802.11p in the U.S. and the global standard C-V2X PC5 radio systems, primarily due to differences in radio access technologies. The EC recognizes this disparity and emphasizes the importance of addressing this issue to ensure seamless communication and interoperability of C-ITS systems on a global scale.

The U.S. has taken a significant stride towards advancing V2X services by allocating dedicated spectrum within the 5.9 *GHz* band. However, the effective utilization of this spectrum has encountered substantial delays. In October 1999, the Federal Communications Commission (FCC) of the U.S. assigned 75 *MHz* of the 5.9 *GHz* spectrum exclusively for intelligent transportation systems. Two prominent SDOs, namely the Institute of Electrical and Electronics Engineers (IEEE) and the Society of Automotive Engineers (SAE), oversee V2X communications in the country. The IEEE working groups have played a pivotal role in the development of the 802.11 wireless LAN and 1609 standards, while the SAE's technical committee has focused on establishing the dedicated short-range communication (DSRC) protocol. The IEEE 1609 standard family of protocols was designed to complement the IEEE

802.11 physical (PHY) transmission and medium access control (MAC) layers. Collectively known as wireless access for the vehicular environment (WAVE), this combination of IEEE 802.11 and 1609 standards aims to provide comprehensive V2X communication capabilities. Furthermore, the SAE specifies additional layers above the protocol stack, encompassing V2X message sets and associated performance requirements, thereby ensuring comprehensive V2X communication capabilities. In January 2017, the U.S. Department of Transportation (DoT) made a momentous announcement, mandating that all newly sold light vehicles in the country must support V2V communication. Concurrently, the Federal Highway Administration initially made its infrastructure deployment guidelines available to assist transportation planners in integrating V2I communications. However, these guidelines were subsequently withdrawn, albeit temporarily. They offer detailed specifications pertaining to V2I communications, providing valuable guidance for the seamless incorporation of these technologies into transportation infrastructure.

In China, the Ministry of Industry and Information Technology (MIIT) has designated a license-exempt spectrum of 50 *MHz* within the 5.9 *GHz* band specifically for ITS services. Furthermore, in November 2016, the Chinese government allocated a dedicated 20 *MHz* frequency range from 5905 to 5925 *MHz* for conducting trials of cellular vehicle-to-everything (C-V2X) technology in six major cities. In Japan, the 5.9 *GHz* band has been utilized for a wireless technology called electronic toll collection (ETC). On September 5, 2016, the Ministry of Communications in South Korea allocated 70 *MHz* of the spectrum ranging from 5855 to 5925 *MHz* for technology-neutral ITS services. In Australia, the national telecommunications regulator conducted a consultation process in September 2017 to explore the allocation of the 5.9 *GHz* spectrum for ITS applications, while proposing technology-neutral regulations.

1.2 Construction and design of VANETs

In general, VANETs typically support two common types of vehicular communications, V2I and V2V, described as follows.

1.2.1 V2I communications

V2I communication establishes a vital connection between vehicles and roadside infrastructure. With the widespread deployment of cellular networks in recent years, leveraging cellular networks for supporting V2I communication has become economically feasible. Another option for V2I communication is the utilization of WAVE protocols, specifically through DSRC technology, which adheres to IEEE 802.11p/1609 standards [15]. Cellular network-based V2I communication commonly employs two modes of transmission: unicast and multicast broadcasting [16]. Unicast refers to a point-to-point communication mode used for both uplink and downlink transmissions between the vehicle and the evolved NodeB (eNB), which serves as the base station. On the other hand, multicast/broadcast mode is exclusively used for distributing downlink messages, facilitating point-to-multipoint transmissions. Each broadcast area, defined by the mobile operator, encompasses multiple cells. In Fig. 1.3, a scenario is depicted where network servers transmit "Pre-crash warning" messages to various broadcast areas through the utilization of multimedia broadcast and multicast services (MBMS). This enables efficient and targeted communication to multiple vehicles within the designated areas.

1.2.2 V2V communications

The term V2V pertains to direct communication between vehicles, with the objective of enhancing traffic efficiency and minimizing traffic accidents. In order to mitigate the risk of accidents caused by slow or non-visible vehicles, adjacent vehicles can exchange crucial information pertaining to velocity, acceleration, and vehicle status [15]. Extensive research and trials have been conducted on V2V systems to facilitate various traffic services, including vehicle warnings and notifications concerning abnormal vehicle status.

1.2.3 An overview of VANET protocol stacks

Generally, VANET is a decentralized communication network in the vehicle domain in which network terminals are communicating through the U.S.'s DSRC protocol (IEEE 802.11p/1609), or Europe's C-ITS standards.

1.2.3.1 The DSRC in the U.S.

IEEE 802.11p, which falls under the broader IEEE 802.11 standards family, has been specifically designed to facilitate wireless connectivity within vehicular environments, as depicted in Fig. 1.4 [17]. To address the unique requirements of vehicular communication, the IEEE 1609 working group has developed an extensive suite of standards dedicated to DSRC networks. These standards include IEEE 1609.2, which focuses on security services, IEEE 1609.3, which incorporates the WAVE short message protocol (WSMP) for network services, and IEEE 1609.4, which han-

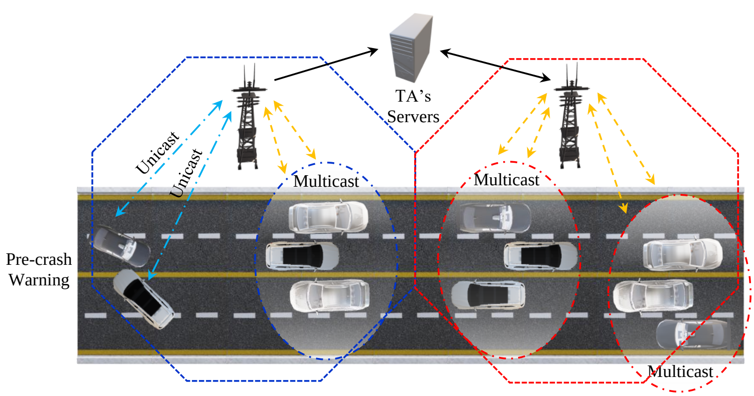

Figure 1.3 An example of eNBs unicast and multicast transmissions [16].

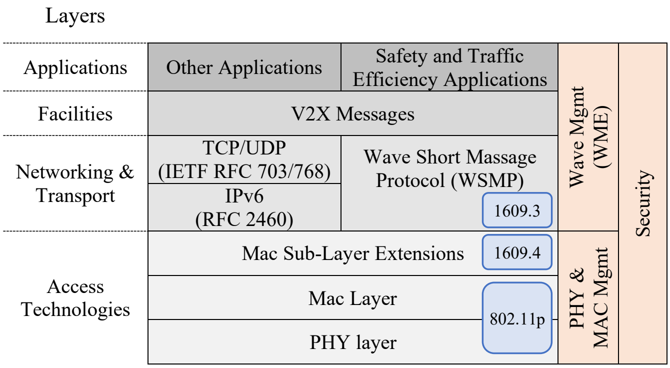

Figure 1.4 A schematic of the WAVE stack used by the U.S. DSRC [17].

dles channel switching. In order to optimize functionality, the DSRC spectrum is divided into service and control channels, which are separate from conventional Wi-Fi channels.

In the U.S., the FCC has assigned a dedicated bandwidth of 75 *MHz* for applications related to VANETs within the frequency range of 5.85 *GHz* to 5.925 *GHz*, as depicted in Fig. 1.5 [17]. In contrast to Wi-Fi, which operates within a 20 *MHz* bandwidth, the DSRC spectrum is divided into 10 *MHz* channels utilizing a half-clocked mode. This particular configuration has been purposefully designed to enable dependable communication for high-speed terminals in vehicular environments. The PHY and MAC mechanisms employed in DSRC are based on the IEEE 802.11P standard, with modifications tailored to fulfil the distinctive requirements of vehicular communication. These adaptations account for the wireless channel characteristics encountered in vehicular environments, effectively addressing challenges such as intercarrier interference resulting from the Doppler spread caused by the rapid movement of vehicles. DSRC utilizes orthogonal frequency division multiplexing (OFDM) as its transmission scheme, which has demonstrated remarkable effectiveness in mitigating interference and fading effects. By efficiently utilizing the available spectrum and minimizing the impact of channel impairments, OFDM contributes to reliable and robust communication in vehicular scenarios.

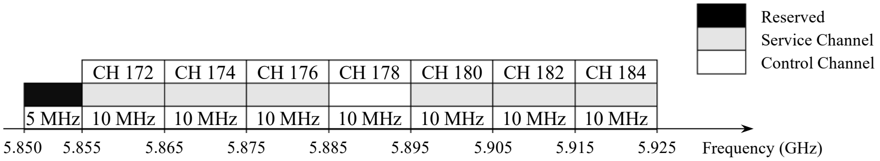

Figure 1.5 The U.S. dedicated spectrum for the IEEE 802.11p [17].

1.2.3.2 The C-ITS in Europe

A comparison can be made between the implementation of C-ITS standards in Europe and the adoption of DSRC standards in the U.S. Within the C-ITS framework, the ITS-G5 technology encompasses the PHY and MAC layers, which correspond to the IEEE 802.11p DSRC standard. The "G5" in ITS-G5 signifies the operation of the network within the 5 *GHz* frequency range. In Europe, the frequency spectrum allocation for C-ITS is divided into different segments, designated as A to D. The ITS-G5A band, with a bandwidth of 30 *MHz*, is specifically designated for safety and traffic efficiency applications. The ITS-G5B band, occupying 20 *MHz*, is dedicated to non-safety applications. The ITS-G5C band is shared with the radio local area network (RLAN) band, while the ITS-G5D band is reserved for future use in ITS, as shown in Fig. 1.6 [18]. It is crucial to ensure minimal interference within the 5.8 *GHz* band for the ITS-G5 spectrum in Europe. Despite some differences, the IEEE 802.11p DSRC standard and ITS-G5 share similar fundamental characteristics. Both standards employ OFDM in the PHY layer, utilizing the same parameters as IEEE 802.11a, with adaptations to accommodate the respective spectrum allocations. Furthermore, V2X messages and Networking & Transport mechanisms in both standards utilize the Internet Protocol (IP). While both standards employ TCP/UDP and IP version 6 (IPv6) in a similar manner, C-ITS specifies a distinct ad-hoc routing protocol called GeoNetworking. This protocol enables multi-hop communication capabilities and is defined in the standard series ETSI EN 302 636, as depicted in Fig. 1.7 [18]. Notably, the C-ITS stack incorporates the use of geographical coordinates for addressing and forwarding messages, which is a notable feature of the system.

1.3 Security and privacy objectives

In DSRC, each vehicle within the network transmits a safety-related message at intervals of 100-300 *msec*. These messages include vital information such as the vehicle's speed, heading, location, and other relevant details. The utilization of wireless channels for communication among terminals in vehicular networks exposes them to various forms of attacks, such as impersonation, modification, and replay attacks. To prevent these attacks, ensuring message authentication and integrity becomes critical security measures. Furthermore, security solutions need to incorporate privacy-

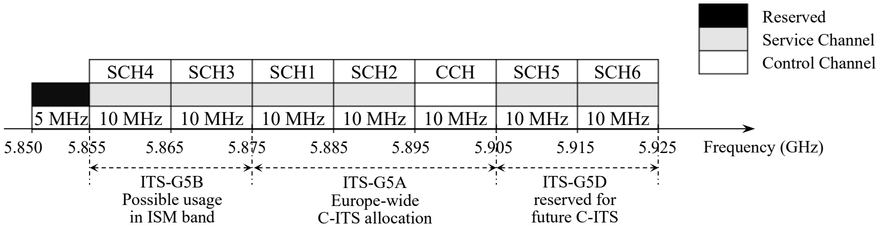

Figure 1.6 The Europe's ITS-G5 channel frequency band [18].

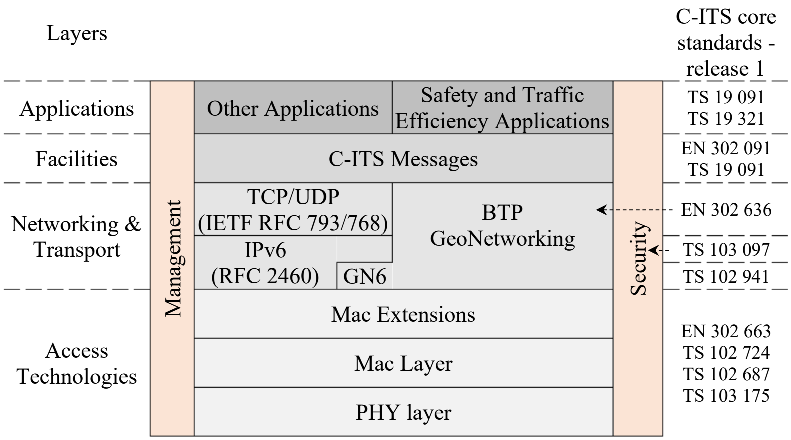

Figure 1.7 A schematic of the C-ITS stack used in Europe [18].

preserving methods to safeguard users' privacy and prevent the disclosure of their real identities. This section focuses on discussing the security and privacy requirements associated with VANET applications.

1.3.1 Privacy requirements

The communication protocols employed in VANET applications must fulfil the following privacy objectives:

1. *Preservation of privacy*: Message contents from surrounding terminals, vehicles, and RSUs, cannot be analyzed for identifiable data.
2. *Unobservability*: Legitimate terminals can broadcast their messages without being noticed by others.
3. *Unlinkability*: Distrusted terminals cannot track the transmitter behavior by determining the source of two different signals.

1.3.2 Security requirements

The communication protocols must satisfy the following security objectives.

1. *Message authentication*: Every safety-related message sent from a particular terminal must be authenticated by the intended receiver.
2. *Message integrity*: The receiver is able to detect any modifications to the contents of the message.
3. *Entity authentication*: A receiver's ability to determine whether the received safety-related message came from a legitimate source.
4. *Non-repudiation*: The transmitter cannot deny the signal's authorship.

5. *Low overhead*: A high-security level can be achieved with low communication and computation costs that can be evaluated according to the following classification:
   - *Communication overhead* (bytes): Low (1:50) & Medium (51:100) & High (101:140).
   - *Computation overhead* (*msec*): Low (1:3) & Medium (3.1:6) & High (6.1:10).
6. *Message confidentiality*: Data contents cannot be identified by unauthorized terminals.
7. *Traceability*: Vehicles in VANETs communicate based on pseudo-identities (PIDs) in order to maintain their real identities (RID) from unknown terminals, preserving vehicles' privacy. It is only the TA that can reveal a vehicle's RID in the case of misbehaviour.

1.4 Challenges and security concerns

This part discusses the security challenges associated with vehicular communication as follows.

1. *Location tracking attack*: Eavesdropper is trying to track the vehicle's location from the broadcasted safety-related message. In this regard, each message must be generated using dynamically updated parameters and pseudo-identity in order to ensure that the adversary cannot link two captured messages from the same vehicle, thus supporting unlinkability.
2. *Man-in-the-Middle (MITM) attack*: The eavesdropper is trying to masquerade as a legitimate terminal and make it appears as a normal flow of data.
3. *Replay attack*: The attacker re-transmits a previously captured message after a certain period of time.
4. *Modification attack*: The attacker alters the message content and broadcasts it to nearby terminals.
5. *Denial of service (DoS) attack*: The intruder is trying to affect the network performance by flooding and overwhelming a specific terminal in the network with an enormous amount of data and requests.
6. *Sybil attack*: The intruder obtains multiple fabricated identities and attempts to masquerade as multiple legitimate users, posing a significant threat to the functionality and security of the network.
7. *Side channel attack*: The attacker attempts to extract sensitive and private data from the vehicle's tamper-proof device (TPD) based on power consumption or electromagnetic wave radiations.

1.5 Towards 6G-based V2X communication

In recent years, the dominant technology for V2X communication has been DSRC. However, DSRC encounters several limitations, particularly in environments that are dense and mobile. These limitations encompass restricted coverage, low data rates, and inadequate quality-of-service (QoS) guarantees. In response to these challenges, the 3GPP has been actively developing a standardized solution known as C-V2X for vehicular cellular communication. The evolutionary progression of V2X communications is visually represented in Fig. 1.8 [19, 20]. Within 3GPP Release 14, LTE V2X communication introduced two air interfaces: PC5, also known as LTE sidelink, for direct communication, and LTE-Uu for wide area network connectivity. The PC5 interface is responsible for enabling V2V and V2I communications, while the LTE-Uu interface facilitates vehicle-to-network (V2N) communication. In 3GPP Release 14, data transport services were introduced to support critical road safety messages, such as cooperative awareness messages and basic safety messages. The introduction of 5G New Radio (5G NR) in 2018 laid the foundation for advanced V2X services, including vehicle platooning, advanced driver assistance, and remote driving [20]. In 2020, 3GPP announced Release 16, the second phase of 5G NR, aiming to enhance reliability, throughput, and enable ultra-low-latency communication (URLLC) for V2X applications. It is important to note that 3GPP is currently actively involved in the development of Release 17, which will incorporate architectural enhancements to support advanced V2X services.

It is expected that urbanization, higher living standards, and technological advancements will lead to a rapid increase in autonomous vehicles in the future. Accordingly, the proliferation of intelligent autonomous vehicles will necessitate a rapid expansion of communication devices and digital applications. Moreover, the V2X network will encounter novel communication challenges as an increasing number of autonomous vehicle services emerge. These services encompass a diverse range of innovations, including 3D displays that provide immersive viewing experiences, free-floating holographic control display systems, as well as enhanced in-car infotainment systems and immersive entertainment features. In light of these advancements, existing wireless networks will encounter substantial capacity constraints, thereby introducing new scientific and technical challenges in terms of data rate, spectral efficiency, latency, intelligence level, coverage, security, networking, and other aspects. As we transition towards the era of 6G V2X communication, the integration of advanced technologies becomes crucial. These technologies will encompass more robust and efficient communications, resource allocation mechanisms, decision-making processes, and computation capabilities. Various vehicu-

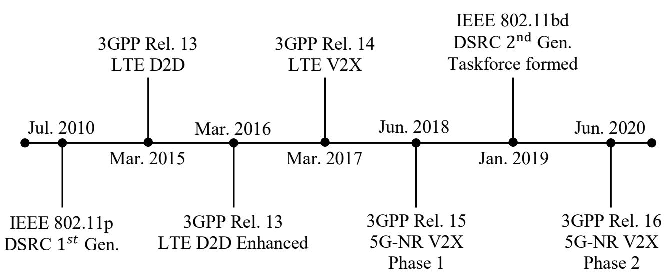

Figure 1.8 V2X communication evolution [19].

lar communication technologies can be utilized to realize 6G-V2X, which can be broadly classified as either revolutionary or evolutionary approaches.

1.5.1 Revolutionary technologies for 6G-V2X

In this section, we explore some intriguing and promising technologies that can be applied in the context of the 6G-V2X communications network. Traditional wireless networks typically treat channels as indivisible units, which can lead to increased training overhead and limited bandwidth utilization when noisy received waveforms are considered. A notable challenge in V2X communication networks is the presence of time-and-frequency selective channels, which are particularly challenging due to the dynamic nature of the V2X environment. Additionally, the V2X communication network may experience shadowing loss caused by obstacles such as buildings or elevated terrains. To address these issues, 5G NR-based V2X networks have been designed with relatively large sub-carrier spacing (SCS) to facilitate robust data transmission in highly dynamic environments. The use of a large SCS is necessary for such environments to mitigate the impact of inter-carrier interference, which can adversely affect the bit error rate (BER) performance of the vehicular network due to vehicle mobility. In a study conducted by the authors of [21], it was found that an SCS of 60 *kHz* performs reasonably well at high speeds (280 and 500 km/h) compared to an SCS of 15 *kHz*. However, it is important to note that the adoption of a larger SCS can have implications for the overall system throughput.

1.5.1.1 Intelligent Reflecting Surfaces (IRSs)

In recent times, IRSs have emerged as a promising technique to improve performance, aiming at establishing an intelligent propagation environment to reconfigure the transmitted signal. IRSs are programmable meta-surfaces, which have the ability to fine-tune the phase, amplitude, and frequency of the transmitted signals to address the negative effects of the environment. A study in [22] presents that the usage of large IRSs can enhance spectral efficiency and reduce complexity as compared to the existing relay-aided systems. IRS can be utilized in 6G-V2X communication networks to improve the coverage (V2V pairs may suffer from shadowing) and poor channel conditions. Shadowing due to the obstruction affects the received signal strength power of V2V communication. To address this problem, IRS can be mounted on the surfaces of objects or buildings. Fig. 1.9 shows the IRS-based V2V communication scenario. IRS can be used to reduce the Doppler effect, making it a more desirable research direction for future 6G-V2X networks. A study in [23] shows that the Doppler effect can be suppressed by utilizing the IRS. There are still a few challenges associated with IRS integrating with 6G-V2X networks. The challenges at hand involve determining the optimal placement, ensuring precise channel estimation in a dynamic and rapidly changing channel environment, and effectively adapting to diverse spectrum bands.

1.5.1.2 Tactile communication

Tactile communication allows real-time communication of tactile or sensual signals. In the 6G-V2X network, tactile communication allows the integration of sensual sig-

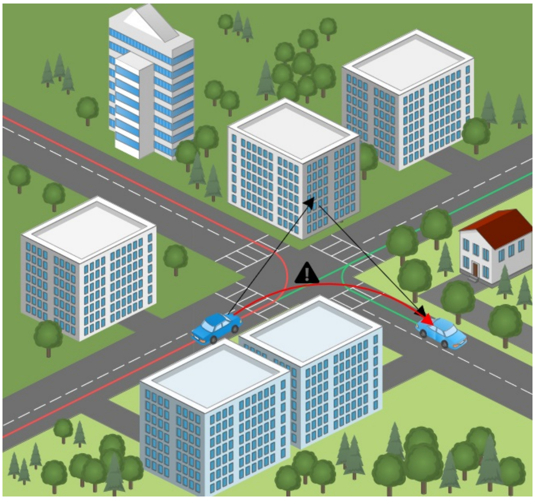

Figure 1.9 IRS at the intersection point.

nals such as touch and motion, offering immersive interactions for users in vehicular environments [24]. Further, it helps to improve vehicular-related application services such as autonomous driving, platooning, and reliable sensor data transfer services. Numerous tactile-based automotive applications such as warning information have been proposed and tested to enhance the safety of vehicles [25]-[27]. In addition, it can be useful for vulnerable road users (VRUs) by allowing them suitable tactile information, which improves their safety on the roads. Despite its vast promise, there are still a few challenges associated with tactile communication such as its need to meet the high rate low-latency communications (HRLLCs) and QoS requirements [28]. It is quite challenging to meet these requirements in a highly dynamic vehicular environment. Thus, there is a need for a dynamic approach to meet the HRLLC requirement that can also consider traditional 5G services.

1.5.1.3 Brain–vehicle interfacing

A brain–vehicle interfacing (BVI) is a concept of controlling the vehicle through the human brain without any physical involvement with the vehicle. BVI technology can be a great help for disabled people as it offers a huge prospect for independence by allowing an interface. Further, by using AI techniques, BVI may also enhance the manual driving experience to predict the actions of the driver. Even though the current priority is to make it available for fully automated vehicles. A BVI is expected to reduce the challenges of autonomous driving in ambiguous scenarios, such as rural and unstructured environments. Recently, few studies have been conducted [29]-[32] by academia and industry and presented the concept of brain–machine interface-based target terminal selection system of vehicles.

1.5.1.4 Blockchain-based V2X

The implementation of V2X communication systems highly depends on improved security mechanisms for extensive vehicular message broadcasting and authentication [6]. Improving the security mechanism inflicts new limitations for radio resource management in V2X communication networks. For example, multimedia applications (e.g. eMBB services) may need only a low level of security but mission-critical applications (e.g. URLLC) should have a high level of security to combat hostile cyber-attacks. These security requirements may affect resource allocation, power control, and frame structure techniques. The integration of a blockchain-based approach can offer significant enhancements to the security mechanisms within the 6G-V2X network. By leveraging blockchain technology, the network can benefit from a disruptive solution that enables secure and decentralized transactions among various entities. This approach presents several advantages, including enhanced security and privacy mechanisms on a large scale, all achieved without the need for intermediaries or third-party involvement [33]. The 6G-V2X network can execute different tasks by using the decentralized blockchain approach such as a decentralized security system, offloading specific functions with cloud, fog, or edge computing. A decentralized security management approach in the 6G-V2X network will not only provide the verification of the authenticity of a sender but will also protect privacy. The 6G-V2X network can also use a decentralized spectrum resource-sharing framework, which has the ability to enable different users to utilize securely and intelligently the same spectrum resources at a low cost. Many studies have been carried out to implement the blockchain-based V2X network but due to the limitations of current blockchain technology, it cannot support the highly dynamic nature of the V2X communication network [33]. Despite its ability to provide a higher layer of security solution, the existing blockchain technology experiences high latency. In this regard, a new approach related to blockchain technology considering the ultra-low latency should be proposed before it can be implemented in the 6G-V2X network.

1.5.1.5 Terahertz-based V2X networks

THz communication has the potential to reduce the increasingly congested spectrum as it utilizes the *THz* bands (0.1–10 *THz*). *THz* communication will enable the users to achieve higher transmission rates ranging from 100 Gbps to several Tbps by using the ultra-wide bandwidth [34]. Such higher transmission rates will open the new gates of V2X applications (e.g. eMBB services), which will allow the vehicles and tactile communication users to transfer data rapidly. Since it enables higher transmission rates between multiple nodes, it can also be utilized on onboard scenarios, such as the BVI scenario, where HRLLC is needed. There are also some challenges associated with *THz* communication that needs to be addressed, which include transmitter and receiver antenna design and architectures, channel modeling, utilization of existing cellular (e.g. 5G, 4G) and new *THz* bands, and new waveform design. Though it provides higher transmission rates, it is only applicable at a distance of a few meters. The IRS approach can be an option to extend the *THz*-based V2X network coverage. Specifically, it is required to analyze *THz* radio propagation in urban, rural, and highway V2X use cases. An effective and intelligent resource management approach is required to utilize the *THz* communication benefits.

1.5.1.6 Quantum computing-aided V2X

Quantum computing has the potential to play a significant role in the 6G-V2X network, although practical implementation is still in its early stages. It is expected that quantum computing will become increasingly important in 6G and future wireless networks [35]. One area where quantum computing can make a valuable contribution is in enhancing the security features of the V2X network. Security is of utmost importance in V2X networks, as a breach could have severe consequences, including life-threatening accidents. Given that V2X networks share radio spectrum resources and are susceptible to cyber attacks, existing security measures may not be sufficient. Quantum computing offers inherent security properties through quantum entanglement, which makes it challenging for eavesdroppers to gain unauthorized access. This makes quantum computing a vital component in improving the security of the 6G-V2X network. Quantum key distribution (QKD) is another security feature enabled by quantum computing, which can help identify any malicious activities within the network. Moreover, the development of quantum computing brings about a significant boost in computational capabilities, allowing for faster implementation of complex and time-consuming optimization algorithms in 6G-V2X networks. For instance, tasks such as finding optimal policies that require extensive data processing and extensive training can be accelerated through quantum computing. However, it is important to note that quantum computing is still an evolving technology that requires further investigation to make it feasible for the 6G-V2X network. Current quantum computing-enabled microchips operate at extremely low temperatures, making them more suitable for base stations rather than onboard vehicle applications. Thorough research is needed to ensure thermal stability and suitability for vehicle-side deployment.

1.5.2 Evolutionary technologies for 6G-V2X

There are various evolutionary technologies for 6G-V2X networks. This part introduces the technologies that can be labelled as evolutionary technologies.

1.5.2.1 Advanced resource allocation

Advanced resource allocation for V2X communication involves the efficient distribution and utilization of network resources in V2X communication systems [38]. This approach aims to improve the performance, reliability, and scalability of V2X networks, enabling seamless communication between vehicles, infrastructure, pedestrians, and other entities [36]-[38]. One of the key advantages of advanced resource allocation is enhanced QoS. By optimizing resource allocation based on QoS requirements, advanced techniques ensure reliable and low-latency V2X communication. This is particularly important for real-time applications such as autonomous driving and collision avoidance. Moreover, efficient resource allocation increases the capacity of V2X networks. By optimizing spectrum utilization and managing resources effectively, advanced techniques can support a larger number of concurrent V2X connections, facilitating the growing demand for V2X communication. Improved reliability is another advantage of advanced resource allocation. These techniques mitigate interference and enhance the signal-to-noise ratio, leading to more reliable communication in V2X networks. Additionally, advanced resource allocation contributes to low-latency communication. By minimizing communication delays, real-time constraints can be met, enabling the timely transmission of critical information. Traffic management is another benefit of advanced resource allocation. By prioritizing safety-critical messages and balancing the network load, resource allocation techniques facilitate intelligent traffic management in V2X systems. Lastly, advanced resource allocation algorithms promote energy efficiency by optimizing transmission power and resource utilization in V2X devices, thereby reducing energy consumption.

Despite these advantages, challenges exist in implementing advanced resource allocation for V2X communication. Heterogeneous environments require resource allocation algorithms that can accommodate different communication modes and capabilities. Scalability is also a challenge, as resource allocation mechanisms must efficiently handle the increasing number of connected vehicles and devices. Real-time constraints necessitate algorithms that can make rapid decisions to meet latency and reliability requirements. Interference management is crucial, as V2X networks coexist with other wireless systems and potential sources of interference. Security and privacy concerns must be addressed to ensure secure communication and protect sensitive information. Finally, standardization and interoperability are key challenges that need to be overcome to develop standardized resource allocation frameworks, promoting seamless communication between different V2X systems and stakeholders. In conclusion, advanced resource allocation techniques offer various advantages in V2X communication, including enhanced QoS, increased capacity, improved reliability, low latency, traffic management, and energy efficiency. However, challenges related to heterogeneous environments, scalability, real-time constraints, interference management, security and privacy, and standardization must be addressed to fully exploit the potential of advanced resource allocation in V2X networks.

1.5.2.2 Hybrid RF-VLC V2X system

The future of 6G-V2X technology aims to achieve high-speed data transfer and low latency for seamless communication between vehicles and their occupants. However, the conventional standalone radio frequency (RF)-based V2X communication faces challenges in meeting these objectives. In dense traffic scenarios, issues such as interference, latency, and low packet delivery rates often arise with traditional RF-based vehicular communication [39]. To overcome these challenges, an alternative approach worth exploring involves integrating radio frequency (RF) and visible light communication (VLC) technology for V2X communication. This approach combines the use of radio waves and visible light to transmit information within vehicular networks. This hybrid approach leverages the strengths of both RF and VLC systems to enhance connectivity and address the limitations of each technology [40]. RF-based V2X systems utilize DSRC or cellular networks to transmit data between vehicles and infrastructure. They offer long-range communication capabilities but are susceptible to interference, signal degradation, and limited bandwidth in dense urban environments. VLC, on the other hand, utilizes light-emitting diodes (LEDs) for wireless data transmission. It provides high bandwidth, low latency, and immunity to RF interference, making it ideal for communication in indoor environments or areas with high RF congestion. However, VLC has a limited range and is highly directional, requiring line-of-sight between communicating devices. Hybrid RF-VLC V2X systems aim to combine the advantages of both RF and VLC technologies to overcome their individual limitations. By integrating RF and VLC modules in vehicles, these systems can switch dynamically between RF and VLC communication modes based on the surrounding environment and available resources.

This hybrid approach offers several benefits. Firstly, it improves communication reliability by leveraging RF for long-range connectivity and VLC for short-range, line-of-sight communication. Secondly, it enhances data throughput by utilizing RF for large data transfers and VLC for low-latency, high-bandwidth applications. Moreover, hybrid RF-VLC V2X systems provide increased robustness against interference, as they can switch between RF and VLC frequencies depending on the quality of the wireless channel. This adaptability enables seamless communication in challenging environments, such as urban areas with high RF congestion or areas with limited RF coverage. Additionally, hybrid RF-VLC V2X systems can support diverse V2X applications. The combination of RF and VLC technologies allows for a flexible and scalable architecture that can cater to different communication requirements. Hybrid RF-VLC V2X systems present a promising solution for enhancing V2X communication. By integrating the strengths of RF and VLC technologies, these systems offer improved connectivity, higher data throughput, and increased resilience in challenging wireless environments. However, the VLC performance can be affected by ambient light sources, both natural and artificial, which can introduce interference. Additionally, the mobility of vehicles can result in significant variations in the received signal strength of VLC [41]. Therefore, before deploying VLC in 6G-V2X systems, it is crucial to find effective solutions that mitigate interference caused by ambient lighting and address channel variations induced by vehicle mobility.

1.5.2.3 Non-orthogonal multiple access scheme (NOMA)

In the forthcoming 6G-V2X network, the establishment of robust and extensive transmission of V2X messages plays a crucial role in facilitating continuous perception and interaction between vehicles and their surroundings, thereby enhancing situational awareness and safety. To meet these requirements, the 6G-V2X networks would employ a pivotal technology known as non-orthogonal multiple access (NOMA). NOMA has emerged as a promising technique for V2X communications, offering several advantages and limitations for unicast and multicast transmissions. NOMA provides advantages for unicast V2X transmissions [42]. Firstly, NOMA allows the simultaneous transmission to multiple vehicles within the same resource block, enabling higher spectral efficiency and improved system capacity. This is especially beneficial in congested V2X scenarios where a large number of vehicles need to be served simultaneously. Secondly, NOMA supports power-domain multiplexing, where users with strong channel conditions can be allocated more power, ensuring fairness and enhancing the overall system performance. Thirdly, NOMA reduces latency by transmitting multiple unicast messages concurrently, enabling faster and more efficient communication between vehicles and infrastructure.

Regarding multicast transmissions, NOMA offers several advantages. Firstly, NOMA can efficiently support multicast services by dividing users into multiple groups and assigning different power levels to each group. This enables simultaneous multicast transmission to multiple groups within the same resource block, enhancing spectral efficiency and overall system capacity. Secondly, NOMA allows flexible power allocation, where users with stronger channel conditions can receive higher power, improving the quality of service for multicast transmissions. This is particularly beneficial for applications such as traffic safety warnings and traffic information dissemination. Nevertheless, NOMA also has limitations for V2X transmissions. Firstly, as the number of vehicles increases, the interference between users becomes more pronounced, potentially degrading the performance and reliability of communications. Effective interference management and resource allocation techniques are required to address this issue. Secondly, the transmissions in NOMA rely on accurate channel state information (CSI) estimation for all users within the same range of communication, which can be challenging in V2X scenarios with a large number of vehicles and dynamic channel conditions. In conclusion, NOMA offers significant advantages for both unicast and multicast V2X transmissions, including increased spectral efficiency, enhanced system capacity, and reduced latency. However, it also poses challenges such as interference management, accurate CSI estimation, and scalability issues for both transmission modes. Addressing these limitations will be crucial for realizing the full potential of NOMA in V2X communications.

1.5.2.4 UAV-/satellite-assisted V2X

Unmanned aerial vehicles (UAVs) hold substantial potential as airborne radio access points within the 6G-V2X network due to their expansive coverage capabilities. UAVs offer a diverse range of services to mobile users, including signal relaying, data caching, and computing [43]. Particularly in densely populated areas with high traffic, UAVs can collaborate with stationary network infrastructure nodes, such as base stations, to effectively manage the wireless network and enhance user experience. Leveraging their unrestricted three-dimensional mobility, UAVs can act as aerial agents for various unique V2X applications. These applications encompass timely reporting of road accidents before the arrival of rescue teams, monitoring traffic violations to support law enforcement agencies, and broadcasting warnings about road hazards in areas without existing RSUs [44]. Despite significant advancements in UAV technology, several challenges persist in the realm of UAV-assisted V2X systems. One prominent challenge involves establishing consistent and high-speed wireless communication between UAVs and ground vehicles, as the movements of both UAVs and ground vehicles introduce constantly changing channel characteristics. Overcoming this challenge is paramount to ensure reliable connectivity and seamless information exchange in UAV-assisted V2X systems.

Aerial communication via satellites holds the potential to become a fundamental component of 6G-V2X networks. Currently, satellites are heavily relied upon in V2X standards for localization purposes; however, this paradigm may undergo advanced development in the future. It is important to acknowledge the notable increase in satellite data rates observed in recent years. Consequently, exploiting satellites for signal transmission shows promise in enabling 6G-V2X to facilitate communication between vehicles and remote data servers in scenarios where terrestrial coverage is not available. Similar to UAV-based V2X communication, satellites possess the capability to handle computing and network management tasks. Nevertheless, the establishment of satellite-assisted V2X communication necessitates precise investigation and modelling of channel characteristics between high-mobility vehicles and satellites. Furthermore, integrating diverse communication mechanisms, such as transmission protocols at the PHY or MAC layer in V2X and satellite communications, poses a significant challenge. From a PHY perspective, a primary research concern revolves around achieving maximum power transmission efficiency for long-range and high-rate satellite communications. The use of OFDM may prove inadequate in attaining this objective due to its high peak-to-average power ratio (PAPR), which restricts its maximum communication coverage.

1.5.2.5 Integrated computing

Cloud computing, a widely utilized technology in vehicular networks, may face limitations when it comes to fulfilling the stringent time-critical demands of V2X networks. Fortunately, a promising alternative known as edge/fog computing has emerged to address this challenge. Edge computing enables decentralized data processing by executing computational tasks on nodes situated in close proximity to end users. Fog computing involves interconnected layers that facilitate seamless communication between remote cloud and edge nodes [45]. By leveraging the computational capabilities of edge/fog nodes located at the periphery of the network, the 6G V2X network holds the potential to provide personalized, scalable, and highly responsive services to vehicles. The intricate algorithms inherited in V2X networks can be efficiently handled by offloading complex computing operations to edge/fog nodes. An illustrative example is real-time navigation in congested traffic scenarios, which can greatly benefit from the integration of fog computing. This approach offers rapidly distributed computing, enhanced security, and cost-effectiveness, rendering it highly suitable for the specific requirements of V2X networks.

1.6 Conclusions

This chapter provides a comprehensive analysis of NET-Zero ITSs and highlights the crucial role of 6G networks in ITS technology, mitigating carbon emissions. The findings underscore the significance of integrating advanced technological solutions to address the pressing global challenge of climate change. Firstly, NET-Zero ITSs have emerged as a promising approach to curbing carbon emissions in the transportation sector. By leveraging intelligent systems, data analytics, and connectivity, these systems enable efficient traffic management, optimized routing, and enhanced V2V communication. The research demonstrates that the implementation of such systems can lead to substantial reductions in fuel consumption, congestion, and overall environmental impact. Furthermore, the advent of 6G technology is poised to revolutionize the transportation industry and further enhance the effectiveness of NET-Zero ITSs. The ultra-high-speed, low-latency, and massive connectivity capabilities of 6G enable seamless integration of various components, such as autonomous vehicles, smart infrastructure, and real-time data analytics. This integration unlocks new possibilities for optimizing transportation networks, reducing energy consumption, and improving overall sustainability. Importantly, the research reveals that the successful implementation of NET-Zero ITSs and 6G technology requires collaborative efforts from stakeholders across multiple domains. Policymakers, industry leaders, researchers, and the public must collaborate to establish supportive regulations, invest in infrastructure development, foster innovation, and promote public awareness. Looking ahead, this chapter provides valuable insights into the future prospects of NET-Zero ITSs and 6G technology. In conclusion, the convergence of NET-Zero ITSs and 6G technology presents an unparalleled opportunity to address carbon emissions in the transportation sector. By leveraging advanced connectivity, data analytics, and collaborative efforts, we can pave the way towards a more sustainable and environmentally conscious future.

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