Chapter 7

Wireless Communications Advancements for Future Transportation*

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7.1. Introduction

The transportation sector is undergoing a revolutionary transformation driven by the convergence of wireless communications, autonomous systems, and intelligent mobility solutions. Modern transportation systems rely heavily on seamless communication between various entities through Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Vulnerable Road User (V2VRU) channels, collectively forming Vehicle-to-Any (V2X) communications that serve as the backbone of Intelligent Transportation Systems (ITS). These systems enable real-time information exchange supporting Advanced Driving Assistance

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Systems (ADAS), autonomous driving, traffic management, and emergency response services across vehicular, railway, and aviation domains.

The unique characteristics of transportation environments present significant challenges for wireless communication system design, including high mobility, rapidly changing propagation conditions, and stringent latency requirements for safety-critical applications. Radio channel characterisation becomes crucial for understanding propagation characteristics across V2V, train-to-train, and aircraft-to-aircraft scenarios, each presenting distinct challenges in terms of modelling and system design due to fast fading, Doppler effects, and intermittent connectivity.

This chapter provides a comprehensive exploration of wireless communication for transportation, examining advanced technologies that promise to address evolving mobility demands. We investigate integrated sensing and communication, Multiple Input Multiple Output (MIMO) systems with beam management, cell-free networks, and dynamic frequency selection mechanisms. Additionally, we explore Uncrewed Aerial Vehicle (UAV) integration through drone-mounted Base Stations (BSs) and cooperative awareness systems, concluding with essential testing and validation methodologies including Digital Twin (DT) technology for system development and optimisation.

7.2. Radio Channel Characterisation for High-mobility Systems

7.2.1. Vehicle-to-Vehicle Communication

The characterisation and modelling of V2X channels are crucial for evaluating performance of V2X communication systems. Currently, there have been several researches on V2X channel measurement and modelling. These include both scenario-specific and frequency-specific cases, such as measurements for urban [1], rural [2], highway [3], and intersection [4] environments, as well as for various frequency bands such as Sub-6 GHz [5], millimetre-wave band (mmWave) [6], and Terahertz (THz) [7]. A realistic V2X real-time simulation framework named SIVERT is introduced in [1], specifically addressing the challenges of urban environments. This framework integrates the VENERIS project implemented in Unity3D and Network Simulator 3 (NS-3), adopting the Geometry-Based Stochastic Channel Model (GSCM) approach to ensure spatially consistent channel modelling in complex urban multi-path propagation environments. The framework supports accurate modelling of urban scenarios where buildings, intersections, and dynamic vehicle interactions contribute to highly variable channel conditions. Moreover, it enables detailed antenna modelling through the Effective Aperture Distribution Function (EADF), which is essential for capturing the intricate propagation effects typical of urban environments. The study in [8] discusses the wireless channel measurements for V2V, V2I, and vehicle-to-pedestrian communication, which were conducted at two frequency bands: 3.2 GHz and 5.81 GHz. The dataset includes synchronised sensor data such as Radar, Light Detection And Ranging (LiDAR), and Global Positioning System (GPS). The measurement system employs an Orthogonal Frequency Division Multiplexing

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(OFDM)-based multi-band channel sounder, with an effective bandwidth of 150.25 MHz and 601 Subcarriers (SCs) spaced by 250 kHz. The dataset also provides Frame Error Rate (FER) measurements based on Institute of Electrical and Electronics Engineers (IEEE) 802.11p communication systems. The results enable a detailed study of V2X channel characteristics and their interaction with environmental factors, offering valuable insights for the development and evaluation of future V2X communication systems. In [6], a joint Sub-6 GHz and mmWave V2I MIMO channel measurement campaign was conducted with a particular focus on characterising the mmWave band at 26.5 GHz. This frequency band is of particular interest due to its potential to provide ultra-high data rates and low-latency communication required for advanced V2X systems. The measurements were performed in an urban environment using two real-time channel sounders operating simultaneously at 5.93 GHz (Sub-6 GHz) and 26.5 GHz (mmWave). The experimental setup involved distributed antennas for the Sub-6 GHz band and a single omnidirectional antenna for the mmWave band, specifically designed to evaluate Power Delay Profile, Doppler Spectral Density, and Path Loss (PL).

7.2.1.1. Dynamic Vehicular Integrated Sensing and Communication (ISAC) Channel Model

Existing research is insufficient for addressing vehicular sensing channels. As a key application in Sixth Generation (6G) networks, ISAC-aided V2X communication plays an essential role in enhancing vehicle safety and performance. For example, many communication transceivers and sensors are equipped on autonomous vehicles, and it is possible to reuse the current dense deployment of roadside units for sensing environments with only minor modifications in hardware, signalling strategy, and standards.

To fully realise the potential of ISAC-aided V2X communications, a deep understanding of the radio propagation mechanisms in vehicular sensing channels is essential. Due to their strong sensitivity to environmental variations, modelling dynamic vehicular sensing channel remains a challenging task. In particular, the key characteristics of vehicular sensing channels – such as Sensing Multipath Components (S-MPCs) and Clutter Multipath Components (C-MPCs) – need to be effectively captured in measurements [9]. The dynamic vehicular sensing channel measurement is conducted in the Songshanhu district of Dongguan, located in Guangdong, China, at a frequency band of 28 GHz as in [10]. The mean vehicle speed during the measurements is 30 km/h. The vehicular sensing channel measurement system based on Vector Signal Transceiver (VST) is designed, including a signal generator-based Transmitter (Tx), a signal digitizer-based Receiver (Rx), and a power supply based on the vehicular battery. The Tx and Rx use a directional horn antenna and a 4×8 array antenna, respectively. The sounding signals are multicarrier signals with 1 GHz bandwidth, and are transmitted with the maximum power of 28 dBm. During the measurement, Red Green Blue (RGB) video data from the camera and point-cloud data from the radar are collected and stored simultaneously to aid in mapping between channel multipaths and environmental scatterers. As illustrated in Fig. 7.1, S-MPCs generally exhibit

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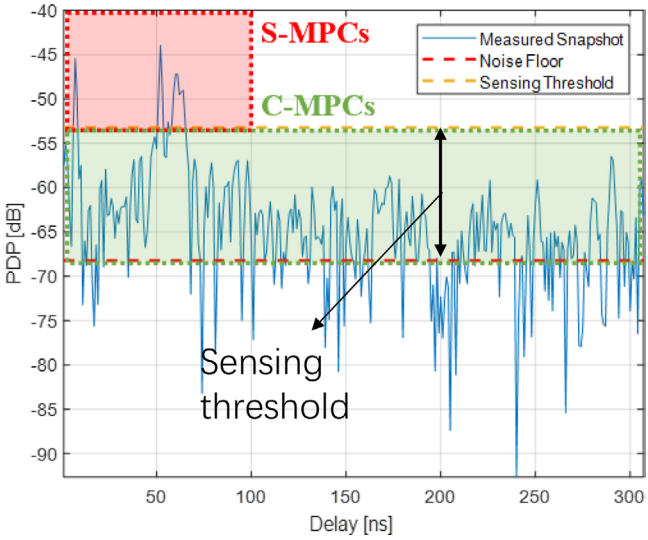

Fig. 7.1. Sensing Multipath Components (S-MPCs) (Red, Upper, Square) and Clutter Multipath Components (C-MPCs) (Green, Lower, Rectangle) in Vehicular Sensing Channels. (Colour interpretations are provided. Please refer to the digital version for colour figures.)

higher power and form more distinct clusters, which can be attributed to strong reflections from sensing targets. These components evolve continuously over time, reflecting the dynamic interaction between the vehicle and its surroundings. In contrast, C-MPCs usually have lower power and a more scattered distribution across the delay domain, resulting from reflections by unknown scatterers. Moreover, typical characteristics such as multipath birth and death, sparsity, and non-stationarity differ significantly from those observed in conventional vehicular channels, highlighting the need for dedicated investigation.

7.2.1.2. Vehicle-to-Vulnerable Road Users Channel Models

Direct V2VRU communication can prevent accidents by enabling 360° awareness and improving localisation, detection, and tracking of both Vulnerable Road Users (VRU) and vehicles. To develop a reliable V2VRU communication system, an accurate and realistic propagation channel model is required. The first complete parametrization and validation for WINNER-type V2VRU GSCM at 5.2 GHz based on channel sounding measurements is presented in [11]. Three critical accident scenarios between a vehicle and a VRU in urban streets were considered. A detailed description of the measurement systems and scenarios can be found in [12].

To parametrise the GSCM channel model following the WINNER approach, the Large-Scale Parameters (LSPs) and their correlation properties are estimated in the logarithmic domain. The findings indicate that the LSPs follow the log-normal distribution with good accuracy. The proposed model is validated by

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comparing the distributions of the model parameters derived from the simulated channels against those obtained from the measured channels. The validation confirms that the proposed channel model provides a very good representation for the V2VRU propagation channel in the studied scenarios. Consequently, this channel model can be employed in simulations aimed at developing and evaluating V2VRU communication and collision avoidance algorithms in critical accident scenarios. In [13], further validation of the channel model is presented. The link-level performance of IEEE 802.11p in terms of Packet Error Ratio (PER) is evaluated using several channel models. As can be seen in Fig. 7.2, when comparing the PER of the measured channel with that of other channel models, the proposed GSCM provides a more realistic performance compared to the optimistic performance obtained by the Tapped Delay Line (TDL) channels.

7.2.2. Train-to-Train Communication

Wireless communication systems and technologies have become indispensable to modern railway operations. This section explores the foundations and advancements of railway communication systems, with a focus on Train-To-Ground (T2G) and Train-To-Train (T2T) communications. It highlights the importance of channel sounding and modelling to ensure robust, low-latency, and reliable wireless links for applications such as autonomous trains, virtually coupled train sets, remote operations, and next-generation train control and management system. In order to draw conclusions about the wireless propagation conditions and

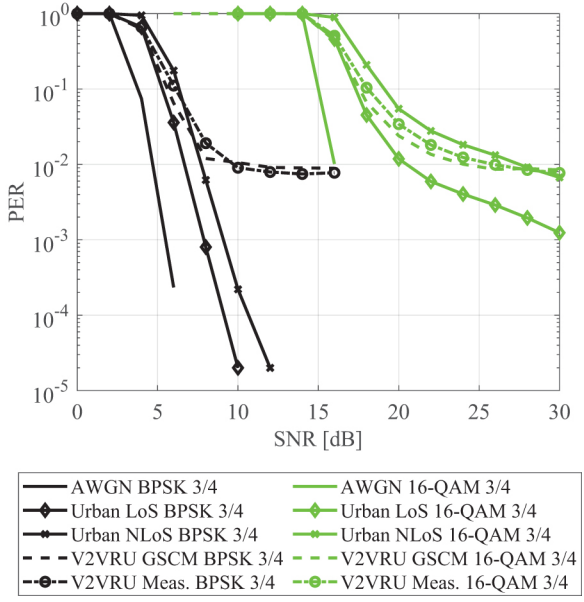

Fig. 7.2. Packet Error Rate Versus Signal to Noise Ratio for Two Modulation and Coding Schemes (MCSs) and Different Fading Channel Models.

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to derive State-of-the-Art (SoA) channel models in different scenarios, measurements are of utmost importance. In recent years, different channel measurements have been conducted for T2G and T2T.

Channel sounding results of T2G massive MIMO measurements at two frequencies (1,890 MHz and 748 MHz) for a railway station scenario were presented in [14]. The results show differences in Root Mean Square (RMS) Delay Spread (DS), hardening factor, and PL coefficients between the two frequency bands.

For railway station communication, the signal propagation is influenced by several unique factors including the architecture of the station, moving trains, and various obstacles like lifts and underpasses. The complexity of these environments necessitates advanced modelling techniques to ensure reliable communication. One study conducted a Ray Tracing (RT) simulation to evaluate Fifth Generation (5G) coverage in railway stations, particularly in medium-sized stations. The study used the 3.7 GHz frequency, as this band provides a good balance between coverage and capacity. The simulation revealed significant coverage gaps due to the interference from metal structures such as trains and lifts. Those objects create shadow areas with poor signal reception [15].

The world's first T2T channel sounding measurements with high speed trains were conducted in railway stations, open field and hilly terrain with cutting scenarios. Based on those measurements in Italy in 2016, several channel models were derived. First, stochastic model parameters for railway station, open field, and hilly terrain environments were derived in [16]. Parameters like PL exponent, log-normal shadow fading distribution, *K*-factor, RMS delay, and RMS Doppler Spread were extracted. Second, a TDL model was derived in [17]. The model was used to analyse IEEE 802.11bd capabilities for T2T communication in typical railway environments. Third, a GSCM for T2T communications was designed. For the open-field environment the GSCM was presented in [18, 19]. The GSCM was also designed for railway stations and in hilly terrain with cutting environments. The model considers typical railway objects like rails and the overhead line system including regular appearing masts, sparsely occurring close buildings, cross bridges, cellular radio masts, and trees, as well as large walls and cuttings close to the tracks. The environment can be adapted like in Fig. 7.3 and the movement model of the trains can be varied which allows the analysis of various scenarios and the time-variant behaviour of the T2T propagation channel. Antenna position and characteristics can be added to the model.

Resilient communication systems with redundant and parallel links need to be designed for T2G and T2T communications. Furthermore, security aspects need to be taken into account on all levels of future railway communication systems. To enable the full potential of future communication systems site-specific channel

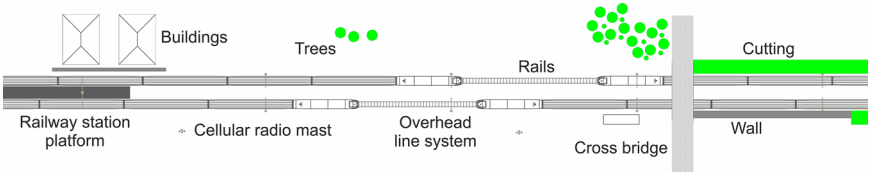

Fig. 7.3. Architecture of the GSCM for T2T Communications.

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models including typical railway objects should be used in standardisation and testing. The authors of [20] present the findings of the IEEE P1944 site-specific channel representation standardisation group, that argues for a geometry-based double-directional multi-path component based channel representation for challenging railway scenarios.

7.2.3. Aircraft-to-Aircraft Communication

Aircraft-to-Aircraft (A2A) communication plays an increasingly important role within the broader ITS framework, particularly as the scope of ITS expands beyond terrestrial modes to include aerial mobility. By enabling real-time exchange of position, velocity, and intent information, A2A communication supports cooperative air traffic management, enhances situational awareness, and facilitates autonomous or semi-autonomous flight operations. These capabilities mirror V2V communication in ground ITS, contributing to improved safety, efficiency, and scalability of airspace usage. Furthermore, A2A communication is integral to emerging applications such as unmanned aerial systems traffic management and urban air mobility, making it a vital component of future multimodal, connected, and intelligent transportation ecosystems.

Mobile-to-Mobile (M2M) propagation channels have garnered increasing attention in recent years, driven by the development of advanced communication systems for a wide range of mobile platforms, including aircraft, drones, automobiles, and maritime vessels. However, most existing channel models are designed for average or worst-case conditions and typically overlook the specific characteristics of the environment in which the Tx and Rx operate. As a result, they lack the ability to accurately capture channel behaviour in non-stationary scenarios. This limitation is especially evident in the treatment of scattering components, which are often neglected or modelled using coarse approximations derived from unrelated environments. For M2M channels, one of the most severe problems when modelling the channel is its non-stationarity. This is especially true for A2A channels, since the velocities of both Tx and Rx are higher compared to other M2M channels. Another important difference is the more complex geometry, where a full Three-dimensional (3D) model is needed, whereas for car-to-car channels often Two-dimensional (2D) models are adequate.

Channel models are used to take the propagation effects into account that affect the transmitted signal on its way to the Rx. Those effects include reflection, scattering, and diffraction. Compared to other mobile-to-mobile channels, the aircraft-to-aircraft channel is quite different from the others. For aircraft flying at high altitudes, there is mostly only the Line of Sight (LoS) channel. For aircraft flying at low altitudes, the specular reflection and the scattering from the ground have a larger effect on the propagation.

The classical channel model used in the aeronautical community stems from Bello in [21]. There, the channel consists of a LoS component, a specular reflection, and scattered components. Both the LoS component and the specular reflection can be modelled by means of RT. This can be directly extracted from the geometry or from global navigation satellite system positions. The LoS component is mainly characterised by a complex gain determined by the free-space loss and the antenna

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patterns. For the specular reflection, the complex gain describes the effects of Tx and Rx gain in the specular reflection direction and free-space PL. Additionally, a complex gain accounts for the electrical and roughness properties of the surface.

The scattering coming from the ground is much harder to model compared to the LoS and the specular reflection components, since its statistics are highly non-stationary for certain scenarios. Especially for aircraft flying at low altitudes, like military aircraft in a sortie or civil aircraft landing as shown in Fig. 7.4, the scattering has enough power to affect the communication signal [22].

For modelling non-stationary scattering, we present in [23] a channel modelling method for M2M propagation that utilises an explicit geometric representation of the environment to derive the time-varying channel between two mobile stations. The proposed method is applied to a range of scenarios – including A2A, drone-to-drone, V2V, and ship-to-ship communications – and its performance is evaluated against empirical data from multiple channel measurement campaigns. Across all scenarios, the model demonstrates high accuracy in reproducing the non-stationary channel characteristics, including LoS, specular reflection component, and scattering components. The highest fidelity is observed in environments where scatterers can be effectively approximated by planar surfaces, that is, when their geometric irregularities are minor relative to the overall structure. Furthermore, the method enables dynamic tracking of the channels evolution as the Tx and Rx move, and provides insight into the specific reflectors or scatterers responsible for distinct features in the delay and Doppler domains.

7.3. Advanced Technologies for Future Mobility

7.3.1. Integrated Sensing and Communication

ISAC unifies data exchange and environmental perception in a single system, promising spectrum and energy efficiency for ITS [24–26]. Despite its potential, ISAC in ITS faces challenges from dynamic radio environments, stringent reliability and latency needs, and network congestion [27–29]. Addressing these requires innovations in system integration – from shared spectrum and waveform

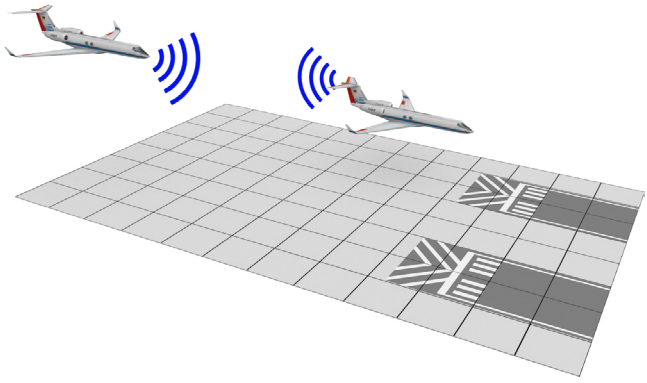

Fig. 7.4. Schematic Aircraft-to-Aircraft Communication Link While Landing on Parallel Runways to Enable Tighter Scheduling.

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design to dynamic task scheduling and architecture adaptations. Use-cases span from intrusion detection and parking assistance to emergency vehicle routeing and smart traffic management [30–32].

Reliable ISAC operations depend on advanced propagation models that reflect urban complexity, mobility, and frequency diversity. For example, the single road bridge model captures additional losses from obstructions [33]. Waveform design is also pivotal, with OFDM remaining dominant for its communication advantages, while radar-centric and joint designs (e.g., CAESAR, Orthogonal Time Frequency Space (OTFS), Orthogonal Chirp Division Multiplexing (OCDM)) address sensing accuracy and Doppler resilience [34–40]. Time-synchronised multi-band channel measurements reveal correlations exploitable for efficient beam alignment [41]. Meanwhile, sub-6 GHz Multipath Components (MPCs) are leveraged in Multipath-enhanced Device-Free Localisation (MDFL) [42, 43]. Machine Learning (ML) also plays a growing role, such as using neural networks for real-time radar-based angle estimation [44] and reflectivity-based classification of road users [45]. These advances in channel modelling, waveform design, and intelligent inference underpin the viability of scalable, reliable ISAC systems in future ITS deployments. As illustrated in Fig. 7.5, for example, an ISAC node with both communication and sensing capabilities can be used to detect (illustrated with radio beams) cyclists and passengers around an intersection, while the detected information can be communicated (illustrated with arrows) with the vehicles approaching the intersection.

7.3.2. MIMO System and Beam Management

In its design phase, the automotive industry has been considered a key vertical sector, where 5G is expected to provide the connectivity platform for early automated driving deployment. 6G V2X communications will support fully automated vehicles in complex scenarios, requiring extreme data rates (~ 1 Tbps) and ultra-low latency (< 1 ms). This necessitates spectrum shifting to high frequencies, as envisioned by

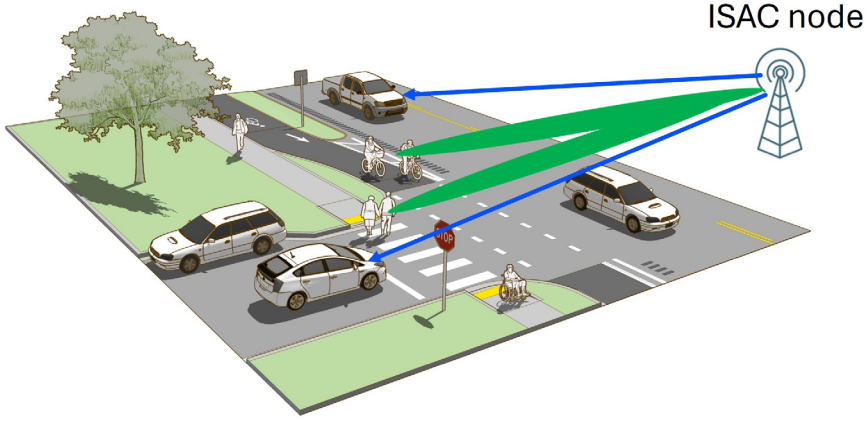

Fig. 7.5. Illustration of ISAC Application at Road Intersections (Edited on an Intersection Figure of www.ruraldesignguide.com).

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3rd Generation Partnership Project (3GPP), which introduced Frequency Range 2 for V2X in both Uplink (UL)/Downlink (DL) and Sidelink modes.

This revolution demands a radical transformation of the physical layer and advanced processing for precise spatial beamforming. Narrow-beam communications enhance spectral and energy efficiency. Studies on electromagnetic propagation highlight MIMO antenna arrays as essential for spatial radiation confinement and PL compensation.

Effective high-frequency communication requires beam alignment at both ends during initial access or after disruptions, incurring high beam training overhead. Vehicular mobility further complicates beam tracking.

Recent developments in vehicular communication systems underscore the importance of robust MIMO architectures and advanced beam management strategies to support reliable connectivity in dynamic, high-mobility scenarios. For example, in [46], a predictive relaying framework is proposed that proactively selects communication links based on anticipated radio conditions, effectively addressing challenges such as PL and beam-blockage in sub-THz internet of vehicles. Similarly, Conserva *et al.* introduce a UAV-assisted beamforming approach for Sidelink V2V communications, optimising radio-resource assignment by dynamically adjusting UAV parameters, such as altitude, in response to traffic density and network load [47]. These approaches highlight the shift towards context-aware, adaptive solutions for beam management that can ensure sustained Quality of Service (QoS) in the demanding environments of next-generation vehicular networks.

7.3.3. Cell-Free Networks for Vehicular Applications

An alternative to cellular networks is the recently introduced cell-free network architecture, which removes cell boundaries [48, 49]. In this system, multiple Access Points (APs) jointly serve all User Equipments (UEs) within a given area, rather than assigning a UE to a single AP. These APs are connected to a Central Processing Unit (CPU) via wired or wireless fronthaul links. The CPU coordinates AP cooperation, improving network efficiency. The network is divided into an edge and core, similar to cellular networks: APs and CPUs form the edge, while backhaul links connect CPUs to the core network, facilitating internet access and other data services. The fronthaul links serve three key purposes: sharing physical-layer signals for DL transmission, forwarding UL data signals to be decoded, and exchanging Channel State Information (CSI) to optimise signal processing.

The MaMIMOSA sounder from the University of Lille (France) was set up to emulate a small, yet realistic cell-free network and measure the time-varying radio channel at 5.89 GHz with an 80 MHz bandwidth in a suburban environment. Four AP configurations were investigated from fully co-located to fully distributed antennas to study the Signal to Noise Ratio (SNR), delay and Doppler spread values, or PL [6, 50]. The first one consists of one AP equipped with eight antennas (Config. 1), the second consists of two APs equipped with four antennas each (Config. 2), the third consists of four APs equipped with two antennas each (Config. 3), and the fourth consists of eight single-antenna APs (Config. 4).

Cumulative Distribution Function (CDF) of the SNR (Fig. 7.6a) and DS (Fig. 7.6b) depicted reveal a distinct benefit of the three distributed configurations

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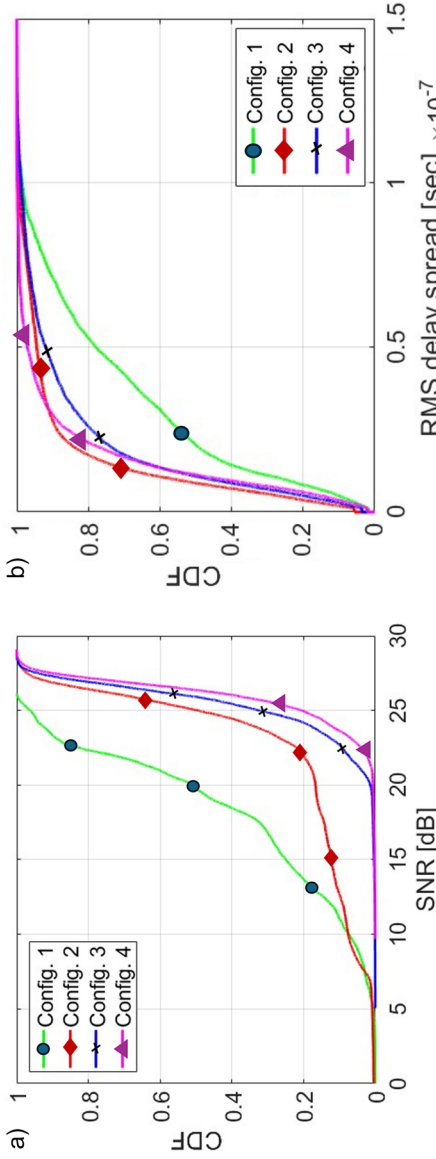

Fig. 7.6. For the Four AP Configurations, CDF of (a) the SNR and (b) the RMS DS.

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over the centralised one. Despite using only eight transmit antennas – a figure lower than typically expected in a functional distributed massive MIMO network – the study confirms the potential advantages of cell-free networks compared to co-located antennas, exhibiting a higher and more spatially consistent SNR. Additionally, examining the PL properties in the cell-free network offered essential insights for effectively placing APs in the given scenario.

7.3.4. Dynamic Frequency Selection

Dynamic spectrum management is a critical enabler for reliable V2X communication in ITS, particularly as Radio Frequency (RF) demand surges due to the growing density of connected vehicles and mobility services [51]. This work builds on the concept of vehicular dynamic spectrum access [52], proposing the offloading of autonomous platooning traffic from the heavily used 5.9 GHz ITS band to underutilised Television White Space (TVWS). The TVWS offer a relatively stable spectral environment due to the static nature of Digital Terrestrial Television (DTT) Txs and frequency allocations, making them well-suited for predictable vehicular communication. A key component of this approach is the use of an Edge Intelligence System (EIS) [53], supported by a context database that stores measurements of DTT signal strengths, platoon transmission data, and regulatory constraints. The EIS dynamically selects frequencies to optimise both communication reliability and protection of primary DTT users. Three EIS architectural models – centralised, distributed, and hybrid – can be considered, as depicted in Fig. 7.7. The hybrid model provides the best trade-off, maintaining high message reception success rates, strong DTT protection (in terms of Signal-to-Interference Ratio), and reduced frequency switching. The centralized model, while strong in interference mitigation, degrades communication at the platoon

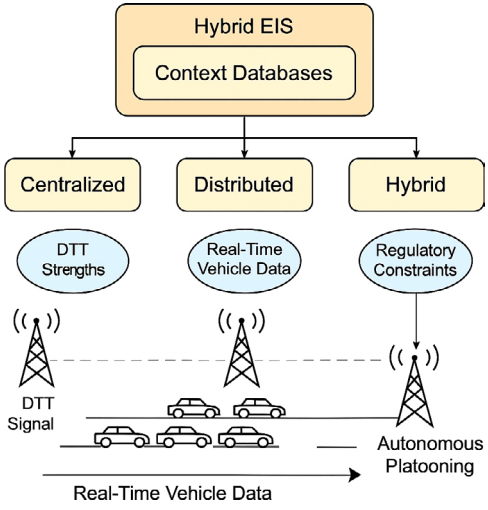

Fig. 7.7. Proposed Model Architecture.

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tail due to its conservative frequency choices. The distributed model allows local autonomy but suffers from coordination delays and frequent reconfiguration.

To complement these strategies, a reinforcement learning method based on Q-learning is introduced to guide frequency allocation decisions. The system state is defined by discretised platoon positions, and the actions represent channel assignments. The Q-learning algorithm, trained offline with a low exploration rate ($\varepsilon = 0.01$), outperforms distributed baselines, particularly in scenarios with high communication latency. It minimises channel switching – avoiding the "ping-pong" effect – and delivers stable performance across varying traffic dynamics. Despite scalability challenges due to exponential state–action growth, the Q-learning-based VDSA method demonstrates strong potential when applied with offline training. These findings align with recent studies [54–56], which emphasise the importance of adaptive, hybrid, and AI-driven spectrum sharing frameworks for managing dynamic and interference-prone ITS environments. In summary, combining EIS with machine learning strategies offers a promising pathway to scalable, low-latency, and interference-aware spectrum access for next-generation vehicular networks.

7.4. UAV Integration into Transportation Systems

7.4.1. Drone-Mounted Base Stations

Network densification, introduced in 5G technology [57], is considered a promising approach to enhance network capacity and meet growing traffic demands by deploying a dense infrastructure of small cells. However, this strategy incurs significant Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). Moreover, densification often leads to over-provisioning, deploying more network resources than necessary to handle peak traffic. Studies show that, during 30% of weekday hours, BS traffic load is less than one-tenth of the peak value [58]. While this ensures network stability and high availability, it results in substantial resource underutilisation. An alternative approach was introduced in [59, 60], based on the integration of Macro Base Stations (MBSs) into the network landscape. In this paradigm, MBSs are typically small cells mounted on vehicles or other mobile platforms that can be dynamically deployed to deliver additional capacity precisely where and when it is needed. This enables more effective handling of localised traffic surges and has the potential to reduce the need for static over-provisioning. UAVs are emerging as promising platforms for the deployment of antennas due to their unique operational capabilities, so they can be used to deploy MBSs.

However, mobility necessitates wireless backhauling. Integrated Access and Backhaul (IAB) has been proposed as a solution that leverages the same technologies and spectrum resources already used in cellular networks to provide backhaul connectivity, thereby eliminating the need for additional infrastructure deployment. While the installation cost of IAB is minimal, the consumption of network resources for backhauling remains non-negligible. In [60], the authors proposed an analytical framework to evaluate the performance of a hybrid network architecture,

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where mobile infrastructures are connected to static, wired infrastructures via in-band wireless backhauling. The system is analysed across various densities of connected users to assess the impact of IAB on network resources. The primary objective is to minimise the total amount of installed infrastructure while considering the density of both mobile and stationary infrastructures, and the round-robin weight ϕ. The round-robin parameter enables stationary infrastructures to adjust the allocation of resources designated for fronthaul transmissions with UEs and backhaul transmissions for macro BSs. This adjustment is made while ensuring that the target QoS standards are met for both fronthaul and backhaul communications. The performance of the system is measured in terms of the per-bit delay, defined as the inverse of the short-term throughput. The performance targets are attained if the per-bit delay is lower than the target value τ_0. To evaluate the benefits of mobility, the study considers the various relative costs associated with static and mobile infrastructures. These costs include installation expenses, reusability, and the ease of use of mobile small cells. The relative cost comparison between mobile and static cells is denoted as μ. As visible in Fig. 7.8a, when the relative cost of macro BSs drops to 0.1 or below, a hybrid deployment becomes optimal for a specific range of user density. In this scenario, MBSs serve the users, while static BSs support backhaul links. For very low and high user densities ($\geq 10^{-2}$ users/km^2), the backhaul cost becomes prohibitive, and the system reverts to a static-only deployment. As visible in Fig. 7.8b, the MBSs density and round-robin weights adapt to maintain a constant low user load per BS, minimising backhaul weight on BS resources. The transition to static-only configurations occurs when round-robin weights become too small, indicating excessive backhaul usage, making MBS-based setups less efficient. These trends highlight the significant impact of QoS-aware inband wireless backhauling on network resource efficiency. However, this is

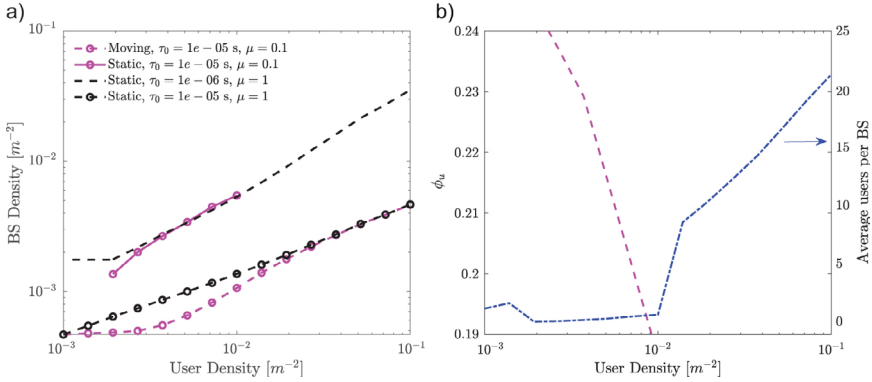

Fig. 7.8. Optimal Network Configurations as a Function of User Density, for Different Target QoS Values, and Different Relative BS Unitary Cost μ (Ratio Between the Unitary Cost of MBSs and Small BSs. (a) Optimal BS Densities; (b) Round Robin Weight ϕ at Optimum for Backhauling Links. The Pink Dashed Curve Corresponds to the ylabel on the Left While the Blue Dash-Dot Curve Corresponds to the ylabel on the Right. (Colour interpretations are provided. Please refer to the digital version for colour figures.)

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mitigated by considering the reusability of MBS and further reducing the relative cost between static and moving infrastructures.

7.4.2. Cooperative Awareness for UAV Communication

Modifications to the existing European Telecommunications Standards Institute (ETSI) Cooperative Awareness Message (CAM) specification are required to provide ITS benefits to UAV communication. One major shortcoming of the current CAM structure is its inability to account for the 3D mobility of UAVs. Addressing this shortcoming, a modified UAV-CAM specification that supports 3D mobility, path planning, and other UAV-specific dimensions has been introduced in [61]. To enable this, new sub-containers have been added to carry information related to the vertical dimension in terms of size, position, and movement. The existing size fields have also been adapted to accommodate the wide range of UAV dimensions. Furthermore, to support improved route management, an optional container has been introduced to share path history and anticipated path points. The high-level structure of this suggested UAV-CAM is shown and compared against conventional CAM in Fig. 7.9a and 7.9b. Established vehicular communication standards such as IEEE 802.11p, IEEE 802.11bd, Long Term Evolution (LTE), and NR-V2X offer high data rates, low latency, and reliable connectivity, making them promising candidates for UAV-CAM [62]. However, their size, power consumption, and infrastructure dependencies may pose challenges for smaller UAVs or those operating in constrained environments. Consequently, alternative communication technologies such as Bluetooth Low Energy (BLE) present a viable solution for lightweight UAVs, ensuring efficient cooperative awareness while maintaining energy efficiency.

The feasibility of utilising BLE for UAV-CAM in miniature UAVs has been demonstrated through BLE-based proof-of-concept implementations [63]. The reported experiment demonstrates the feasibility of sharing cooperative information between UAVs operating up to 90 m apart while utilising BLE 2M physical layer (PHY). In a separate evaluation of BLE performance for UAV-CAM, a communication range of up to 75 m was achieved using the BLE 1M PHY [64]. As an extension of this work, the experimental PER performance of BLE Coded PHY against distance is depicted in Fig. 7.10. The results are compared against analytical models from literature [64].

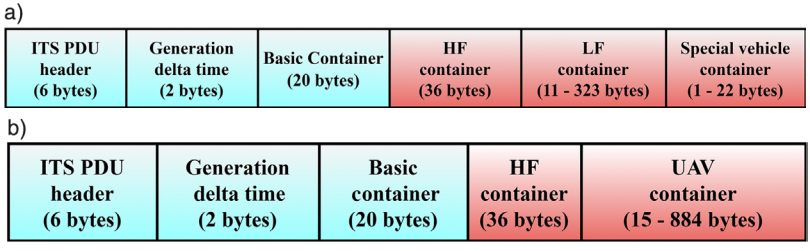

Fig. 7.9. The High-level Structure of (a) ETSI CAM and (b) Modified UAV-CAM.

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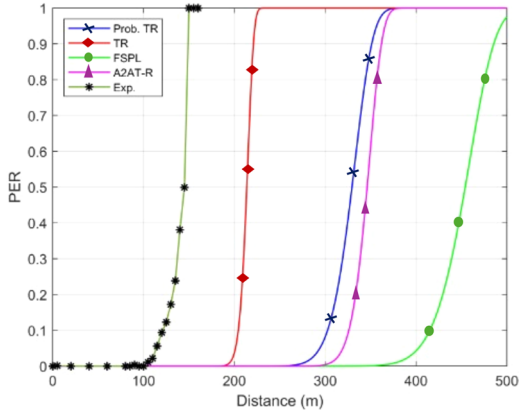

Fig. 7.10. PER Versus Distance for UAV-CAM Operating Over BLE Coded PHY.

7.4.3. Link Quality Monitoring and Drift Detection

Equipped with a plethora of sensors (e.g., motion, positioning or imaging) and communication modules, UAVs can form dynamic Flying *ad hoc* Networks for sensing and data exchange. Thanks to their mobility and rapid deployability, UAVs often establish temporary communication backbones, ensuring continuous coverage across large regions and enabling efficient multi-hop relay communication. However, maintaining reliable performance in highly dynamic and unpredictable environments (e.g., rapidly changing propagation conditions due to obstructions, fluctuating traffic demand or varying interference patterns) remains a critical challenge, as these lead to concept drift [65], that is, changes in the underlying distribution of observed link quality metrics. Detecting significant channel variations is a non-trivial task given the unpredictability of the wireless channel [66] and the challenge of distinguishing persistent from temporary fluctuations [67].

To address these challenges, autonomous UAVs must monitor link performance in real-time and reconfigure the swarm (e.g., adjust inter-UAV distance or add new nodes) upon detecting significant changes through model drift, as static formations become sub-optimal over time. Ineffective link monitoring may trigger unnecessary reconfigurations, degrading system performance. An adaptive, distributed formation control strategy that continuously monitors neighbour links using Packet Delivery Ratio (PDR) to neighbour nodes and employs a lightweight statistical method for channel drift detection has been introduced [68]. Upon detecting significant and persistent changes, three control strategies to dynamically reconfigure the UAV swarm to maximise the end-to-end (E2E) PDR, while maintaining backbone reliability, are proposed and compared. Simulation results show that an optimal placement strategy significantly outperforms baseline approaches for line-based UAV networks.

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7.5. Testing and Validation of Vehicular Communication Systems

7.5.1. Testing of Vehicular Communication Systems

Connected Cooperative and Automated Mobility (CCAM) can benefit from reliable wireless V2X communication links in safety and time critical situations. The ego vehicle's perception with LiDAR, RADAR and cameras is limited by the LoS. It can be augmented by V2X communication beyond the visible LoS with sensor information from other cooperative vehicles or infrastructure elements in the near vicinity.

Exhaustive testing and validation are crucial to ensure that all elements within such a CCAM system function cohesively, resulting in successful performance across various scenarios. Regarding the wireless communication link, two testing methods are possible: (i) drive tests with a fully equipped vehicle and (ii) (scenario-based) closed vehicle-in-the-loop tests. Testing and validating ADAS features requires numerous kilometres to be driven and tackling various challenging traffic scenarios [69]. Therefore, conducting drive tests is not feasible during the design and prototyping phase of ADAS features. However, vehicle-in-the-loop tests can be applied in different development phases [70] and enable cost-efficient tests in controlled environments that can be easily repeated. The local V2X communication channel quality/reliability is a key information required for such vehicle-in-the-loop tests.

In order to address this missing information, a methodology for predicting the FER of V2X communication channels is presented in [71]. Deep Neural Network (DNN) is employed for predicting the expected FER using a *single* received data frame. The DNN is trained in a supervised fashion, where a time-limited sequence of channel frequency responses has been labelled with its corresponding FER values assuming an underlying wireless communication system, for example, IEEE 802.11p, LTE vehicular or 5G. For generating the training data set a GSCM is utilised as well as a hardware-in-the-loop setup. The site-specific channel emulation setup for the hardware-in-the-loop approach is compactly explained in [72].

The ground truth FER is obtained by emulating the time-varying frequency responses using a hardware-in-the-loop setup. The GSCM provides the propagation path parameters per stationarity region, enabling the FER estimation with arbitrary precision. With this unique dataset, [71] achieves an accuracy of 85% for the DNN.

The ML model in [71] was trained with V2I data. To increase the scope of scenarios of the ML model, we investigated Learning without Forgetting (LwF) methods in [73] to efficiently add V2V scenarios to an already pre-trained ML model. The authors of [73] present an adaptive LwF method that achieves 82% combined accuracy for the FER prediction within V2V and V2I scenarios.

In [74] additional CCAM use-cases are identified that benefit from the knowledge about the spatial reliability region of the communication link. FER classes for these regions from the ego car's perspective are provided for the decision-making for the ADAS. The authors of [74] propose a complete testbed architecture for system validation, verification, and test scenario generation that integrates FER prediction through the high-performance open-source computing reference framework, and prove that the measured FER within a city scenario

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matches very well with the predicted FER obtained with a GSCM that uses OpenStreetMap data enriched with event-specific static objects.

7.5.2. Digital Twin

The evolution of vehicular networks towards 6G aims to revolutionise mobility by enhancing wireless connectivity in automotive applications. V2X communications, operating at mmWaves and sub-THz frequencies, enable high data rates and low-latency information exchange, surpassing traditional sensor-based detection methods. However, the high-frequency nature of these bands makes wireless links highly susceptible to LoS blockages, particularly in dense urban environments where buildings and moving vehicles disrupt connectivity. Ensuring continuous and reliable connectivity in such dynamic scenarios is a fundamental challenge for next-generation vehicular networks.

To address these issues, the concept of DT has emerged as a key enabler for 6G networks, facilitating the seamless integration of the physical and digital worlds. A DT is a high-fidelity virtual representation of the physical environment, continuously updated with real-time data to enhance situational awareness and optimise network performance. In the context of V2X communications, DTs leverage high-resolution 3D maps, multi-modal sensor data, and advanced wireless propagation models to provide accurate channel estimations and predictive network optimisation.

The implementation of DTs in vehicular networks involves multi-modal sensing at both infrastructure nodes (e.g., road-side units) and connected vehicles. This includes LiDAR, radar, cameras, and Inertial Measurement Units (IMUs), which collectively capture environmental dynamics. By integrating sensor data with RT-based wireless channel simulations, a DT can dynamically adapt to changing communication conditions, mitigating the impact of blockages and enabling proactive network reconfiguration.

A fundamental advantage of DT-enabled V2X systems lies in their ability to reduce the decision time required for critical tasks such as beam selection, channel estimation, and HandOver (HO) management. Unlike traditional exhaustive search methods, which require testing multiple beam pairs, DTs can leverage data-driven models to predict optimal beamforming configurations with reduced overhead. This is particularly beneficial for high-mobility scenarios where rapid topology changes necessitate real-time network adjustments.

The integration of DTs with automotive simulation platforms further enhances their capability to model realistic vehicular scenarios. By incorporating tools such as high-fidelity 3D urban reconstructions and real-time RT, DTs can provide detailed insights into wireless propagation characteristics under various environmental conditions. This facilitates the development of robust V2X communication strategies that account for dynamic obstacles, multipath effects, and time-varying channel conditions.

As vehicular networks transition towards 6G, DT technology is expected to play a crucial role in achieving Ultra-Reliable Low-Latency Communications (URLLC) for intelligent transportation systems. Future advancements in

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DT-driven V2X communications will focus on improving model accuracy, reducing computational complexity, and integrating AI-driven predictive analytics to further enhance network resilience and efficiency.

Overall, DTs are becoming an important tool for developing and testing V2X communication systems. In [75], the authors present a setup that combines a GSCM with hardware-in-the-loop to estimate packet error rates under changing conditions. Using this, they show that relay-assisted communication can significantly reduce latency and error rates in a safety-critical overtaking scenario. For simulation-based modelling, RT remains essential. A measurement-calibrated RT simulator is used in [76] to study V2I HOs at mmWave frequencies, focusing on how factors like route shape and BS spacing affect signal quality. To speed up these simulations, Brennan *et al.* propose an interpolation method that reuses ray path data across a vehicle's trajectory, reducing computational load without a big drop in accuracy [77]. The authors of [78] take a different approach, estimating reflection points directly from power variations in the received signal, without needing detailed maps or prior knowledge of the environment. Together, these efforts show how DTs and improved simulation techniques can support more reliable and efficient V2X system design.

7.6. Conclusion

This chapter has presented a comprehensive examination of wireless communications for transportation, establishing the critical foundation for understanding propagation phenomena across vehicle-to-vehicle, train-to-train, and aircraft-to-aircraft communication scenarios. Each transportation mode exhibits unique channel characteristics requiring specialised approaches: vehicular channels face complex multipath propagation from traffic and infrastructure, railway systems encounter high-speed mobility and tunnel effects, while aviation channels operate in three-dimensional space with atmospheric considerations and high relative velocities.

The exploration of advanced technologies has demonstrated transformative potential for future mobility systems. Integrated sensing and communication enables multifunctional systems providing simultaneous communication and environmental awareness. MIMO systems with intelligent beam management offer enhanced spectral efficiency through spatial diversity, while cell-free networks promise seamless connectivity by eliminating traditional cellular boundaries. Dynamic frequency selection mechanisms enable adaptive spectrum management, and UAV integration through drone-mounted BSs and cooperative awareness facilitates flexible infrastructure deployment and aerial coordination.

Testing and validation methodologies, enhanced by DT technology, play essential roles in ensuring system reliability and safety. DTs enable virtual testing environments, continuous monitoring, and performance optimisation throughout system lifecycles. However, significant challenges remain including protocol standardisation across transportation modes, cybersecurity frameworks for connected systems, and the need for continued international cooperation between academia, industry, and regulatory bodies.

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The successful deployment of next-generation transportation communication systems will require collaborative efforts to address technical challenges and establish comprehensive standards. As transportation systems become increasingly autonomous and interconnected, the principles and technologies discussed in this chapter provide the essential foundation for developing intelligent, safe, and efficient mobility ecosystems that will transform how we move people and goods in the future.

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