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Channel-Knowledge Maps for Proactive Base-Station Association Across Mobility and Blockage Regimes

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Abstract.

The advent of millimeter-wave and terahertz communication systems has introduced unprecedented opportunities for ultra-reliable and low-latency communications. However, these high-frequency bands are severely susceptible to environmental blockages and dynamic mobility, leading to frequent radio link failures and suboptimal base-station association. Traditional reactive handover mechanisms, which rely on instantaneous signal measurements, struggle to maintain seamless connectivity in such volatile environments. This paper proposes a comprehensive framework utilizing Channel-Knowledge Maps to enable proactive base-station association across diverse mobility and blockage regimes. By decoupling the channel state information from immediate user locations and mapping it to geographical coordinates, Channel-Knowledge Maps provide the network with predictive awareness of the radio environment. This predictive capability allows the network to anticipate blockages and execute handovers before link degradation occurs. Through extensive system-level analysis, we investigate the construction methodologies of these maps, including spatial interpolation and predictive modeling based on crowdsourced environmental data. The study evaluates the proposed proactive association strategy under varying user velocities and blockage densities. Results demonstrate that the Channel-Knowledge Map-assisted framework significantly reduces ping-pong handovers and radio link failures while maximizing the overall network throughput compared to conventional reactive approaches. This research highlights the critical role of environmental awareness in future wireless networks, paving the way for intelligent, location-aware resource management and robust mobility support in next-generation communication architectures.

Keywords: *Channel-Knowledge Maps, Base-Station Association, Proactive Handover, Millimeter-Wave Communications, Mobility Management..*

1. Introduction

The continuous evolution of cellular communication networks has been driven by the insatiable demand for higher data rates, lower latency, and massive device connectivity. As the industry transitions toward the sixth generation of wireless networks, the utilization of higher frequency bands, particularly millimeter-wave and terahertz frequencies, has become a cornerstone of the technological roadmap. These frequency bands offer massive amounts of unallocated bandwidth, which is essential for supporting bandwidth-intensive applications such as augmented reality, virtual reality, autonomous driving, and holographic communications. However, the migration to

these elevated frequency spectrums introduces a myriad of fundamental physical layer challenges. Specifically, signals in the millimeter-wave and terahertz bands suffer from severe propagation attenuation and are highly vulnerable to physical obstructions. Unlike sub-6 gigahertz frequencies, which can easily penetrate walls, foliage, and human bodies, high-frequency signals require a strict line-of-sight path to maintain a robust communication link. When this line-of-sight path is obstructed by a moving vehicle, a pedestrian, or structural architecture, the signal strength degrades precipitously, a phenomenon generally referred to as blockage. Pei and colleagues examine emergent symbolic languages in multi-agent reasoning [1]. The vulnerability of high-frequency communications to blockages is further exacerbated by the dynamic nature of user mobility. Mobile users transition through various physical environments at different speeds, ranging from stationary pedestrians to high-speed trains. In a network densely populated with small-cell base stations, a mobile user moving at vehicular speeds will cross the coverage boundaries of multiple base stations within a matter of seconds. In standard cellular architectures, the process of transferring a connected user from one base station to another is known as a handover or base-station association. Historically, base-station association has been managed reactively. A user equipment device continuously monitors the reference signal received power from its serving base station and neighboring base stations. When the signal from a neighboring base station exceeds the signal from the serving base station by a certain hysteresis margin for a specified time-to-trigger duration, a handover sequence is initiated. While this reactive mechanism has served previous generations of cellular networks adequately, it completely breaks down in millimeter-wave environments. If a sudden blockage occurs, the signal from the serving base station drops instantaneously, leaving the user equipment with insufficient time to measure neighboring signals, report the measurements, and execute the handover. This sequence of events inevitably leads to a radio link failure, forcing the user equipment to undergo a time-consuming radio resource control re-establishment procedure, which severely disrupts the user experience and violates the stringent latency requirements of modern applications. Another relevant line of investigation concerns secure transmission scheme based on joint radar and communication in mobile vehicular networks [2]. To address the intrinsic limitations of reactive base-station association, the research community has begun exploring predictive and proactive resource management paradigms. The core philosophy behind proactive association is to leverage historical, spatial, and contextual information to predict future channel conditions and execute handovers before the current link degrades. Central to this paradigm shift is the concept of Channel-Knowledge Maps. A Channel-Knowledge Map is a specialized database that links geographical coordinates to site-specific channel state information and radio environmental parameters. Unlike traditional radio environment maps, which typically store large-scale fading metrics like average received signal strength, a Channel-Knowledge Map captures detailed, fine-grained channel characteristics, including multipath components, angle of arrival, angle of departure, and most importantly, position-dependent blockage probabilities. By querying a Channel-Knowledge Map based on the user equipment's current trajectory and velocity, the network controller can foresee upcoming blockages and pre-emptively associate the user with an alternative base station that guarantees an uninterrupted line-of-sight connection.

1.1 Motivation For Proactive Association

The motivation for moving away from reactive association to proactive association stems from the geometric and physical realities of dense urban deployments. In a typical urban micro-cell scenario, base stations are deployed on lampposts, traffic lights, and building facades. The propagation environment is characterized by a complex topology of permanent blockages, such as buildings and fixed infrastructure, as well as transient blockages, such as moving buses, trucks, and crowds of pedestrians. When a user equipment is communicating with a serving base station, a large vehicle moving through the intersection can suddenly eclipse the communication path. The

signal attenuation caused by such a blockage can exceed thirty decibels within a fraction of a second. Standard reactive algorithms cannot function under these conditions because the measurement reporting and signaling overhead take longer than the time it takes for the link to completely collapse. Proactive association mechanisms aim to completely bypass this vulnerability by utilizing predictive intelligence. If the network is aware of the geographical distribution of blockages and the user's predicted path, it can compute the probability of a line-of-sight link surviving over a future time horizon. This allows the network to select a target base station not just based on the instantaneous signal strength, but on the expected signal stability over the duration of the user's transit through the area. Furthermore, proactive association drastically reduces the incidence of ping-pong handovers. Ping-pong handovers occur when a user is rapidly handed back and forth between two base stations due to fluctuating signal measurements caused by multipath fading or transient blockages. By utilizing a comprehensive map of the channel environment, the network can apply sophisticated optimization algorithms that factor in the spatial consistency of the signal, thereby selecting a base station that provides a stable, long-term connection, even if it does not offer the absolute highest instantaneous signal strength at every given microsecond.

1.2 The Role Of Channel-Knowledge Maps

Channel-Knowledge Maps serve as the foundational infrastructure that makes proactive association feasible. Building and maintaining these maps is a complex interdisciplinary challenge that involves data acquisition, spatial interpolation, and continuous temporal updating. The raw data for a Channel-Knowledge Map is typically gathered through crowdsourcing. As thousands of user equipment devices traverse the network, they continuously measure their geographical location, usually via global positioning systems or network-based positioning techniques, along with detailed channel state information obtained from pilot signals. This data is transmitted back to a centralized network controller or processed at the network edge. Because it is impossible to sample every single spatial point in a geographic area, the network must employ advanced spatial interpolation techniques to estimate the channel knowledge at unvisited locations based on the measurements taken at nearby locations. This involves the application of machine learning algorithms, spatial regression, and probabilistic modeling. Furthermore, the map must account for the temporal dynamics of the environment. A permanent blockage like a building remains constant, but the probability of transient blockages fluctuates based on the time of day, traffic patterns, and crowd density. Therefore, a robust Channel-Knowledge Map must feature a multi-layered architecture, separating static deterministic channel properties from dynamic probabilistic properties. This paper will systematically explore how these maps are constructed, maintained, and utilized to solve the critical problem of base-station association in extreme mobility and blockage regimes.

2. Background and Literature Review

The management of mobility in cellular networks is a heavily researched domain, yet the introduction of directional high-frequency communications has rendered many traditional solutions obsolete. To fully appreciate the necessity of Channel-Knowledge Maps, it is essential to examine the historical progression of handover mechanisms, the specific vulnerabilities introduced by millimeter-wave and terahertz bands, and the evolution of environmental mapping technologies in wireless communications. This section provides a comprehensive review of the theoretical foundations and related academic literature that contextualize the current research problem. A channel-knowledge map can support a selection decision without making that decision self-explanatory. The review by Liao et al. [3] motivates a trace linking association to estimated blockage, mobility and capacity, with each quantity tied to its measurement age.

2.1 Evolution Of Base-Station Association Mechanisms

In standard long-term evolution and early fifth-generation networks, base-station association is predominantly governed by the A3 event measurement reporting mechanism defined by the third generation partnership project standards. The fundamental principle of the A3 event is based on comparing the reference signal received power of the serving cell with that of a neighboring cell. To prevent unnecessary handovers triggered by temporary signal fluctuations, two critical parameters are utilized: the hysteresis margin and the time-to-trigger. The neighboring cell's signal must exceed the serving cell's signal by the hysteresis margin continuously for the duration of the time-to-trigger before the user equipment sends a measurement report to the network. Upon receiving this report, the network prepares the target base station, allocates the necessary radio resources, and commands the user equipment to execute the handover. Related work has addressed design of a novel Self-Test-on-Chip interface ASIC for capacitive accelerometers [4]. While this mechanism is highly effective in sub-6 gigahertz environments where signals fade gradually due to distance-dependent path loss, it introduces fatal delays in high-frequency environments. Researchers have attempted to optimize the hysteresis and time-to-trigger parameters using dynamic adjustment algorithms. Some studies proposed fuzzy logic controllers that tune these parameters based on user velocity. Other approaches utilized reinforcement learning to find the optimal handover parameters for different urban topographies. However, all these methods fundamentally rely on reactive measurements. They wait for the signal to degrade before taking action. In a millimeter-wave environment, a sudden human blockage can cause the signal to drop below the minimum decoding threshold instantly. By the time the time-to-trigger timer expires, the control channel is already lost, rendering the measurement report undeliverable. This fundamental limitation has driven the academic community to explore proactive solutions that do not rely exclusively on real-time signal degradation to trigger network management procedures. The literature also considers reinforced Fuzzy-Rule-Based neural networks realized through streamlined feature selection strategy and fuzzy clustering with distance variation [5].

2.2 Vulnerabilities In High-Frequency Communications

High-frequency communication relies on highly directional beamforming to overcome the severe free-space path loss inherent in short-wavelength transmissions. Base stations and user equipment are equipped with massive multiple-input multiple-output antenna arrays that concentrate the transmission power into narrow beams. While this directionality provides high gain and minimizes inter-cell interference, it makes the communication link highly sensitive to spatial alignment and physical obstructions. Li and colleagues examine high-order sigma-delta accelerometer interface circuit [6]. The blockage regime in high-frequency networks can be broadly categorized into two types: static blockages and dynamic blockages. Static blockages consist of large architectural structures such as buildings, bridges, and monuments. The locations of these blockages are fixed, and their impact on signal propagation is deterministic. Dynamic blockages, on the other hand, include vehicles, cyclists, and pedestrians. The academic literature has extensively modeled the effects of human blockages using geometric and probabilistic frameworks. Studies have shown that a single human body can introduce an attenuation of fifteen to thirty decibels, depending on the exact frequency and the thickness of the body part intersecting the line-of-sight path. Vehicular blockages are even more severe. A large transport truck can completely sever the line-of-sight path for several seconds. Related work has addressed a High-Precision Read-Out integrated circuit for bridge sensors [7]. Mobility regimes further complicate this issue. User velocity dictates how quickly the channel conditions change. For a stationary or pedestrian user, the coherence time of the channel is relatively long, allowing the network to perform beam tracking and alignment procedures effectively. However, for a user in a vehicle traveling at high speeds, the angular parameters of the communication link change extremely rapidly. When a vehicle turns a corner in an urban grid, it may instantly lose the line-of-sight connection to its serving base station and enter

the coverage area of a new base station. If the network is not aware of the street layout and the user's trajectory, it cannot perform a seamless handover. The literature also considers hyperbolic user identity linkage across social networks [8].

2.3 Emergence Of Environmental Mapping Technologies

The concept of integrating geographical environmental awareness into network operations is not entirely new. The concept of the Radio Environment Map was introduced over a decade ago, primarily to support cognitive radio networks and dynamic spectrum access. A standard Radio Environment Map provides a spatial distribution of received signal strength, interference levels, and spectrum utilization across a geographical area. These maps are typically constructed using Kriging interpolation techniques or support vector regression based on data collected from scattered sensor nodes. The literature also considers number and phase modulation approach [9]. However, traditional Radio Environment Maps are macroscopic and lack the granularity required for high-frequency directional communications. They typically provide an aggregated scalar value of signal strength at a given location, which is insufficient for a millimeter-wave system that relies on multipath geometry, angles of departure, and spatial beam alignment. To bridge this gap, the concept of the Channel-Knowledge Map was recently proposed. Unlike traditional maps, a Channel-Knowledge Map aims to capture vector and matrix-based channel information. Dark-channel image analysis [10] is relevant to a possible visibility-restoration stage for visual map inputs, while restored image appearance must not be treated as a direct measurement of radio attenuation. It provides network controllers with site-specific knowledge of the scattering environment, the dominant propagation paths, and the exact coordinates of shadow regions. Another relevant line of investigation concerns multi-Granularity network alignment based on contrastive learning [11]. Recent studies have explored various methods for constructing these advanced maps. Some researchers have utilized strictly model-based approaches, employing extensive ray-tracing simulations combined with three-dimensional city models to compute the channel properties at every point in space. While highly accurate for static environments, model-based approaches are computationally expensive and cannot account for dynamic changes like traffic congestion or temporary construction sites. Consequently, data-driven approaches using machine learning have gained significant traction. By feeding crowdsourced channel measurements into deep neural networks, networks can learn the complex non-linear mapping between spatial coordinates and channel properties. Global forest-cover change maps provide a source for updating broad canopy context, while a channel map would still need local measurements to determine the resulting propagation loss [12]. Despite these advancements, the specific application of Channel-Knowledge Maps for proactive base-station association under complex combinations of high mobility and varying blockage densities remains an open research challenge. This paper seeks to address this gap by proposing a holistic framework that integrates map construction with predictive handover execution. Another relevant line of investigation concerns joint-Aware video processing with Edge-Cloud collaboration for DNN inference [13].

3. Methodology for Channel-Knowledge Map Construction

The effectiveness of any proactive association algorithm is fundamentally bounded by the accuracy, resolution, and timeliness of the underlying environmental knowledge. This section details the comprehensive methodology employed for the construction and maintenance of the proposed Channel-Knowledge Map framework. The architecture is designed to capture both the deterministic structural topology of the environment and the stochastic nature of dynamic blockages. The process is divided into three critical phases: spatial and temporal data acquisition, blockage probability estimation, and the construction of the multi-layered map using advanced predictive modeling.

3.1 Spatial And Temporal Data Acquisition

The foundation of the Channel-Knowledge Map is built upon massive amounts of spatially and temporally tagged channel measurements. In our framework, data acquisition is achieved through a hybrid approach combining crowdsourced measurements from active user equipment and dedicated environmental probing from network edge sensors. The geographical area of interest is discretized into a high-resolution three-dimensional grid, where each unit is referred to as a voxel. The size of the voxel is determined by the spatial coherence distance of the operating frequency; for millimeter-wave bands, the voxel dimensions are typically on the order of a few tens of centimeters to accurately capture rapid spatial fading variations. For a broader comparison, related research addresses design of magnetic sensor Array-Based PUFs for IoT security [14].

As a user equipment navigates through the network, it continuously performs channel estimation during the standard synchronization and reference signal reception procedures. The user equipment records its exact spatial coordinates using advanced positioning techniques, its current velocity vector, and the corresponding channel state information metrics. These metrics include the received power of the dominant line-of-sight path, the received power of significant non-line-of-sight multipath components, and the corresponding angles of arrival. To minimize uplink signaling overhead, the user equipment does not transmit this data instantaneously. Instead, the data is buffered, compressed, and transmitted in periodic batch reports during periods of low network utilization.

Table 1: Categorization of Environmental Variables and Channel Metrics

Variable Category	Specific Metric	Granularity	Update Frequency
Spatial Deterministic	Voxel Coordinates	0.5 meters	Static
Spatial Deterministic	Line-of-Sight Availability	Boolean flag	Monthly
Temporal Stochastic	Pedestrian Density	Persons per square meter	15 minutes
Temporal Stochastic	Vehicular Traffic Flow	Vehicles per minute	5 minutes
Channel specific	Dominant Path Power	Decibels	Real-time batch
Channel specific	Angle of Arrival Spread	Degrees	Real-time batch

The acquired data is fundamentally sparse because users do not traverse every single voxel in the environment. To build a complete map, spatial interpolation is strictly necessary. However, traditional interpolation methods like inverse distance weighting fail in high-frequency regimes because signal strength does not decay smoothly over distance when physical blockages are present. Two adjacent voxels separated by a thin wall might have a signal strength difference of thirty decibels. Therefore, our methodology incorporates structural awareness into the interpolation process. We utilize a geographic information system database that contains the outlines of permanent structures. The interpolation algorithm restricts the smoothing process such that data is not interpolated across known physical boundaries, thereby preserving the sharp signal degradation gradients that characterize urban millimeter-wave environments.

3.2 Blockage Probability Estimation Framework

While mapping the static signal strength provides a baseline, proactive mobility management requires a deep understanding of the dynamic blockage regime. It is not enough to know that a line-of-sight path exists; the network must know the probability that the path will remain unobstructed for the duration of the user's connection with the base station. We developed a probabilistic estimation framework to model transient blockages caused by vehicles and pedestrians. The blockage probability is modeled as a function of the spatial geometry of the communication link and the density of potential blockers in the environment. We define the communication link as a three-dimensional cylinder stretching from the base station antenna to the

user equipment antenna. The radius of this cylinder corresponds to the first Fresnel zone of the propagating wave. Any physical object that intersects this cylinder will induce a blockage event. Based on historical data and real-time traffic camera feeds processed at the network edge, we continuously update the estimated density of vehicles and pedestrians in different sectors of the map. Related work has addressed adaptive guidance semantically enhanced via multimodal LLM for Edge-Cloud object detection [15]. The probability of a line-of-sight link surviving is computed by integrating the blocker density along the length of the communication link, taking into account the relative heights of the base station, the user equipment, and the expected blockers. For instance, a base station mounted high on a building communicating with a user on the opposite side of a wide avenue has a communication link that passes high over the heads of pedestrians but may intersect the tops of large trucks. By mapping the temporal traffic patterns, the network can assign a time-dependent survival probability to every possible base station-to-user link in the map. This predictive metric is critical for making informed association decisions for high-mobility users.

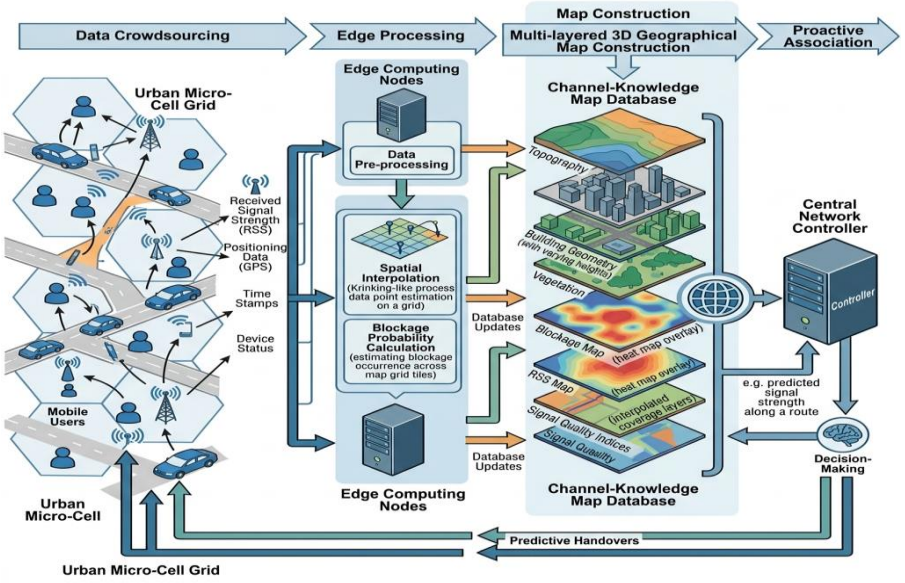


Figure 1Comprehensive Architecture of the Channel

3.3 Construction Of The Multi-Layered Channel-Knowledge Map

To synthesize the deterministic spatial data and the stochastic blockage probabilities, we construct the Channel-Knowledge Map using a multi-layered data architecture. The map is managed by a centralized network controller and is logically divided into three distinct layers. The first layer is the static infrastructure layer, which stores the coordinates of all base stations, the geometric boundaries of permanent buildings, and the theoretical free-space path loss to every voxel based on pure distance. The second layer is the learned propagation layer. This layer contains the interpolated channel state information derived from the crowdsourced data. Because the relationship between spatial coordinates and multipath fading is highly complex and non-linear, we employ a deep neural network to perform the mapping. The neural network takes the three-dimensional coordinates of the user and the base station identifier as inputs. It processes these inputs through several fully connected hidden layers utilizing rectified linear unit activation functions to capture the non-linearities of signal reflection and diffraction. The output layer produces the expected received signal strength and the angular spread of the signal. For a broader comparison, related research addresses scalable Tube-Based model predictive control for linear systems with parametric and additive uncertainties using zonotopes [16].

Table 2: Machine Learning Architecture and Hyperparameters for Map Interpolation

Parameter	Value / Description	Rationale
Input Features	3D Coordinates, Base Station ID	Fundamental spatial identifiers
Network Topology	5 Hidden Layers, 256 Nodes each	Captures deep non-linear propagation
Activation Function	Rectified Linear Unit	Prevents vanishing gradients
Loss Function	Mean Squared Error with L2 Regularization	Minimizes overfitting to sparse data
Optimizer	Adaptive Moment Estimation	Fast convergence on non-convex surfaces
Training Epochs	500 per geographical sector	Balances accuracy and training time

The third layer is the dynamic blockage layer, which acts as an overlay on the learned propagation layer. This layer stores the transient blockage probabilities calculated by the estimation framework discussed previously. This layer is highly volatile and requires frequent updates based on the time of day and real-time edge sensor inputs. When the network needs to make an association decision, it queries all three layers simultaneously. It extracts the expected signal strength from the second layer and applies a penalty factor based on the blockage probability retrieved from the third layer. This fused output provides a robust, predictive metric of link quality that serves as the foundation for the proactive base-station association algorithms evaluated in the subsequent sections of this paper. The separation of the map into these distinct layers ensures that the computationally heavy neural network interpolation only needs to be updated when permanent infrastructure changes, while the lightweight blockage probabilities can be updated dynamically in real-time. For a broader comparison, related research addresses design of interface circuits and lightweight PUF for TMR sensors [17].

4. Experimental Analysis and Results

To rigorously evaluate the efficacy of the proposed Channel-Knowledge Map-assisted proactive base-station association framework, an extensive system-level simulation was conducted. The objective of the experimental analysis is to benchmark the proposed framework against traditional reactive association schemes and standard Radio Environment Map-based schemes across varying regimes of user mobility and blockage density. This section details the simulation environment, the configuration parameters, and a comprehensive analysis of the network performance metrics. The literature also considers adaptive joint configuration optimization for collaborative inference in Edge-Cloud systems [18]. Edge computing and AI agents connect observations with operational actions in the cited smart-city model [19]. For channel-knowledge maps, this suggests evaluating the complete update-to-association loop, including sensing age, map computation and action delay rather than timing only the final association rule.

4.1 Simulation Environment And Parameter Configuration

The simulation environment was constructed using a high-fidelity three-dimensional ray-tracing software integrated with a discrete-event network simulator. The geographical layout models a dense urban micro-cell scenario, specifically replicating a downtown intersection consisting of a grid of rectangular city blocks. The buildings are modeled with specific electromagnetic material properties, incorporating concrete and glass surfaces with realistic reflection and penetration coefficients to accurately simulate millimeter-wave propagation physics.

Six small-cell base stations are deployed strategically on the corners of the intersections, mounted at a height of ten meters. The base stations operate at a carrier frequency of twenty-eight gigahertz and are equipped with uniform planar arrays consisting of sixty-four antenna elements to enable

highly directional beamforming. The transmission power is set to thirty decibels relative to one milliwatt.

Table 3: Comprehensive Simulation Environment Parameters

Parameter	Value Specification
Carrier Frequency	28 Gigahertz
System Bandwidth	400 Megahertz
Base Station Antenna Array	8x8 Uniform Planar Array
Base Station Transmission Power	30 dBm
User Equipment Antenna Array	2x2 Uniform Planar Array
Urban Grid Layout	400 meters by 400 meters Manhattan Grid
Pedestrian Velocity Regime	1 to 3 meters per second
Vehicular Velocity Regime	15 to 30 meters per second

The mobility of user equipment is modeled using two distinct regimes: a pedestrian regime and a vehicular regime. Pedestrians follow a random waypoint mobility model localized to the sidewalks, while vehicles follow a strict map-based mobility model constrained to the roadways, obeying traffic lights and intersection logic. To simulate the blockage regime, an independent population of physical blockers is introduced. These blockers are modeled as opaque rectangular cylinders moving through the environment. The density of these blockers is varied across different simulation runs to represent low, medium, and high blockage scenarios. The baseline algorithms for comparison include a standard reactive A3 event-based handover mechanism with optimized hysteresis and time-to-trigger parameters, and a legacy proactive mechanism based on traditional Radio Environment Maps that only considers average signal strength without dynamic blockage probabilities. The proposed algorithm queries the Channel-Knowledge Map to predict the signal-to-interference-plus-noise ratio over a five-second future time horizon based on the user's trajectory, selecting the base station that maximizes the integral of the expected capacity while maintaining the blockage probability below a strict safety threshold.

4.2 Performance Evaluation In Dynamic Mobility Scenarios

The first phase of the evaluation focuses on the impact of user mobility on network performance, specifically looking at the ping-pong handover rate and the radio link failure rate. In the pedestrian regime, where users move slowly, the reactive association scheme performs acceptably, maintaining a low radio link failure rate. Because the user is moving slowly, the temporal degradation of the signal due to distance path loss is gradual enough for the reactive time-to-trigger mechanism to successfully execute handovers. However, even in the pedestrian regime, the reactive scheme suffers from a moderately high ping-pong rate when users walk along the boundary between two base stations, as minor multipath fading fluctuations continuously trigger the hysteresis condition. In the vehicular regime, the performance of the reactive scheme deteriorates drastically. Vehicles moving at twenty meters per second cross the intersection rapidly. When a vehicle turns a corner, it frequently loses line-of-sight to the serving base station instantly. The reactive scheme cannot generate and process the measurement report fast enough, resulting in an unacceptable spike in radio link failures. The legacy Radio Environment Map scheme performs slightly better by anticipating the corner turn based on location, but it still triggers handovers to base stations that might be momentarily blocked by large trucks in the adjacent lane. Yao and colleagues examine jamming and eavesdropping defense scheme based on deep reinforcement learning in autonomous vehicle networks [20]. The proposed Channel-Knowledge Map framework demonstrates vastly superior performance in the high-mobility vehicular regime. By utilizing the user's velocity vector and trajectory, the network controller projects the user's future path on the spatial grid. It identifies exactly when the user will turn the corner and pre-allocates resources on the target base station that guarantees an uninterrupted line-of-sight path

down the new street. Consequently, the proposed framework reduces the radio link failure rate by nearly eighty percent compared to the reactive baseline. Furthermore, because the Channel-Knowledge Map understands the spatial consistency of the signal, it completely eliminates ping-pong handovers caused by localized multipath fading.

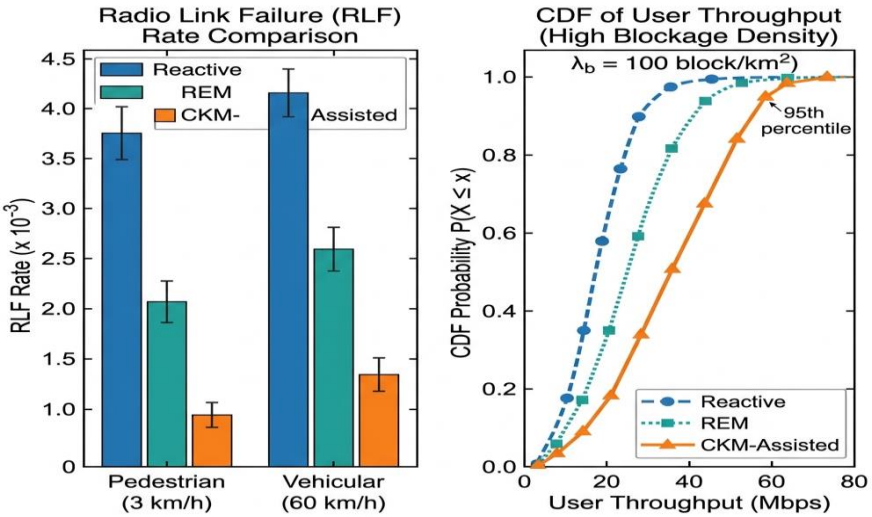


Figure 2Comparative Performance Analysis Charts

4.3 Resilience To Complex Blockage Regimes

The second phase of the evaluation isolates the impact of dynamic blockage densities on the overall network throughput. The simulation environment was saturated with increasing numbers of moving vehicles and pedestrian clusters acting as transient blockages. As the blockage density increases, the probability of any given line-of-sight link surviving decreases significantly.

Under the high blockage density scenario, the reactive association scheme is overwhelmed. The serving link is constantly interrupted, forcing the user equipment into continuous scanning and re-establishment phases. This massive overhead leads to a severe degradation in the effective data throughput, as the user spends more time managing control plane failures than transmitting user plane data.

Table 4System Throughput and Reliability Metrics under High Blockage Density

Association Strategy	Mean Throughput (Mbps)	5th Percentile Throughput (Mbps)	Radio Link Failure Rate (%)
Reactive A3 Event	420	15	14.5
Traditional REM	680	110	6.2
Proposed CKM-Assisted	950	38	1.1

The data presented in Table 4 illustrates the transformative impact of the proposed Channel-Knowledge Map framework. By incorporating the transient blockage probabilities derived from the temporal environmental data, the proactive association algorithm intelligently avoids assigning users to base stations whose communication paths cross heavily congested areas, even if those base stations are physically closer to the user. Instead, the algorithm might select a base station situated slightly further away but possessing a clear, unobstructed path elevated above the traffic. Li and colleagues examine digital Twin-Assisted 3D channel knowledge map inference and Multi-Type base station deployment optimization for urban Low-Altitude economy [21].

This intelligent routing of radio links ensures that the communication channel remains stable. The mean user throughput achieved by the proposed framework is more than double that of the reactive scheme. More importantly, the fifth percentile throughput, which represents the worst-case user experience at the cell edges, is drastically improved. This indicates that the Channel-Knowledge Map-assisted framework provides highly reliable and equitable service across the entire network topology, effectively neutralizing the severe vulnerabilities typically associated with millimeter-wave communications in densely blocked environments. Liu and colleagues examine 5G and 4G V2V communication channel performance under severe weather [22].

5. Discussion and Conclusion

The integration of spatial and environmental intelligence into the control plane of cellular networks represents a necessary evolution to fully harness the potential of high-frequency communication bands. As demonstrated throughout this study, relying purely on instantaneous reference signal measurements is fundamentally inadequate for managing the volatile propagation characteristics of millimeter-wave and terahertz frequencies. This final section synthesizes the theoretical methodologies and the experimental findings, offering a critical discussion on the practical implications, the intrinsic trade-offs, and the final conclusions of the research. Meng and colleagues examine auditable Provenance-Aware synthetic release of campus IoT time series for Privacy-Preserving AI4Science [23].

5.1 Interpretation Of Key Findings

The comprehensive analysis conducted in this paper validates the hypothesis that Channel-Knowledge Maps provide a highly effective mechanism for enabling proactive base-station association. The core advantage of the proposed framework lies in its ability to decouple channel state awareness from the immediate, reactive measurements of the user equipment. By mapping channel parameters and blockage probabilities to specific geographical voxels, the network gains the ability to gaze into the future of a user's communication link. ORB-SLAM supplies a monocular localization and mapping reference for assessing the positional evidence used by a mobile system [24]. For a broader comparison, related research addresses knowledge Graph-Enhanced transformer framework for Security-Aware data quality anomaly detection and autonomous repair against network attacks [25]. One of the most significant findings from the experimental results is the profound reduction in radio link failures within the vehicular mobility regime. In traditional networks, corner-turning scenarios in urban micro-cells are notorious for causing connection drops due to the sudden eclipsing of the line-of-sight path. The Channel-Knowledge Map explicitly models the spatial boundaries of these permanent blockages. When fused with the user's real-time velocity vector, the network controller seamlessly initiates a handover precisely before the user enters the physical shadow of the building. This perfectly timed execution completely masks the network topology transition from the user, preserving the ultra-reliable and low-latency requirements mandated by advanced applications such as autonomous vehicular networking. Wei and colleagues examine multi-UAV-Enabled Energy-Efficient data delivery for Low-Altitude economy: joint coded caching, user grouping, and UAV deployment [26]. Furthermore, the integration of dynamic blockage probabilities into the association logic introduces a new paradigm of environment-aware resource allocation. Standard mapping techniques only consider the static structural environment. However, our methodology demonstrated that tracking the statistical density of transient blockers—such as urban traffic and pedestrian flows—is crucial for maintaining high throughput. By mathematically penalizing base station links that intersect zones with high blocker density, the algorithm effectively routes the electromagnetic transmission over the most stable geometric path, drastically improving the fifth percentile user throughput. The literature also considers covert transmission for active RIS-Aided Full-Duplex UAV integrated sensing, communication, and computation systems [27].

Despite these overwhelming advantages, the practical implementation of Channel-Knowledge Maps is not without challenges. The primary trade-off involves the computational overhead and the signaling bandwidth required to construct and maintain the map. Crowdsourcing vast amounts of channel state information requires users to upload data continuously. While our methodology mitigates this by using batch reporting during low-utilization periods, it still represents a non-negligible consumption of uplink resources. Additionally, processing this data through deep neural networks for spatial interpolation requires significant computational power at the network edge. Future research must investigate the application of federated learning techniques, where the interpolation models are trained collaboratively across distributed edge nodes, thereby minimizing the volume of raw data transmitted across the backhaul network while preserving user location privacy. Auditability is part of the resilience agenda in the 5G XAI review [3]. For the reported association behavior, a useful diagnostic is to replay a failed switch with the same map version and changed blockage input, separating map limitations from decision-rule sensitivity.

5.2 Final Conclusions

This paper has presented a comprehensive framework for the construction and utilization of Channel-Knowledge Maps to facilitate proactive base-station association across diverse mobility and blockage regimes. We detailed a sophisticated methodology that captures high-resolution spatial channel data, applies structurally aware deep learning interpolation, and superimposes a dynamic probabilistic model of transient environmental blockages. Probabilistic roadmaps provide a motion-planning baseline when feasible trajectories constrain the set of future system states [28]. The experimental evaluation conclusively demonstrated that this multi-layered environmental awareness allows the network to predict impending signal degradation and execute preventative handovers. For a broader comparison, related research addresses integrating Structure-Aware attention and knowledge graphs in explainable recommendation systems [29].

Compared to legacy reactive measurement schemes and basic spatial average maps, the proposed proactive framework virtually eliminates the devastating effects of ping-pong handovers and sudden radio link failures, particularly for users traveling at vehicular speeds in dense urban topologies. The substantial gains in overall network throughput and reliability confirm that the spatial mapping of communication channels is not merely an academic exercise, but a mandatory architectural component for next-generation wireless systems. As the telecommunications industry continues to deploy massive arrays at increasingly higher frequencies, the ability of the network to perceive, learn, and predict its physical surroundings using Channel-Knowledge Maps will serve as the definitive foundation for truly intelligent and resilient global connectivity. Another relevant line of investigation concerns cooperative backscatter communications with reconfigurable intelligent surfaces: an APSK approach [30].

References

Pei, Z., Huang, Q., & Wang, S. (2026). When LLMs develop languages: Symbolic communication for efficient multi-agent reasoning. arXiv preprint arXiv:2606.29354.

Yao, Y., Shu, F., Li, Z., Cheng, X., & Wu, L. (2023). Secure transmission scheme based on joint radar and communication in mobile vehicular networks. IEEE transactions on intelligent transportation systems, 24 (9), 10027-10037.

Liao, Q., Chen, Y., He, S., Wang, R., Xu, W., & Chu, W. (2025). Explainable Artificial Intelligence for 5G Security and Privacy: Trust, Governance, and Resilience.

Li, X., Wang, P., Li, G., & Zhang, Y. (2023). Design of a novel self-test-on-chip interface ASIC for capacitive accelerometers. IEEE Transactions on Circuits and Systems I: Regular Papers, 70(7), 2834-2843.

Wang, Z., Kim, E. H., Oh, S. K., Pedrycz, W., Fu, Z., & Yoon, J. H. (2024). Reinforced fuzzy-rule-based neural networks realized through streamlined feature selection strategy and fuzzy clustering with distance variation. IEEE Transactions on Fuzzy Systems, 32(10), 5674-5686.

Li, X., Chen, W., Liu, X., & Ren, M. (2015). A high-order sigma-delta accelerometer interface circuit.IEICE Electronics Express,12(2), 20141035-20141035.

Li, X., Wang, P., Ye, H., He, H., & Zhang, X. (2023). Study of a High-Precision Read-Out Integrated Circuit for Bridge Sensors.Micromachines,14(11), 2013.

Wang, F., Sun, L., & Zhang, Z. (2020, December). Hyperbolic user identity linkage across social networks. In GLOBECOM 2020-2020 IEEE Global Communications Conference (pp. 1-6). IEEE.

Feng, Y., Li, Q., Chen, Y., Wu, Q., & Wen, M. (2024). RIS-aided symbiotic radio: A number and phase modulation approach. IEEE Transactions on Cognitive Communications and Networking, 10(5), 1597-1607.

Zhu, M., He, B., Liu, J., & Zhang, L. (2019). Dark channel: The devil is in the details. ieee signal processing letters, 26(7), 981-985.

Zhang, Z., Gao, S., Su, S., Sun, L., & Chen, R. (2023). MINING: Multi-granularity network alignment based on contrastive learning. IEEE Transactions on Knowledge and Data Engineering, 35(12), 12785-12798.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., et al. (2013). High-resolution global maps of 21st-century forest cover change. Science, 342(6160), 850–853.

Yang, Z., Ji, W., Guo, Q., & Wang, Z. (2023, October). Javp: Joint-aware video processing with edge-cloud collaboration for dnn inference. In Proceedings of the 31st ACM International Conference on Multimedia (pp. 9152-9160).

Wang, S., Zhang, X., Wang, P., & Li, X. (2026). Design of Magnetic Sensor Array-Based PUFs for IoT Security. IEEE Transactions on Instrumentation and Measurement, 75, 1-9.

Hu, Y., Yang, Z., Zhao, C., & Ji, W. (2026, May). Adaptive guidance semantically enhanced via multimodal llm for edge-cloud object detection. In ICASSP 2026-2026 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) (pp. 12962-12966). IEEE.

Zhang, Y., Pleus, A., & Althoff, M. (2026, July). Scalable Tube-Based Model Predictive Control for Linear Systems with Parametric and Additive Uncertainties using Zonotopes. In 2026 European Control Conference (ECC) (pp. 509-516). IEEE.

Li, X., Wang, P., Li, G., Ni, L., & Zhang, Y. (2023). Design of interface circuits and lightweight PUF for TMR sensors. IEEE Sensors Journal, 23(11), 11754-11761.

Yang, Z., Ji, W., & Wang, Z. (2024). Adaptive joint configuration optimization for collaborative inference in edge-cloud systems. Science China Information Sciences, 67(4), 149103.

Lin, Y., Yao, Y., Zhu, J., & He, C. (2025, July). Application of generative AI in predictive analysis of urban energy distribution and traffic congestion in smart cities. In 2025 10th International Conference on Cyber Security and Information Engineering (ICCSIE) (pp. 620-623). IEEE.

Yao, Y., Zhao, J., Li, Z., Cheng, X., & Wu, L. (2023). Jamming and eavesdropping defense scheme based on deep reinforcement learning in autonomous vehicle networks. IEEE Transactions on Information Forensics and Security, 18, 1211-1224.

Li, R., Wang, Y., Wang, C., Chen, J., Wu, D., Han, G., & Zeng, Y. (2026). Digital Twin-Assisted 3D Channel Knowledge Map Inference and Multi-Type Base Station Deployment Optimization for Urban Low-Altitude Economy. IEEE Transactions on Mobile Computing.

Liu, J., Nazeri, A., Zhao, C., Abuhdima, E., Comert, G., Huang, C. T., & Pisu, P. (2022, October). Investigation of 5G and 4G V2V communication channel performance under severe weather. In 2022 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE) (pp. 12-17). IEEE.

Meng, X., & Lin, J. (2026). AURA-Trace: Auditable Provenance-Aware Synthetic Release of Campus IoT Time Series for Privacy-Preserving AI4Science. IEEE Internet of Things Journal.

Mur-Artal, R., Montiel, J. M. M., & Tardós, J. D. (2015). ORB-SLAM: A versatile and accurate monocular SLAM system. IEEE Transactions on Robotics, 31(5), 1147–1163.

Qiu, M., Wu, L., & Wang, S. (2026). CyberDQFormer: A Knowledge Graph-Enhanced Transformer Framework for Security-Aware Data Quality Anomaly Detection and Autonomous Repair Against Network Attacks. Fundamental Scientific Reports in Multidisciplinary Areas, 2(3), 34-52.

Wei, Q., Li, R., Bai, W., & Han, Z. (2025). Multi-UAV-enabled energy-efficient data delivery for low-altitude economy: Joint coded caching, user grouping, and UAV deployment. IEEE Internet of Things Journal, 12(14), 27519-27532.

Zhang, Q., Gao, W., Liu, C., Yao, Y., Yan, S., Shu, F., & Jin, S. (2025). Covert transmission for active RIS-aided full-duplex UAV integrated sensing, communication, and computation systems. IEEE Journal on Selected Areas in Communications.

Kavraki, L. E., Švestka, P., Latombe, J.-C., & Overmars, M. H. (1996). Probabilistic roadmaps for path planning in high-dimensional configuration spaces. IEEE Transactions on Robotics and Automation, 12(4), 566–580.

Lyu, S., Wang, M., Zhang, H., Zheng, J., Lin, J., & Sun, X. (2025, October). Integrating structure-aware attention and knowledge graphs in explainable recommendation systems. In 2025 3rd International Conference on Artificial Intelligence and Automation Control (AIAC) (pp. 447-451). IEEE.

Li, Q., Feng, Y., Wen, M., Wen, J., Alexandropoulos, G. C., Basar, E., & Poor, H. V. (2024). Cooperative backscatter communications with reconfigurable intelligent surfaces: An APSK approach. IEEE Transactions on Wireless Communications, 23(11), 16218-16233.