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Electromagnetic wave property inspired radio environment knowledge construction and artificial intelligence based verification for 6G digital twin channel

Key words: Digital twin channel; Radio environment knowledge (REK) pool; Wireless channel; Environment information; Interpretable REK construction; Artificial intelligence based knowledge verification

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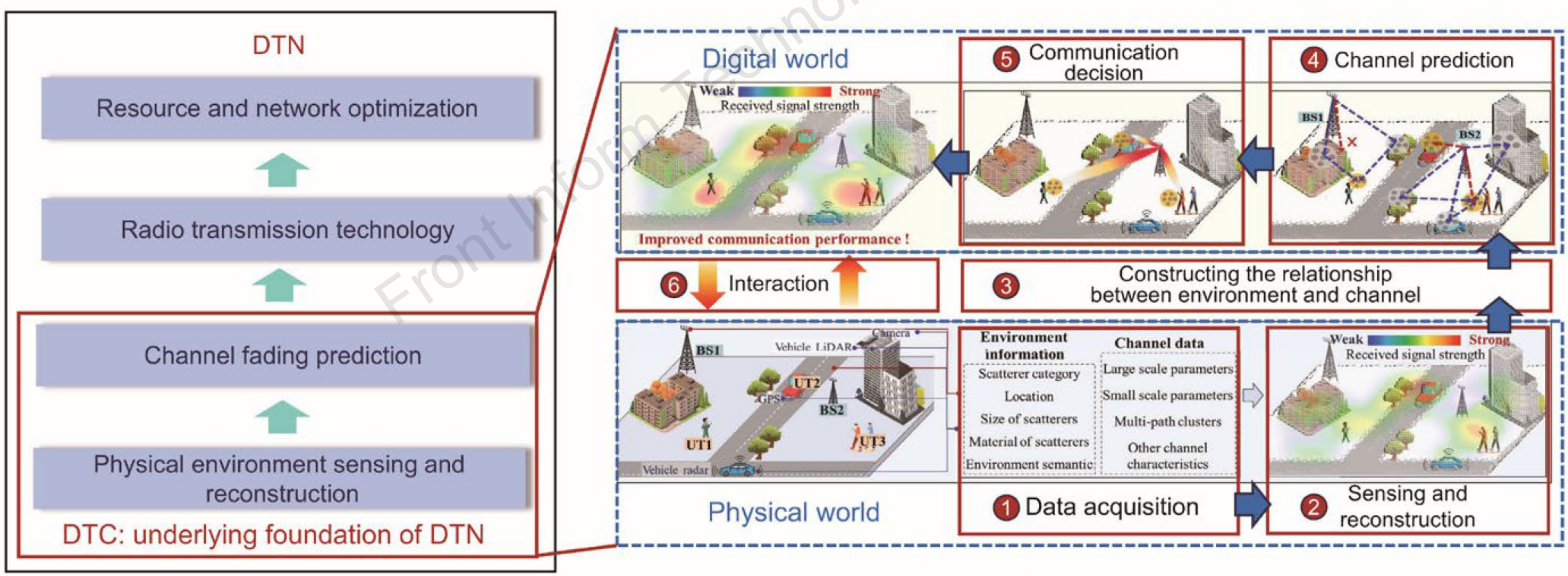
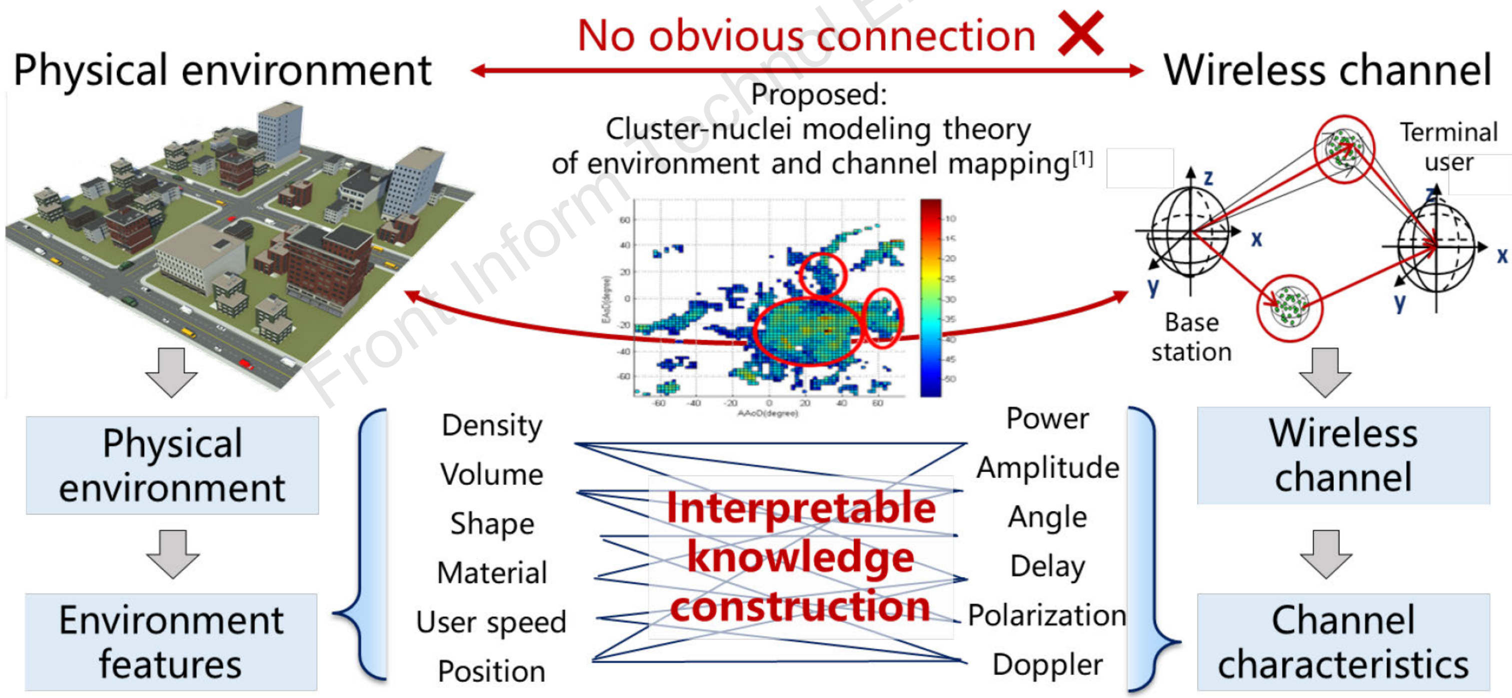
Research background

- DTN creates real-time digital replicas of physical networks, while DTC maps real-world channels to facilitate the precise mapping of channel fading states and variations.
- Current research gap: High-dimensional environmental inputs and unclear environment channel correlations hinder efficient DTC implementation.



Challenges and tendency

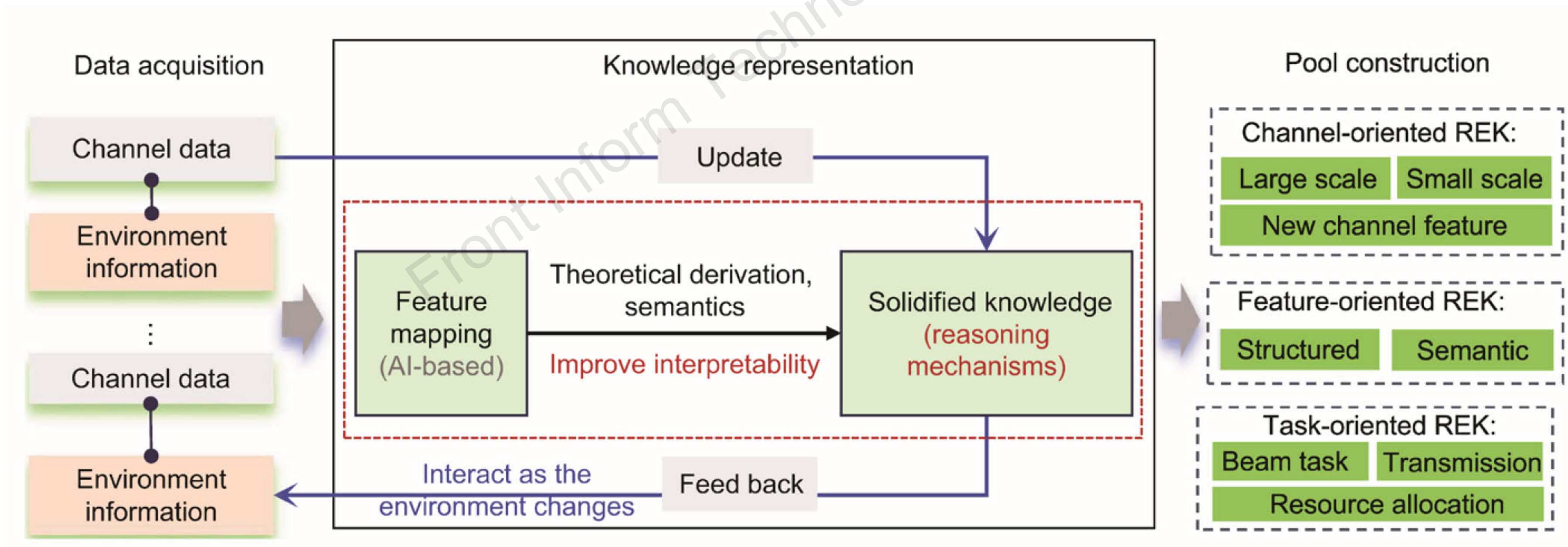
- High redundancy in environmental data complicates the relationship construction between the environment and wireless channel, leading to increased computational complexity.
- Interpretable knowledge driven models are critical for dynamic 6G scenarios, as they enable efficient and real-time adaptation to rapidly changing propagation environments.



[1] Zhang J. The interdisciplinary research of big data and wireless channel: A cluster-nuclei based channel model[J]. China Communications, 2016, 13(2): 14-26.

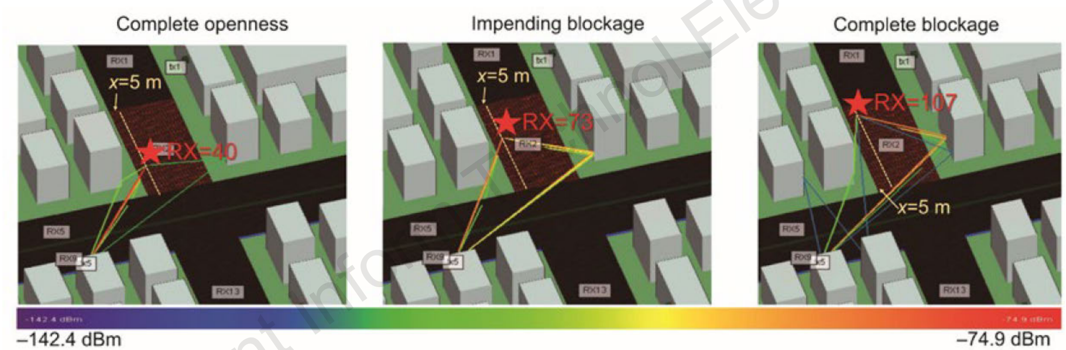
Motivation

- Existing REKP (radio environment knowledge pool) aims to build interpretable, updatable, and generalizable relationships, yet struggles with high-dimensional environmental redundancy and unclear electromagnetic wave contributions (reflection, diffraction, and blockage).
- Enhance REKP via quantified propagation knowledge and lightweight AI to achieve real-time DTC.



1) Effective scatterer determination

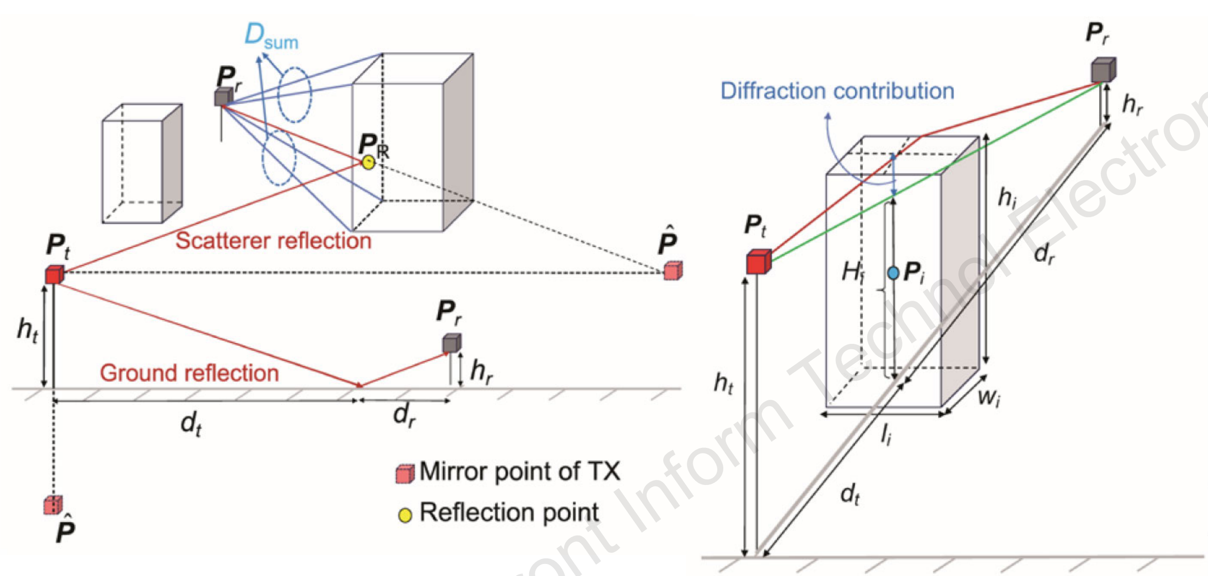
- An ellipsoid model leveraging stochastic geometry identifies critical scatterers by analyzing spatial distributions, reducing redundancy by 90% in complete openness scenarios.
- Achieve ≥90% accuracy in selecting scatterers for propagation modeling, with 87% and 81% redundancy reduction in impending and complete blockage scenarios, respectively.



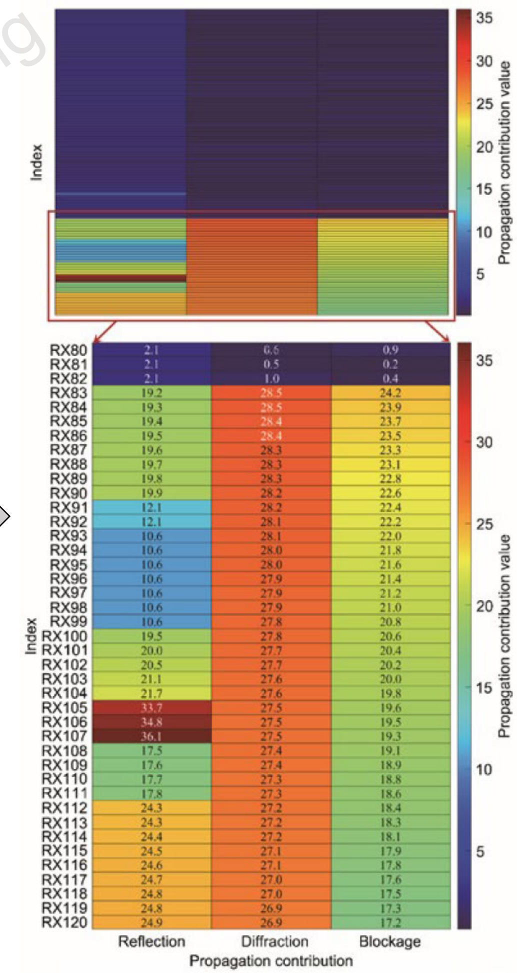
Case	Scatterer number		Accuracy (%)	Reduction in redundant data (%)
	Proposed method	RT method*		
Complete openness	4, 5, 23	5, 11, 23, 4, 10, 6, 2, 22	65	90
Impending blockage	4, 5, 11, 23	5, 11, 23, 4, 10, 6	90	87
Complete blockage	4, 5, 6, 8, 11, 23	11, 6, 5, 4, 23, 10, 27, 28, 29, 7	90	81

2) REK construction via electromagnetic principles

- Proposed REK integrates geometric optics, uniform theory of diffraction, and Fresnel criteria to quantify reflection, diffraction, and blockage contributions through spatial geometric relationships.



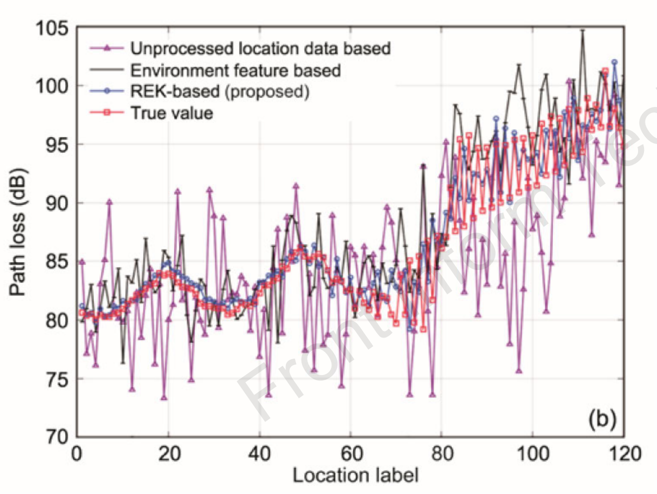
Scatterer reflection contribution	Diffraction contribution
$K_{\text{ref-}i}=\dfrac{c_{\text{ref-}i}\lVert P_t-P_r\rVert}{\lVert P_r-P_R\rVert+\lVert P_R-P_t\rVert}$	$K_{\text{df}}=c_{\text{df}}\left(h_i-h_r-\dfrac{(h_t-h_r)d_r}{d_t+d_r}\right)$
Ground reflection contribution	**Blockage contribution**
$K_{\text{refg-}i}=\dfrac{c_{\text{refg-}i}\lVert P_t-P_r\rVert}{\sqrt{(d_t+d_r)^2+(h_t+h_r)^2}}$	$K_{\text{block}}=\dfrac{P_i\cdot(P_{\text{t}}-P_r)}{\lVert P_{\text{t}}-P_r\rVert}\cdot\dfrac{c_{\text{block}}}{\sqrt{l_i^2+w_i^2}}$

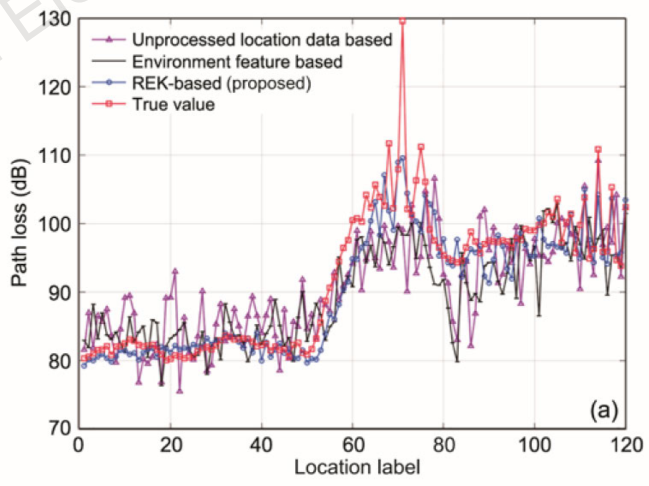


Generated REK spectrum

3) REK-based lightweight CNN for prediction

- A two-layer CNN with 3×3 kernels and ReLU activation leverages REK spectrum as input, reducing training time to 5 s and testing time to 4 ms via optimized dimensionality. Achieve 0.3 NRMSE, outperforming unprocessed data (29.4%↑) and feature-based methods (27.5%↑), enabling real-time prediction in dynamic 6G environments.





Method	NRMSE	Training time (s)	Testing time (s)
Unprocessed location data based	0.565	8.21	0.227
Environmental feature based	0.456	7.67	0.170
Proposed REK-based	0.271	4.07	0.004

Conclusions

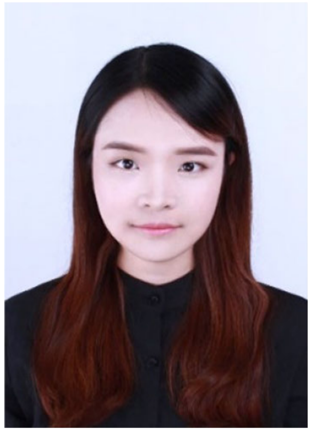
- Our work bridges environment channel mapping with low complexity and high accuracy, enabling interpretable DTC for 6G through quantified electromagnetic contributions.

  - An electromagnetic-inspired REK construction flow is proposed, offering generalizability and interpretability across multiple scenarios, from open to blocked environments.
  - REK quantifies propagation modes via geometric optics and UTD, reducing input dimensions by 81%-90% while maintaining interpretability and accuracy.
  - Proposed REK-based lightweight CNN achieves 0.3 NRMSE with 4 ms testing time, outperforming existing methods by ≥27.5% in accuracy and speed.

- Accelerate real-time digital twin networks and empower dynamic 6G optimization for adaptive beamforming and channel management.

References

[1] J. Wang, J. Zhang, Y. Sun, Y. Zhang, T. Jiang and L. Xia, “Electromagnetic Wave Property Inspired Radio Environment Knowledge Construction and AI-based Verification for 6G Digital Twin Channel,” FITEE, 2024. doi: 10.1631/FITEE.2400464.
[2] J. Wang, J. Zhang, Y. Zhang, Y. Sun, L. Shi, P. Zhang and G. Liu, “Radio Environment Knowledge Pool for 6G Digital Twin Channel,” IEEE Communications Magazine, 2025. doi: 10.1109/MCOM.003.2400168.
[3] H. Wang, J. Zhang, G. Nie, L. Yu, Z. Yuan, T. Li, J. Wang and G. Liu, “Digital Twin Channel for 6G: Concepts, Architectures and Potential Applications,” IEEE Commun. Mag., 2024. doi: 10.1109/MCOM.001.2400213
[4] J. Zhang, L. Yu, S. Liu, Y. Cai, Y. Zhang, H. Xing, T. Jiang, “Wireless Environmental Information Theory: A New Paradigm towards 6G Online and Proactive Environment Intelligence Communication,” submitted to Engineering, arXiv preprint arXiv: 2412.11479, 2025.
[5] J. Zhang, Y. Cai, L. Yu, Z. Zhang, Y. Zhang, J. Wang, T. Jiang, L. Xia, and P. Zhang, “Wireless Environment Information Sensing, Feature, Semantic, and Knowledge: Four Steps Towards 6G AI-Enabled Air Interface,” submitted to IEEE Commun. Mag., arXiv preprint arXiv: 2409.1933, 2024.
[6] L Yu, L Shi, J Zhang, J Wang, Z Zhang, Y Zhang, G Liu, “ChannelGPT: A Large Model to Generate Digital Twin Channel for 6G Environment Intelligence,” submitted to IEEE Commun. Mag., arXiv preprint arXiv:2410.13379, 2025.
[7] L Shi, J Zhang, L Yu, Y Zhang, Z Zhang, Y Cai, G Liu “Can Wireless Environmental Information Decrease Pilot Overhead: A CSI Prediction Example,” IEEE Wireless Commun. Lett., 2025. doi: 10.1109/LWC.2025.3526271.
[8] Z. Zhang, J. Zhang, Y. Zhang, L. Yu, F. Gao, Q. Shi, G. Liu, Z. Yuan, and W. Fan, “Deep Reinforcement Learning Based Dynamic Beam Selection in Dual-band Communication Systems,” IEEE Trans. Wireless Commun., vol. 23, no. 4, pp. 2591-2606, Apr. 2024.
[9] Y. Liu, J. Zhang, Y. Zhang, Z. Yuan, and G. Liu, “A Shared Cluster-based Stochastic Channel Model for Integrated Sensing and Communication Systems," IEEE Trans. Veh. Technol., vol. 73, no. 5, pp. 6032-6044, May 2024.
[10] Y. Sun, J. Zhang, L. Yu, Z. Zhang, P. Zhang, “How to Define the Propagation Environment Semantics and Its Application in Scatterer-Based Beam Prediction,” IEEE Wireless Commun. Lett., vol. 12, no. 4, pp. 649-653, Apr. 2023.
[11] J. Zhang et al., “Channel Measurement, Modeling, and Simulation for 6G: A Survey and Tutorial,” submitted to Proceedings of the IEEE, arXiv preprint arXiv: 2305.16616, 2023.
[12] G. Nie, J. Zhang, Y. Zhang et al., “A Predictive 6G Network with Environment Sensing Enhancement: from Radio Wave Propagation Perspective,” China Commun., vol. 19, no. 6, pp. 105-122, Jun. 2022.



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