Jialin WANG, Jianhua ZHANG, Yutong SUN, Yuxiang ZHANG, Tao JIANG, Liang XIA, 2025. Electromagnetic wave property inspired radio environment knowledge construction and artificial intelligence based verification for 6G digital twin channel. *Frontiers of Information Technology & Electronic Engineering*, 26(2):260-277.
https://doi.org/10.1631/FITEE.2400464

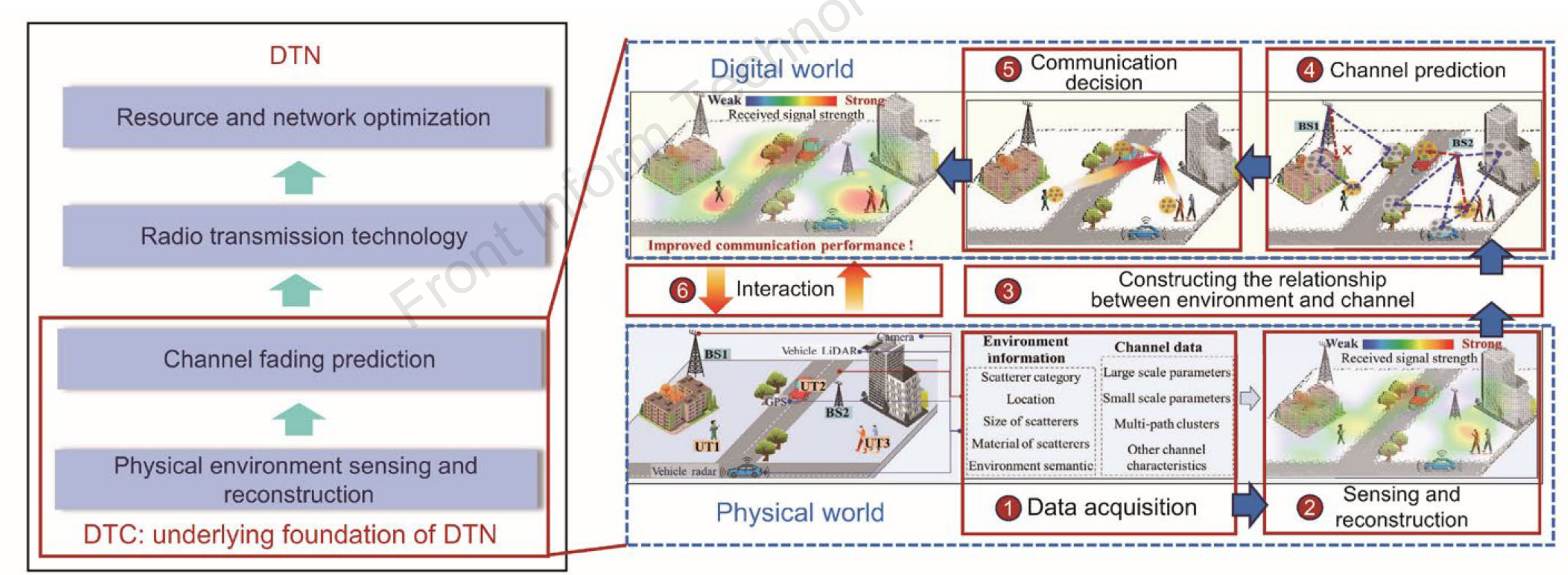
Electromagnetic wave property inspired radio environment knowledge construction and artificial intelligence based verification for 6G digital twin channel

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

Jialin Wang, Jianhua Zhang
E-mail: wangjialinbupt@bupt.edu.cn; jhzhang@bupt.edu.cn
ORCID: https://orcid.org/0000-0003-0484-6188
https://orcid.org/0000-0002-6492-3846

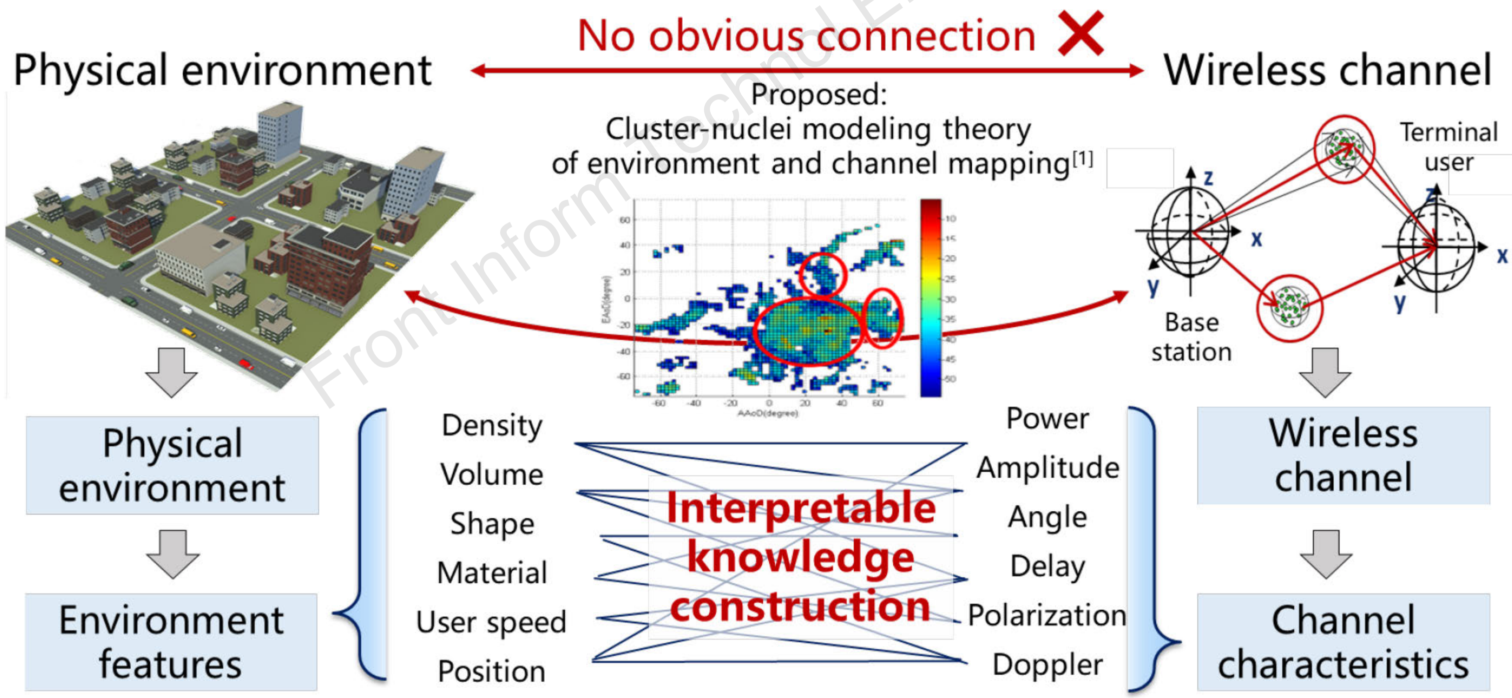
Research background

- 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

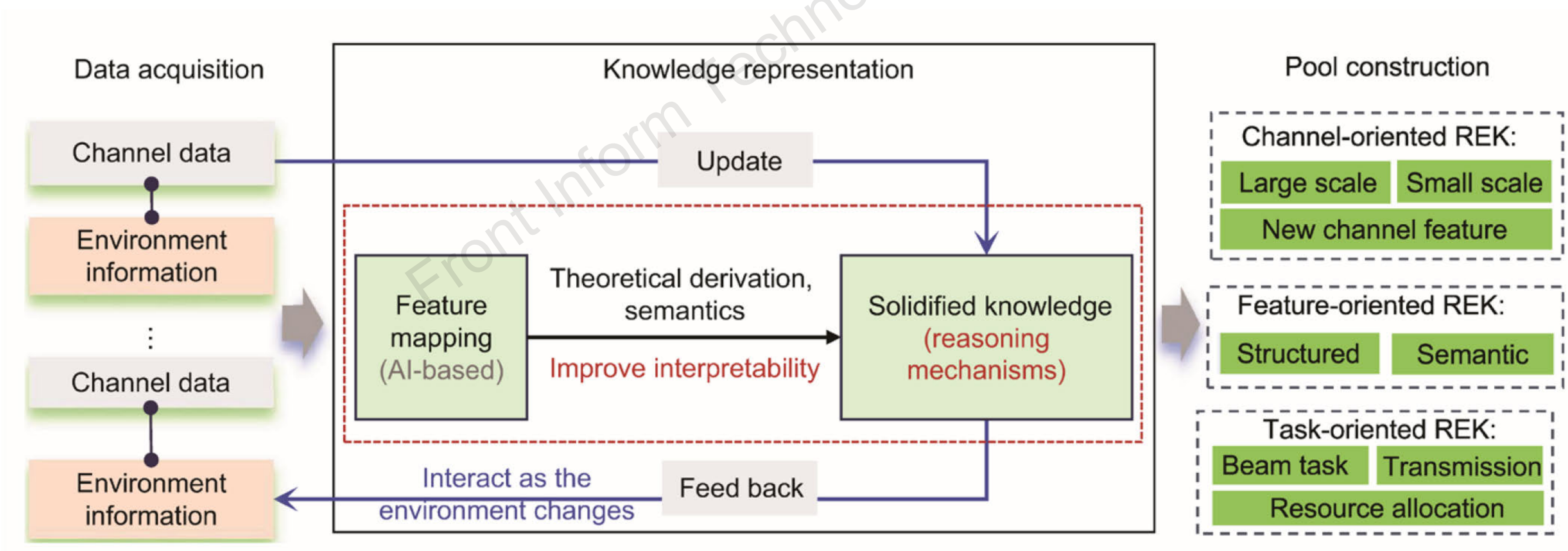
- High redundancy in environmental data complicates the relationship construction between the environment and wireless channel, leading to increased computational complexity.
- Interpretable knowledge driven models are critical for dynamic 6G scenarios, as they enable efficient and real-time adaptation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

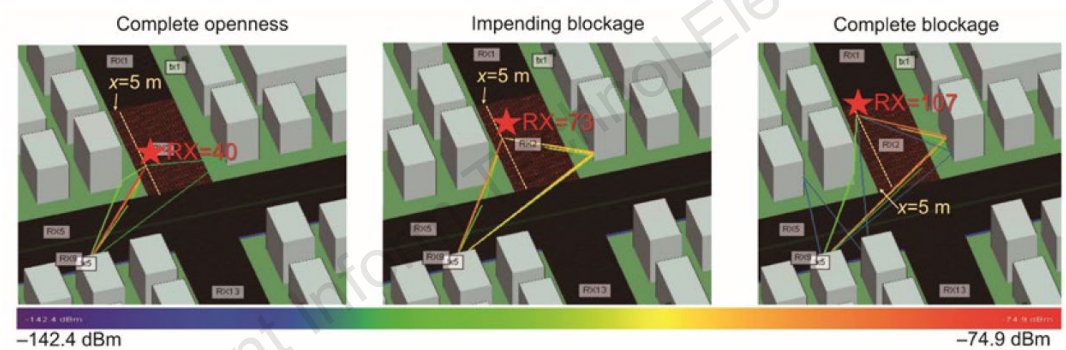
Motivation

- 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

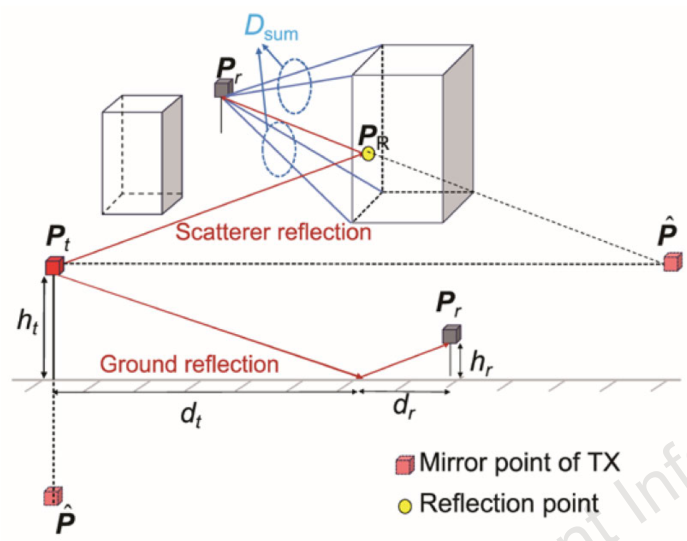
- An ellipsoid model leveraging stochastic geometry identifies critical scatterers by analyzing spatial distributions, reducing redundancy by 90% in complete openness scenarios.
- Achieve ≥90% accuracy in selecting scatterers for propagation modeling, with 87% and 81% redundancy reduction in impending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

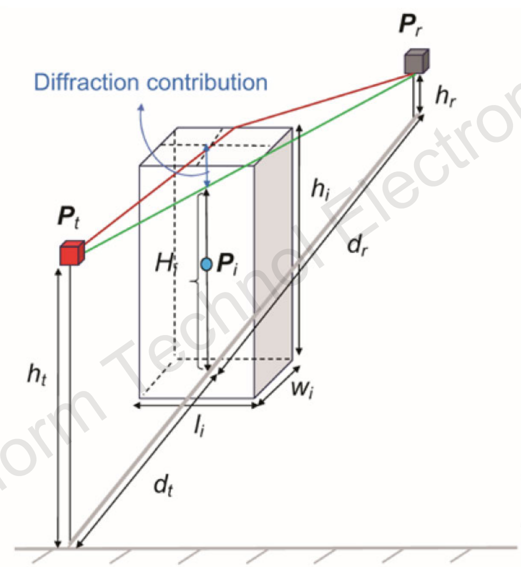


Case	Scatterer number		Accuracy (%)	Reduction in redundant data (%)
	Proposed method	RT method*		
Complete openness	4, 5, 23	5, 11, 23, 4, 10, 6, 2, 22	65	90
Impending blockage	4, 5, 11, 23	5, 11, 23, 4, 10, 6	90	87
Complete blockage	4, 5, 6, 8, 11, 23	11, 6, 5, 4, 23, 10, 27, 28, 29, 7	90	81

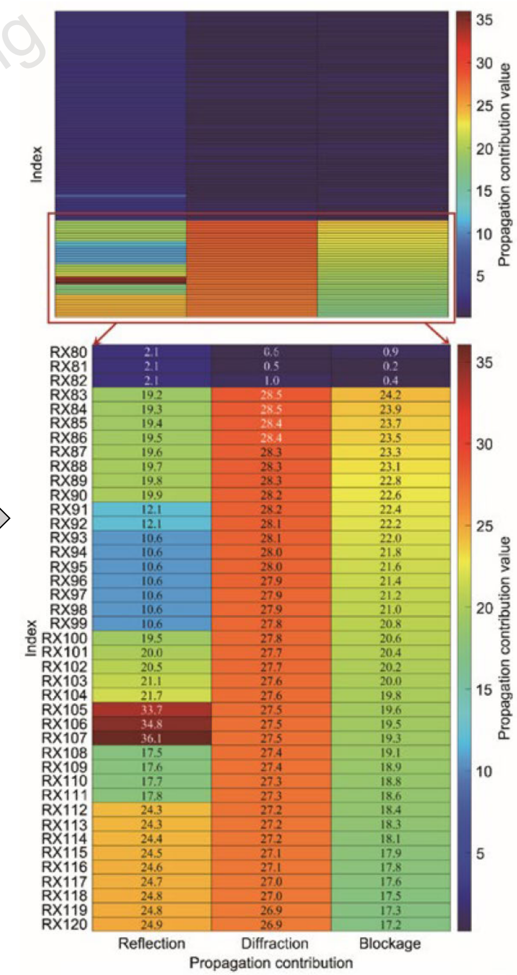
2) REK construction via electromagnetic principles

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





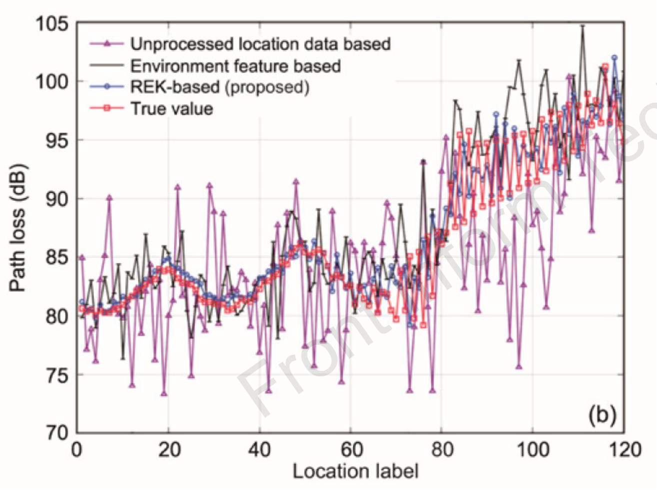
Scatterer reflection contribution	Diffraction contribution
$K_{\text{ref-}i}=\dfrac{c_{\text{ref-}i}\left\Vert \boldsymbol{P}_t-\boldsymbol{P}_r\right\Vert}{\left\Vert \boldsymbol{P}_r-\boldsymbol{P}_R\right\Vert+\left\Vert \boldsymbol{P}_R-\boldsymbol{P}_t\right\Vert}$	$K_{\text{df}}=c_{\text{df}}\left(h_i-h_r-\dfrac{(h_t-h_r)d_r}{d_t+d_r}\right)$
Ground reflection contribution	**Blockage contribution**
$K_{\text{refg-}i}=\dfrac{c_{\text{refg-}i}\left\Vert \boldsymbol{P}_t-\boldsymbol{P}_r\right\Vert}{\sqrt{(d_t+d_r)^2+(h_t+h_r)^2}}$	$K_{\text{block}}=\dfrac{\boldsymbol{P}_i\cdot(\boldsymbol{P}_{\text{t}}-\boldsymbol{P}_r)}{\Vert \boldsymbol{P}_{\text{t}}-\boldsymbol{P}_r\Vert}\cdot\dfrac{c_{\text{block}}}{\sqrt{l_i^2+w_i^2}}$

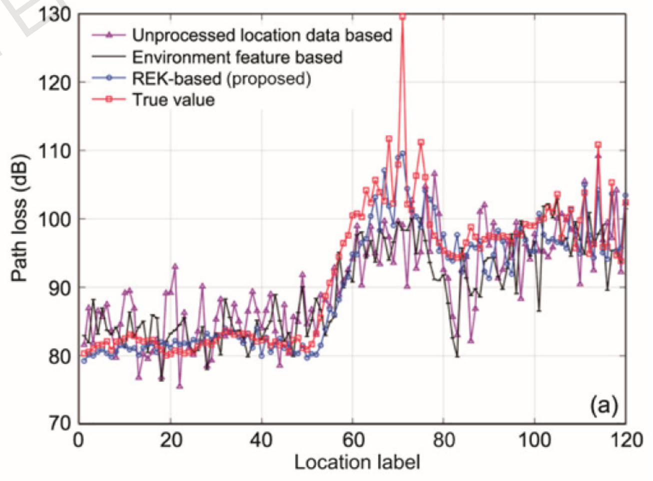


Generated REK spectrum

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

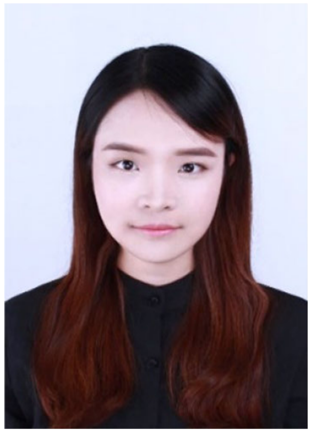
- Our work bridges environment channel mapping with low complexity and high accuracy, enabling interpretable DTC for 6G through quantified electromagnetic contributions.

  - 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.



Jialin WANG received the B.S. degree in 2018, and the M.S. degree in 2021. She is currently pursuing the Ph.D. degree in Beijing University of Posts and Telecommunications (BUPT). Her current research interests include channel modeling theory, channel digital twin technology, wireless AI, and 6G-oriented physical layer transmission technology.

Jianhua ZHANG received the B.S. degree from North China University of Technology in 1994 and the Ph.D. degree from BUPT in 2003, where she is currently a professor. She is the Chairwomen of China IMT-2030 tech group - channel measurement and modeling subgroup and works on the 6G channel model. Her current research interests include beyond 5G and 6G, artificial intelligence, and data mining, especially in mmWave, THz, and massive MIMO channel modeling.

Yutong SUN received the B.S. degree and M.S. degree from Changchun University of Science and Technology (CUST) in 2015 and 2018, respectively. Since 2020, she has been pursuing the Ph.D. degree in BUPT. Her current research interests include channel prediction, computer vision, machine learning, etc.

Yuxiang ZHANG received the B.S. degree from Dalian University of Technology in 2014 and the Ph.D. degree from BUPT in 2020. From 2018 to 2019, he was a visiting scholar with University of Waterloo. He is now a post-doctoral researcher. His current research interests include transmission techniques for physical layer, OTA testing, etc.

Tao JIANG received the B.S. degree from Huazhong University of Science and Technology in 2015, and the Ph.D. degree from BUPT in 2021. His current research interests include mmWave channel modeling, ISAC channel modeling, and wireless communication system design.

Liang XIA received the B.S. degree in electronic and information engineering in 2005 and the M.S. degree in information and communication engineering in 2008 from Tsinghua University, Beijing, China. He was a researcher at LTE physical layer in Huawei from 2008 to 2014 and was a researcher at 5G physical layer in China Mobile from 2015 to 2019. His current research interests include millimeter-wave, THz, and visible light communication.