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XL-MIMO channel measurement, characterization, and modeling for 6G: a survey

Key words: 6G; XL-MIMO; Near-field; Channel measurement; Channel modeling

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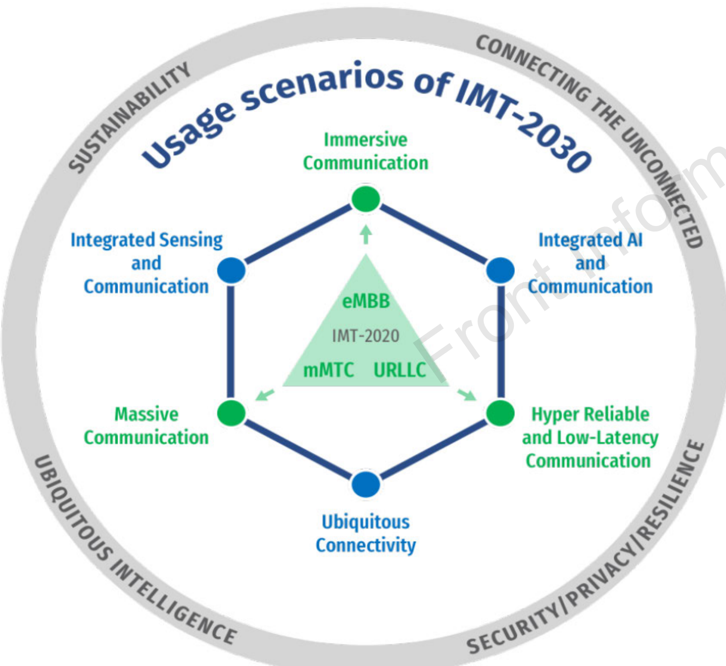
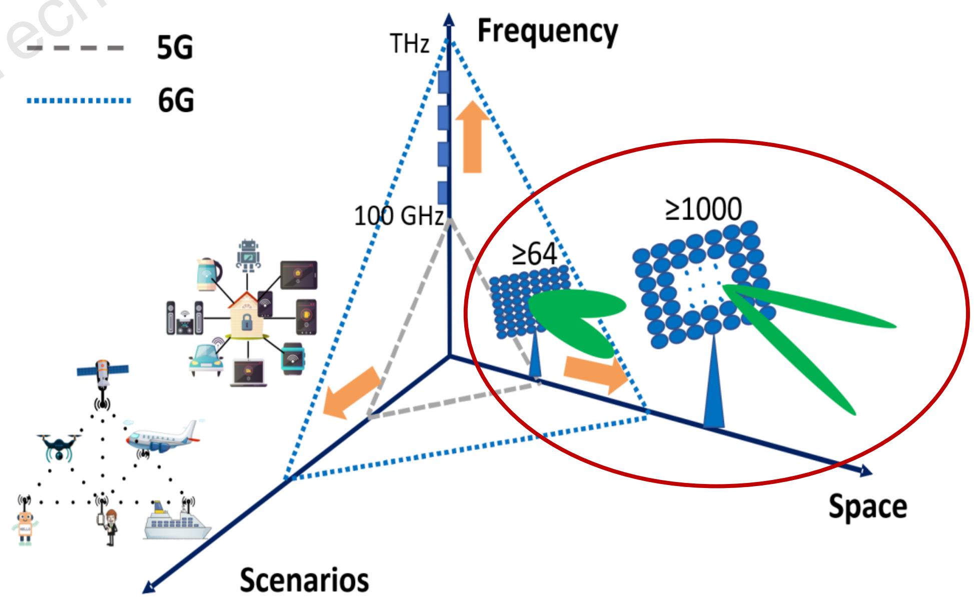
Framework and objectives of 6G

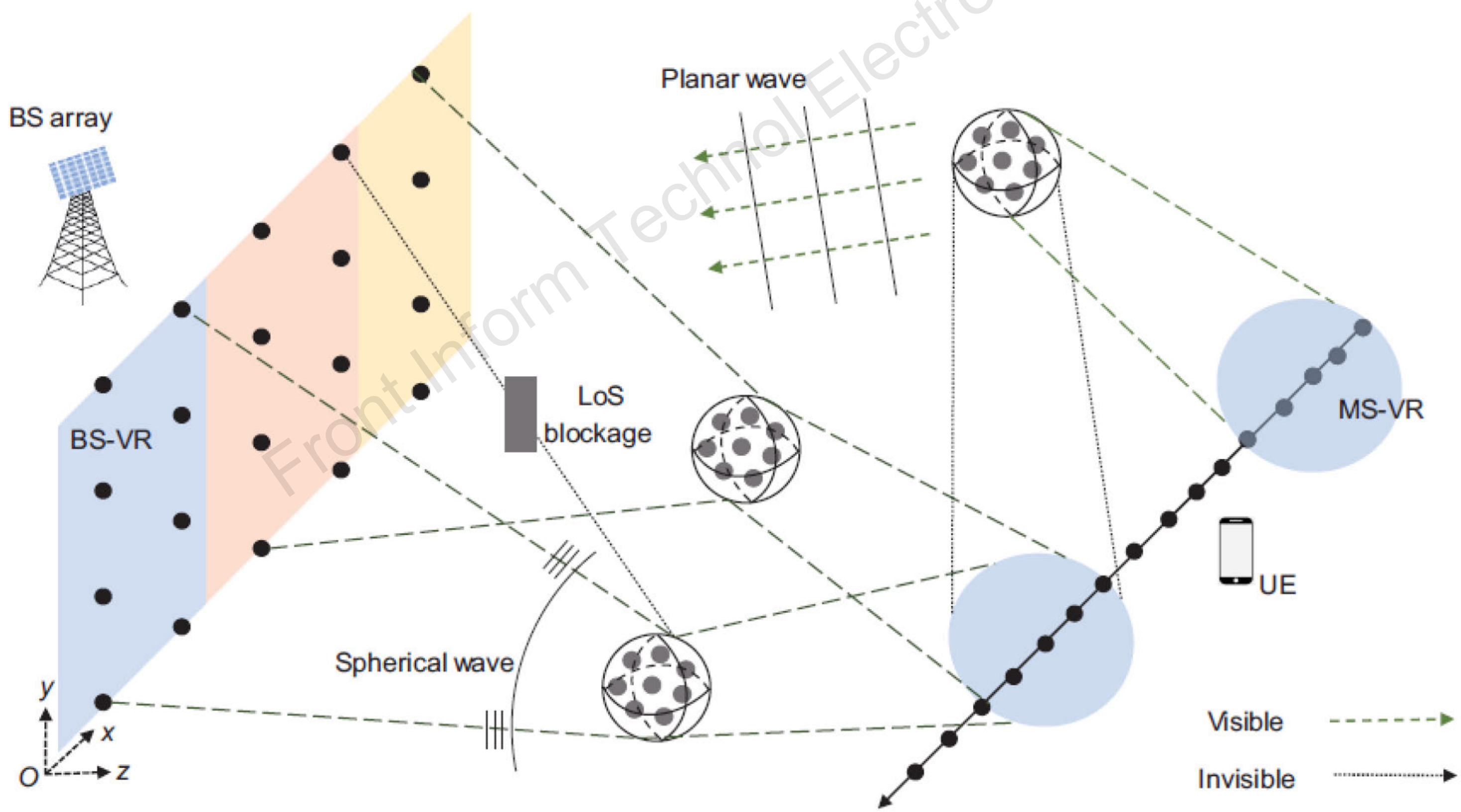
- International Telecommunication Union-Radiocommunication Sector (ITU-R) Working Party (WP) 5D agreed with the draft new recommendation.
- 6G is expected to provide evolving and new capabilities compared to 5G, such as a larger peak data rate and user-experienced data rates, positioning, sensing-related capabilities, and coverage.





XL-MIMO channel

- Except for spatial non-stationarity (SnS) inherited from massive MIMO channels, new channel characteristics, e.g., spherical wave and visible region (VR), simultaneously arise in XL-MIMO channels. Subsequently, the distances and incident wave directions between the Tx and Rx antenna elements vary over the antenna array.

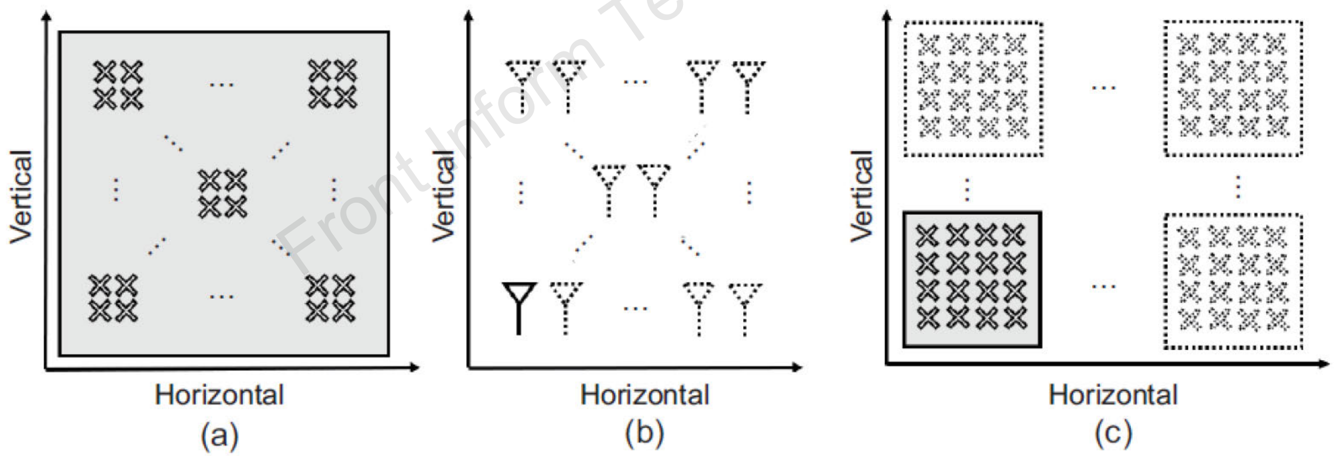


Main idea/contribution

- This paper gives a survey of the current research progress in XL-MIMO channel measurements, including channel measurement methods and parameter extraction methods.
- Recent research on the XL-MIMO channel characteristics, including near-field effects, SnS characteristics, channel capacity, and channel hardening, are reviewed.
- In terms of XL-MIMO channel modeling methods, statistical channel models, deterministic channel models, and hybrid channel models are surveyed. Specifically, the 3GPP-like channel modeling method is discussed.
- Future research directions are presented in terms of channel measurement, characterization, and modeling, giving insights into future XL-MIMO channel research.

1) XL-MIMO channel measurements: challenges

- The channel sounder should have at least the same or even better radio frequency (RF) specifications, e.g., bandwidth and antenna number.
- It is extremely expensive to build hundreds or thousands of RF channels to drive each antenna element.
- It is challenging to complete a round of sub-channel measurements within coherence time in environments with high mobility.



XL-MIMO array configuration: (a) RAA; (b) VAA formed by a single antenna; (c) VAA formed by a small array (RAA: real antenna array; VAA: virtual antenna array)

1) XL-MIMO channel measurements: progress

- There are mainly two ways to build antenna arrays in XL-MIMO channel sounders.

Table 1 Recent progress in XL-MIMO channel measurements

Scenario		Antenna and number of elements	Carrier frequency (GHz)	Parameter extraction algorithm	Channel characteristics	Reference
Indoor	Lecture hall	Virtual UPA, 144	5.6	NM	SnS: DS, condition number, etc.	Li JX and Zhao, 2014
	Stadium	Virtual ULA, 128	1.47/4.45	NM	SnS: channel envelope coefficient, rice K-factor, DS, etc.	Liu L et al., 2015
	Office	Virtual URA, 2601/5776/ 8281/14 641	11/16/28/38	SAGE	Spherical wavefront, SnS: cluster birth-death, DS, AS, channel capacity, etc.	Huang J et al., 2017
	Theater	Virtual UPA, 256	11	SAGE	PL, SF, SnS: DS, etc.	Li JZ et al., 2017
	Theater	Virtual UPA, 256	11	SAGE	SnS: MPC birth-death, AS, etc.	Li JZ et al., 2018b
	Lobby	Virtual UPA, 256	11	SAGE	SnS: MPC power, spherical wavefront, etc.	Li JZ et al., 2018a
	Laboratory	Virtual UPA, 441	28	SAGE	RMS DS, AS, SnS: number of MPCs, etc.	Mudonhi et al., 2020
	Room	Virtual uniform circular array, 720	26.5–32.5	NM	SnS: spherical wavefront, etc.	Yuan ZQ et al., 2023b
	Meeting room	Virtual UPA, 1800	26–30	NM	Near-field: CIR, PADP, etc.	Mbugua et al., 2024
Outdoor	Court yard	Virtual LA, 128	2.6	SAGE	SnS: rice K-factor, etc.	Payami and Tufvesson, 2012
	Campus	Virtual ULA/uniform cylindrical array, 128	2.6	NM	SnS: PAS, etc.	Gao X et al., 2012
	UMa	Virtual UPA, 256	3.5	SAGE	PDP, PAS, etc.	Yu et al., 2016
	UMa	Virtual UPA, 256	3.5	SAGE	PAS, SnS: VR, etc.	Wang C et al., 2017
	Top of building	Virtual UPA, 1600	15	SAGE	Rice K-factor, RMS DS, AS, SnS, etc.	Chen JJ et al., 2017
	UMa/UMi	Virtual UPA, 256	3.5/6	SAGE	PAS, RMS AS, channel capacity, etc.	Zhang JH et al., 2018
	UMi	URA, 128	142	NM	PAS, RMS AS, etc.	Ju and Rappaport, 2021
	Urban	ULA/DULA, 128	5.3	SAGE	Non-stationarity: RMS DS, RMS AS, spherical wavefront, channel capacity, etc.	Zheng et al., 2023
O2I		Virtual UPA, 256	3.5	NM	DS	Xu et al., 2017

AS: angular spread; CIR: channel impulse response; DS: delay spread; DULA: distributed uniform linear array; LA: linear array; MPCs: multipath components; NM: not mentioned; O2I: outdoor-to-indoor; PADP: power angle delay profile; PAS: power angular spectrum; PDP: power delay profile; PL: path loss; RMS: root-mean-square; SAGE: space-alternating generalized expectation–maximization; SF: shadow fading; SnS: spatial non-stationarity; ULA: uniform linear array; UMa: urban macrocell; UMi: urban microcell; UPA: uniform planar array; URA: uniform rectangular array; VR: visible region

2) Parameter extraction methods: challenges

- The accuracy of the channel model relies on an accurate characterization of the distribution of relevant channel parameters. Therefore, it is necessary to use accurate and computationally efficient signal processing tools to extract channel parameters from measured data.
- In traditional channel parameter estimation algorithms, it is commonly assumed that the distance between scatterers and the antenna array is much greater than the size of the antenna array, and the radio wave is considered planar.
- However, in the case of XL-MIMO channels, as the size of the antenna array increases, the far-field assumption may be violated and the radio wave is a spherical wavefront. This brings challenges to traditional channel parameter estimation algorithms that assume a planar wavefront.

2) Parameter extraction methods: progress

- The existing channel parameter estimation algorithms can be classified mainly into three categories: beamforming algorithms, parametric subspace based estimation (PSBE) algorithms, and maximum likelihood estimation (MLE) based algorithms.
- A generic mode-selection guideline is proposed to guide the implementation of an FIBF in broadband 3D near-field scenarios.

Table 2 XL-MIMO channel parameter estimation algorithms

Category	Algorithm	Reference
Beamforming		
PSBE	MUSIC	Schmidt, 1986; Saleh and Valenzuela, 1987
	ESPRIT	Fayad et al., 2015
MLE-based	EM	Regier and Moodie, 2016
	SAGE	Fleury et al., 2002
	RiMAX	Gaillot et al., 2011

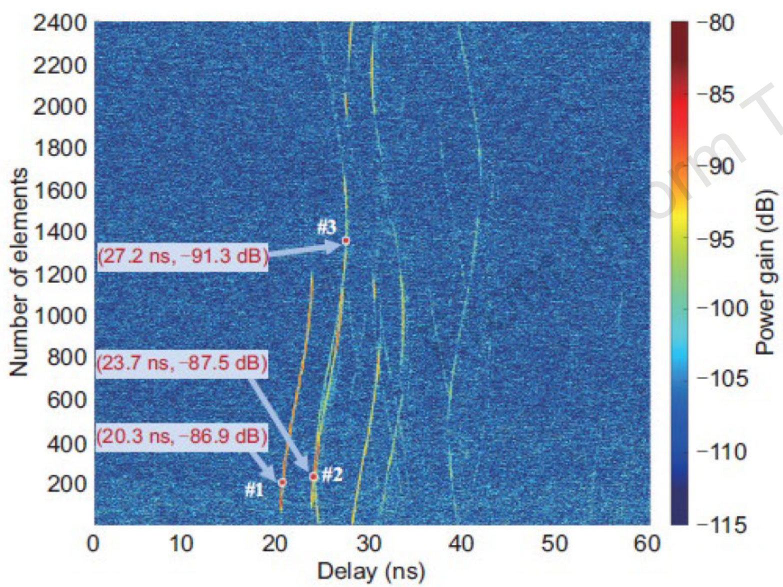
EM: expectation–maximization; ESPRIT: estimation of signal parameters via the rotational invariance techniques; MLE: maximum likelihood estimation; MUSIC: multiple signal classification; PSBE: parametric subspace based estimation; RiMAX: Richter's maximum likelihood estimation; SAGE: space-alternating generalized expectation–maximization

$$\hat{a}_m(f, \Theta_k) = \mathrm{e}^{\mathrm{j}m\phi_k} G_m(f) \sum_{l=-L}^{L} \left[B_l(f, r, d_k, \theta_k) \cdot \mathrm{j}^{m+l} J_{m+l}(wr\sin\theta_k) \right], \quad (1)$$

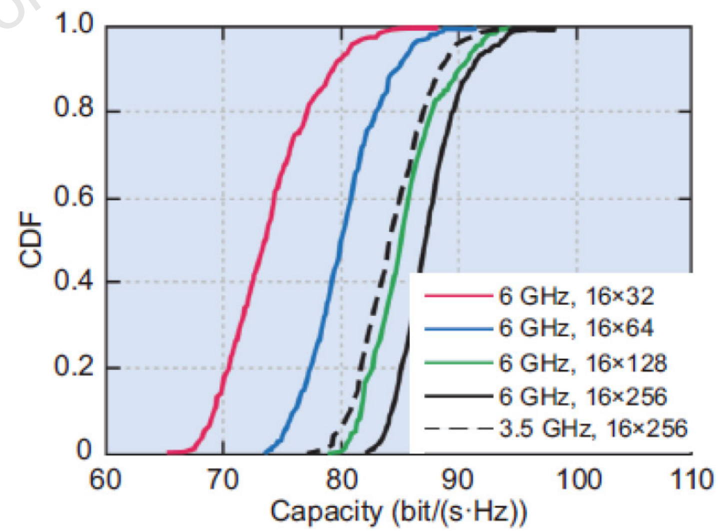
where B_l are the coefficients of the Fourier series, dependent on $\{f, r, d_k, \theta_k\}$. L denotes the series order. Generally, a smaller d_k results in a larger L. In far-field scenarios, $L = 0$ holds. Due to the property $J_n(x) \approx 0$ for $n > x$, some high-order (i.e., high m) phase modes suffer from weight drop as $m+l$ exceeds $wr\sin\theta_k$, while the low-order phase modes retain the same normalized power in the transformation from the far field to the near field. Hence, the high-order

3) XL-MIMO channel characterization: challenges

- The characterization of the spherical wavefront and SnS phenomenon is a new challenge introduced in the XL-MIMO channel.
- Under which channel conditions XL-MIMO can have better performance in actual mobile communications has been a matter of concern and research.



Schematic representation of near-field phenomena in space



Capacity CDF for XL-MIMO of 3.5 GHz and 6 GHz

3) XL-MIMO channel characterization: progress

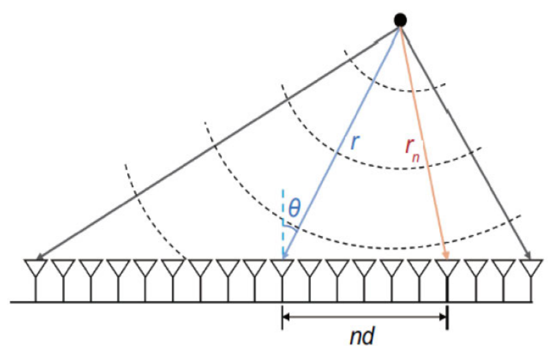
- SnS has been observed in several XL-MIMO channel measurement campaigns. At 3.5 GHz, the radius of MS-VR under different scenarios was investigated by deducing and calculating the lifecycle of clusters.
- In the phase aspect, the true phase of an incident electromagnetic wave on a BS antenna must be computed based on an accurate spherical wave model.
- As the number of BS antennas increases, the channel vectors between users and BS become very long random vectors, under “favorable” propagation conditions.

Table 3 Distribution of VR radius in different scenarios

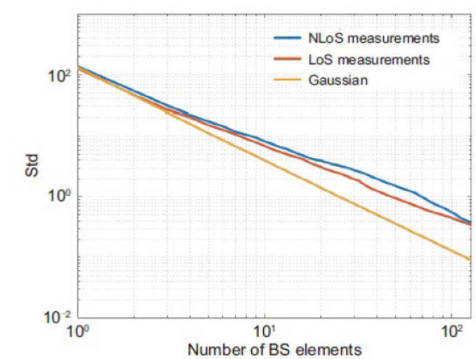
Parameter		UMa		UMi		InH	
		LoS	NLoS	LoS	NLoS	LoS	NLoS
Radius of VR	μ	0.5	0.2	0.6	0.3	1.6	0.8
	σ	0.4	0.1	0.4	0.4	0.6	0.3
	Max (m)	2.6	1.1	3.1	1.7	3.6	2.2
Fitted lognormal distribution	μ	−1.6	−2.2	−1.6	−1.9	−1.3	−1.7
	σ	1.5	0.9	1.7	0.9	1.9	1.1

InH: indoor hotspot; LoS: line of sight; NLoS: non-line of sight; UMa: urban macrocell; UMi: urban microcell; VR: visible region

Spatial non-stationarity



Near-field spherical wave propagation



Variation in mean channel vector energy

4) XL-MIMO channel modeling: challenges

- Statistical channel modeling: The traditional statistical models assume spatial stationarity, but XL-MIMO channels exhibit SnS characteristics, and the statistical distribution of SnS characteristics of different antenna array types is different, so describing the statistical distribution is a challenge to be faced.
- Deterministic channel modeling: First, it is difficult to obtain the material electromagnetic medium parameters required for deterministic modeling. Second, it is difficult to accurately describe the radio wave propagation environment, which leads to reduced accuracy of the channel model. Finally, as the number of XL-MIMO array elements increases, the complexity increases exponentially.
- Hybrid channel modeling: Some challenges exist, including the basic modeling principles and methods, how these channel modeling methods are specifically combined, and the balance between complexity and precision.

4) XL-MIMO channel modeling: progress

- The assumption of planar wave and spatial stationarity is normally used in the 3GPP 38.901 channel model for 5G. The expanded array size results in the Fraunhofer distance being violated in a real deployment scenario. In this case, the user equipment (UE) or scatterer is most likely to be in the near field of the BS.

Table 4 XL-MIMO channel modeling methods and models

Modeling method	Model	Channel characteristic	Reference
Statistical modeling	KBSM	SnS, spherical wave	Wu et al., 2015
	WM	SnS, spherical wave	Zhai et al., 2016
	COST 2100	SnS	Gao X et al., 2013
	GBSM	Spatial consistency	Ademaj et al., 2019
	GBSM	SnS, spherical wave	Gao TY et al., 2023
	GBSM	SnS, spherical wave	Yuan ZQ et al., 2023b
	GBSM	SnS	Li JZ et al., 2019a
	GBSM	SnS, spherical wave	Jing et al., 2023
	GBSM	SnS, spherical wave	López et al., 2022
	GBSM	SnS, spherical wave	Wu et al., 2014
	COST 2100	SnS	Liu LF et al., 2012
Deterministic modeling	RT	SnS, spherical wave	Yuan ZQ et al., 2024
	RT	PL, etc.	Yao et al., 2017
Hybrid modeling	RT/GBSM	SnS	Zhang JH et al., 2024a

GBSM: geometry-based stochastic model; KBSM: Kronecker-based stochastic model; PL: path loss; RT: ray tracing; SnS: spatial non-stationarity; WM: Weichselberger model

4) XL-MIMO channel modeling: summary

- Statistical channel modeling: To solve the problem, a feasible 3GPP simulation framework scheme is proposed, but a lot of measurement work needs to be carried out in the real communication environment to extract the model parameters.
- Deterministic channel modeling: Due to the large number of antenna elements, simulations require geometric tracking of interaction points for each pair of antenna elements and result in high complexity. The lack of knowledge of EM properties and computational complexity also hinders the use of the XL-MIMO deterministic modeling method.
- Hybrid channel modeling: There is no unified definition of hybrid channel modeling methods for XL-MIMO. The accuracy and complexity of the hybrid method that can capture new features of XL-MIMO channels need to be considered.

5) Open issues of XL-MIMO channel research

Channel research	Outlook
Cost- and time-efficient channel sounder	• Highly costly measurement equipment • To bring a serious challenge to the stationarity assumption during VAAs channel measurements
Non-stationarity in spatial, frequency, and time domains	• Non-stationarity in the spatial, frequency, and time domains in XL-MIMO channels should be further investigated and characterized.
New channel characteristics arising from combination with other technologies	• To obtain better capabilities, XL-MIMO is expected to combine other enabling technologies, e.g., RIS and ISAC.
Antenna-independent channel characterization and modeling	• 3D radiation patterns of practical XL-MIMO • Visibility regions of scatterers at the BS depend on the shape of antenna arrays. • To further decouple channel statistical properties and antennas.
Intelligent channel modeling	• Deployed in various scenarios, e.g., IIoT and SAGIN • Intelligent channel modeling is a promising research direction but it is in its infancy.

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