# 无线信道硬件孪生技术研究进展与挑战

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**摘 要：**无线信道特性对通信系统性能至关重要，信道孪生技术是指通过物理或数字方式精确地复现信道特性对信号传播的失真影响，为通信系统性能评估提供有效测试手段。其中，数字孪生方式更为灵活方便，特别是无线信道硬件孪生平台已广泛应用于通信设备的批量化测试。然而，随着通信系统向大带宽、高动态和大规模网络发展，现有无线信道硬件孪生技术难以满足未来系统性能验证需求。鉴于此，该文首先给出了硬件孪生技术面临的主要挑战，然后对国内外研究进展进行分类阐述与分析比较，最后探讨了无线信道硬件孪生技术的未来发展趋势和应用前景。

**关键词：**无线信道；数字孪生；信道硬件孪生；信道特性；通信性能测试

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## 1 引言

无线信道作为通信收发端之间信号传输的媒介，其复杂的传播特性直接决定了通信系统的性能和可靠性[1]。为了有效设计和优化通信系统，准确复现信道特性至关重要，信道孪生技术通过在实验室内模拟真实传播环境，为系统设计与算法优化提供了可控且可重复的测试手段[2,3]。信道孪生技术分为物理孪生和数字孪生两种方式。其中，物理孪生通过灵活调整封闭环境内的散射体布局(如混响室)，实现真实传播环境的等效模拟，该方式实现过程复杂且应用范围有限[4]；数字孪生在数字空间中对真实信道传播特性进行复现，具备更高的灵活性。根据实现平台的不同，信道数字孪生技术可进一步细分为软件孪生和硬件孪生，对应的实现系统分别称为信道仿真器(Channel Simulator, CS)和信道模拟器(Channel Emulator, CE)。CS通过软件平台生成精确的信道响应，支持多种信道模型与灵活场景配置，适用于无线信道的模型仿真和特性分析；而CE通过硬件平台实时产生无线信道并叠加至传输信号，更注重射频接入与实时性能，适用于通信系统和设备的性能测试验证。

信道硬件孪生技术因其在实时性和系统测试中的优势受到广泛关注，然而，伴随着无线通信系统的发展演进，信道的带宽、频率和空间维度的不断扩展，对通信设备性能测试的需求也在不断升级。比如，在第1代(First Generation, 1G)通信系统中，服务功能仅限于语音，CE只需模拟无线信号传输过程中的功率变化[5]。进入第2代(Second Generation, 2G)通信系统后，抽头延时线(Tapped Delay Line, TDL)信道模型被广泛采用，它要求CE能够模拟多径传播效应[6]。从第3代(Third Generation, 3G)到第5代(Fifth Generation, 5G)通信系统，CE在TDL框架上持续优化，支持模拟多径特性、多普勒特性以及非平稳特性等。下一代无线通信系统将引入新频段、新终端和新技术，对信道硬件孪生技术又提出了新挑战。例如，第6代(Sixth Generation, 6G)通信系统将通信频段拓展至太赫兹(Terahertz, THz)，带来更高的频率和更宽的带宽，要求CE具备更强的实时处理能力。同时，随着卫星和无人机等高速移动终端的发展，通信场景将扩展到空、天、地、海一体化的多维动态场景，亟需CE支持模拟信道的非平稳特性。此外，随着各类设备数量的急剧增加，CE还要求支持大规模的多节点通信网络信道模拟。部分典型的数字信道孪生系统如表1所示。

总之，现有的信道硬件孪生技术难以实现大带宽、动态场景和大规模网络的信道实时模拟，也无法有效支撑未来通信设备系统的验证、优化和测试。因此，开发新一代信道硬件孪生技术以满足未来系统需求，已成为亟待解决的关键问题。本文全面系统地梳理了无线信道硬件孪生技术，首先分析其面临的挑战，接着总结主流硬件孪生技术的分类

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和研究进展，最后展望无线信道硬件孪生技术的未来发展方向及其应用潜力。图1展示了无线信道硬件孪生技术的挑战、研究进展及其未来发展与应用场景之间的内在关系。

## 2　无线信道硬件孪生面临的挑战

### 2.1　大带宽高频段

6G系统将采用频谱资源丰富的THz频段，传输带宽也由5G的2 GHz增加到10 GHz，以支持Tbit/s的通信速率。由表1可得，当前CE大多针对sub-6 GHz通信系统，覆盖频率范围最高支持毫米波频段，可支持的带宽最大仅为1.2 GHz，与6G系统所需的10 GHz带宽存在数量级差距，不足以支撑高频段大带宽的通信系统测试验证。

通过外接频率扩展模块，可以将现有CE升级实现高频段的覆盖。例如，文献[22]使用混频器对

**表 1　部分典型的无线信道数字孪生系统**

| 开发团队 | 系统名称 | 类型 | 系统特点 |
|---|---|---|---|
| 美国纽约大学[7] | NYUSIM | CS | 基于MATLAB平台；支持0.5～150 GHz频段信道建模；支持UMi, UMa, RMa, InH和InF场景；支持基于真实测量的确定信道模型 |
| 德国弗朗霍夫海因里希赫兹研究所[8] | QuaDRiGa | CS | 基于MATLAB平台；支持0.5～100 GHz频段信道建模；支持UMi, UMa, RMa, 、InH和卫星场景；支持3GPP和WINNER+等信道模型 |
| 阿卜杜拉国王科技大学[9] | TeraMIMO | CS | 基于MATLAB平台；支持0.1～10 THz频段信道建模；支持室内/室外短程通信场景；支持宽带太赫兹信道模型 |
| 乌拉圭共和国大学[10] | PyWiCh | CS | 基于MATLAB平台；支持0.5～100 GHz 频段信道建模；支持UMi, UMa, InH和InF场景；支持3GPP信道模型 |
| 任康无线智能实验室[11] | DeepMIMO | CS | 基于MATLAB和Python平台；支持毫米波频段信道的建模；支持DeepMIMO网站提供的确定场景；支持基于射线追踪的确定性信道模型 |
| 北京邮电大学[12] | BUPTCMG-IMT2030 | CS | 基于MATLAB平台；支持0.5～132 GHz频段信道建模；支持UMi与InH等典型场景；支持ITU-R信道模型 |
| 北京交通大学[13] | CloudRT | CS | 基于MATLAB和C++等平台；支持sub-6 GHz、毫米波即THz等频段信道建模；支持铁路、城市室内和室外等场景；支持基于射线追踪的确定性信道模型 |
| 东南大学[14] | SEU-PML-6GPCS | CS | 基于MATLAB平台；支持6G全频段信道建模；支持卫星、无人机、陆地和海洋等场景；支持3GPP和ITU-R等信道模型 |
| 美国国防高级研究计划局&美国东北大学[15] | Colosseum | CE | 基于NI USRP平台；支持10 MHz-6 GHz射频信号接入；支持100 MHz带宽信号处理；时延精度可达1 ms；最大支持256×256通信网络验证 |
| 奥地利理工学院[16] | AIT CE | CE | 基于NI USRP平台；支持sub-6 GHz射频信号接入；支持20 MHz带宽信号处理；时延精度可达100 ns |
| 南京航空航天大学[17] | NUAA-UAVChEm | CE | 基于FPGA平台；支持sub-6 GHz的射频信号接入；支持100 MHz带宽信号处理；最大支持8×8通信网络验证 |
| 是德科技[18] | PROPSIM F64 | CE | 基于FPGA平台；支持3 MHz～43.5 GHz射频信号接入；支持400 MHz带宽信号处理；最大支持16×16通信网络验证 |
| 坤恒顺维[19] | KSW-WNS04A | CE | 基于FPGA平台；支持1.5 MHz～7.5 GHz射频信号接入；支持1 GHz带宽信号处理；时延精度可达0.1 ns |
| 思博伦[20] | Vertex | CE | 基于FPGA平台；支持30 MHz～5.9 GHz射频信号接入；支持1.2 GHz带宽信号处理；最大支持64×8通信网络验证 |
| 罗德&施瓦茨[21] | SMW200A | CE | 基于FPGA平台；支持100 kHz～3 GHz射频信号接入；支持160 MHz带宽信号处理；最大支持8×8通信网络验证 |

注：第三代合作伙伴计划(3rd Generation Partnership Project, 3GPP)；国际电信联盟(International Telecommunication Union, ITU)；无线世界研究论坛(Wireless World Initiative New Radio, WINNER)；城市微小区(Urban Microcell, UMi)；城市宏小区(Urban Macrocell, UMa)；农村宏小区(Rural Macrocell, RMa)；室内热点(Indoor Hotspot, InH)；室内工厂(Indoor Factory, InF)；通用软件无线电外设(Universal Software Radio Peripheral, USRP)；现场可编程门阵列(Field Programmable Gate Array, FPGA)

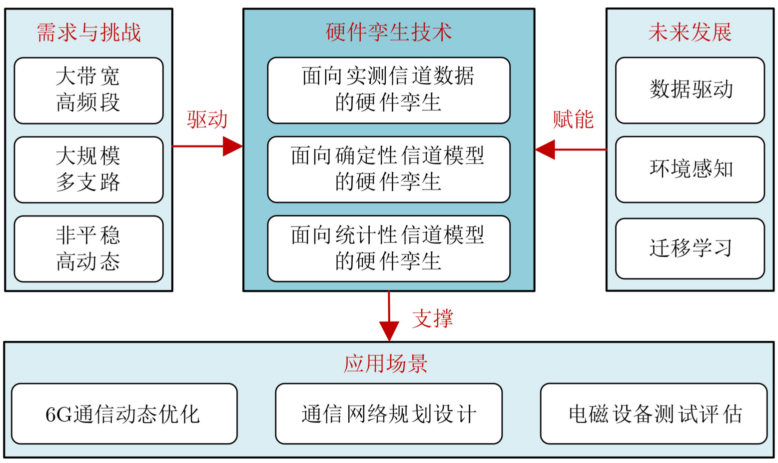


图 1 无线信道硬件孪生技术研究内容

信号频率进行变频处理，将传统的sub-6 GHz扩展到毫米波频段；文献[23]则介绍了一种频率扩展模块，可以将基带信号变频到THz频段。然而，受限于硬件实时处理性能，10 GHz带宽信号的实时处理面临根本性挑战：根据奈奎斯特采样定理，硬件需要以20 GS/s的速率连续处理样本，而主流FPGA的主频仅为1～2 GHz，难以直接实现20 GS/s的实时数据处理需求。为了解决该问题，文献[24,25]采用子带拼接的思想，将宽带信号分割成多个窄带的子带信号，以降低硬件对实时处理速度的要求。然而，子带拼接方法在实现过程中需要不断地进行校准，以确保拼接信道的频率响应达到一定的平坦度，这一过程耗时较长且受限于调谐分辨率和硬件自有频率响应的影响[26,27]。此外，文献[28]利用FPGA特有的并行处理特性，提出了串并转换方法，在160 MHz带宽上实现了600 MHz信道带宽的等效模拟，并且避免了繁琐的频率响应校准过程。但是，该方法仍受到硬件频率响应的影响，并对硬件性能也有较高要求。

### 2.2 非平稳高动态

未来通信网络将扩展至空、天、地和海等多样化场景，卫星、高铁和无人机等高速移动终端也将成为一体化通信网络的重要组成部分。与传统陆地通信场景不同，卫星等高速移动终端在通信过程中，信号传播场景快速变化，信道呈现显著的非平稳特性，实测结果表明平稳假设仅在亚毫秒级时间间隔内有效[29–31]，对CE的实时参数更新能力提出严苛要求。

现有CE主要面向静态或准静态场景，在高动态场景下的实时性与参数更新能力存在显著短板。当前主流方法通过划分“局部平稳时间间隔”实现非平稳信道模拟，即定义局部平稳时间间隔，将信道划分为若干时间段，假设每段时间内的信道特性满足平稳条件，通过不断更新各段内的信道参数来模拟通信场景的高动态切换。例如，文献[32]以256 μs为更新间隔，实现了最大速度为111.1 m/s的车联网非平稳信道的模拟。然而，在卫星通信场景中，低轨卫星的移动速度可达7.9 km/s，现有CE的更新间隔虽能满足111.1 m/s的车联网场景，但无法覆盖卫星通信的高动态切换需求。在实现机制上，针对非平稳信道的硬件模拟，常用参数更新方法包括离线预存和实时传输两种模式。其中，离线预存模式通过预先生成各平稳段的信道参数并存储到硬件平台中，受限于硬件存储容量，无法支持长时间连续动态场景；实时传输模式则通过上位机实时生成并传输信道参数到硬件平台，尽管降低了硬件存储需求，但受限于数据交互速率，难以满足高动态的场景切换。此外，现有各种硬件孪生方法将各个平稳区域看成独立的，并未考虑到在不同区域切换时多普勒相位、路径时延等信道特性的连续性[33,34]。

### 2.3 大规模多支路

随着通信设备数量的急剧增长，多输入多输出(Multiple-Input Multiple-Output, MIMO)、分布式网络以及多节点通信等通信技术也将被广泛应用。以MIMO技术为例，第4代(Fourth Generation, 4G)系统采用2～8个天线阵元，5G系统提升至64～192个，而面向6G的超大规模MIMO (Extremely large-scale Massive MIMO, XL-MIMO)预计将部署1 024阵元阵列以支撑Tbps级传输速率。这一增长直接导致信道模拟数量呈平方级攀升：对于$N$天线系统，信道矩阵维度为$N\times N$，需模拟的信道数量为$N^2$。

现有CE主要针对较少的天线阵元和有限的通信节点数。例如，文献[35]开发了一个支持4×4 MIMO系统的测试验证；文献[36]则提出了一个支持19×19 MIMO的硬件模拟架构。当前世界上最大的信道模拟器(Colosseum)集成超过128片Xilinx UltraScale+ FPGA芯片，支持256×256 MIMO网络测试，可同时模拟65 536个信道[37]。然而，若扩展至1 024×1 024 XL-MIMO系统，需模拟的信道数量将激增至1 048 576个，消耗的硬件资源将达到Colosseum的16倍，对硬件平台的存储和计算资源提出了极大的挑战[38]。为降低硬件资源消耗，文献[39]采用下三角矩阵分解方法优化了空间相关衰落的生成，但其实现较为复杂，系统可扩展性较差，难以支持大规模多支路信道模拟。总之，当前信道硬件孪生技术需在保证模拟精度的前提下，进一步降低硬件资源消耗并提升系统的可扩展性，以应对超大规模通信网络的测试验证需求。

## 3 无线信道硬件孪生技术研究进展

### 3.1 面向实测信道数据的硬件孪生

面向实测信道数据的硬件孪生技术通过采集真实世界的无线传播信号进行存储回放，以复现真实场景下无线信道对信号传输的影响。该方法进一步分为两种实现方案，信号复播和信道复播，整体实现架构如图2所示。

信号复播方案通过在真实环境采集记录不同位置的电磁接收信号，并在实验室利用复播设备直接回放这些信号，以再现特定时间、特定位置的不同电波传播环境的特性，主要用于无线通信设备的测试和校准[40–42]。例如，文献[40]实现了一种复杂电

磁环境特性的采集回放系统，用于芯片的电磁可靠性检测；文献[41,42]搭建了GNSS信号采集回放系统，用于卫星导航设备高精度接收器的测试和校准。在信号复播时，由于采集设备的差异，系统需支持不同采样率和带宽的信号回放[43,44]。为此，文献[45]采用了一种基于Farrow结构的重采样滤波器，可将信号从任意采集速率转换到固定回放速率，解决了采样速率与回放速率不匹配问题；文献[46]设计了一种宽窄带雷达信号直接采样和数字处理系统，宽带和窄带信号共享模拟接收通道，以支持多种带宽的数据回放。

信号复播方案只需直接回放采集的信号，而信道复播方案则通过对采集数据进行处理，提取特定场景的信道冲激响应(Channel Impulse Response, CIR)，并将其叠加到输入信号，从而复现该场景对无线信号传播的失真影响。整体而言，对于一些物理特性未明且没有标准模型的信道(如水声信道)，面向信道实测数据的硬件孪生技术能够更准确地反映信道特性[47,48]。例如，文献[49]提出了一种数据驱动的CE，从单一测量的CIR中估计散射函数以表征信道的统计特性，并生成具有相似散射函数的随机信道；文献[50,51]则分别通过局部散射函数和趋势平稳模型，提升了随机重放信道的真实性。信道复播方案的准确性很大程度上依赖于信道提取的精度，不准确的信道估计会导致性能预测结果存在误差[52]。为此，文献[53]通过利用输入信号之间的相似性，减少了信道估计误差，从而提高了信道复现的精确性；文献[54]则基于信道重放仿真获得的链路层统计数据，进行了通信网络的性能验证。

### 3.2 面向确定性信道模型的硬件孪生

面向确定性信道模型的硬件孪生技术通过模拟产生特定的CIR来复现信道传播特性。该技术首先利用确定性信道仿真方法产生连续的CIR，通过离散采样确定各个延迟抽头的系数，然后在硬件平台通过有限脉冲响应(Finite Impulse Response, FIR)滤波器重构CIR，整体实现架构如图3所示。

面向确定性信道模型的硬件孪生技术在信道响应重构的过程中，重构的信道精度取决于FIR滤波器的非零系数抽头数量。通常而言，非零抽头数目越多，重构后的信道特性越接近理论结果，但随之而来的硬件资源消耗也增多，导致难以实现大规模多支路的信道模拟[55,56]。信道参数计算和信道重构两步需要选择合适的采样策略与非零抽头数目，在有限的硬件资源下取得模拟精度和效率之间的平

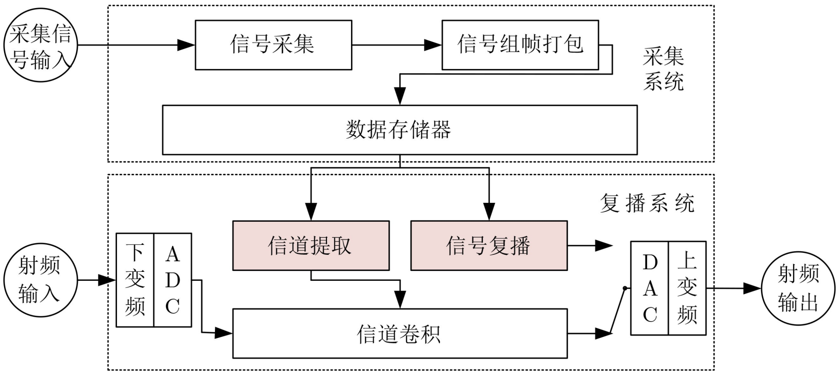


图 2 基于实测信道数据的硬件孪生架构

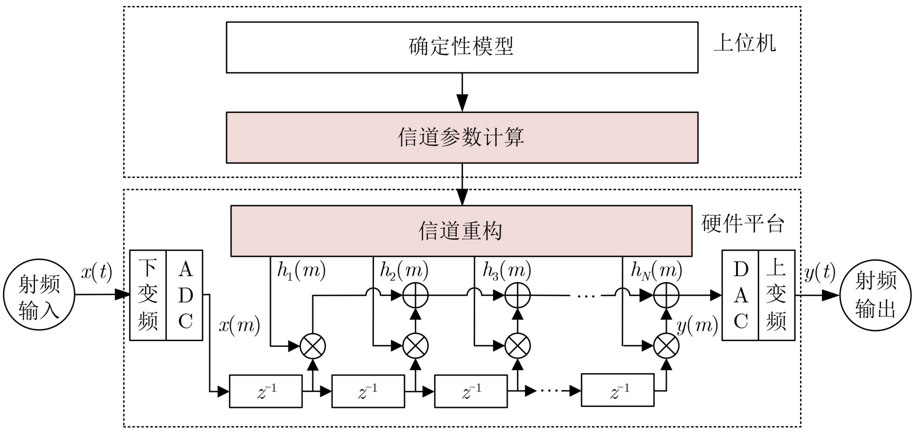


图 3 面向确定性信道模型的硬件孪生架构

衡，最大地保证信道的准确性。文献[57]采用了稀疏FIR滤波器架构进行重构信道，单信道FIR滤波器长度为68，其中最多有10个抽头同时为非零系数抽头；当前规模最大的信道模拟器Colosseum单信道FIR滤波器长度为512，其中仅有4个非零系数抽头，以支持256×256的大规模信道模拟[58]。

尽管减少非零抽头的数目有助于提高系统的资源利用率，但也不可避免地降低了信道模拟的精度。为此，文献[59]提出了一种基于K-medoids算法的信道稀疏化方法，在压缩了抽头数量的同时保留了模拟的精度；文献[60]则通过多径聚类和重采样技术调整抽头延迟，优化FIR系数，从而提高CIR重构的精度；文献[61]则采用时延分割和抽头缩减方法，在降低资源消耗的同时保持重构信道的平均延迟不变。然而，由于硬件时钟分辨率有限，上述方法采用舍入法使延迟与时钟周期对齐，导致CIR的相位特性失真，从而造成重构的信道频率响应(Channel Frequency Response, CFR)与理论信道存在误差。为进一步提高精度，文献[62,63]分别采用广义最小二乘FIR滤波器和minimax FIR滤波器来近似理想的分数时延滤波器，精确对齐时延，进而更好地匹配理论CFR。

此外，面向确定性信道模型的硬件孪生技术大多采用离线生成信道并将其系数存储在硬件中，模拟时通过周期性读取这些系数进行信道重构。然而，这种方法存在实时性差和硬件存储资源消耗大的问题[64,65]。例如，Colosseum仿真30min需要2.2 TB的空间，不足以支持信道长时间仿真[66]。因此，文献[67]提出了一种基于频域的子空间映射方法，通过将CFR投影到低秩子空间，并用投影系数来表征完整信道，从而减少信道重构过程中的数据量。文献[68]则将CFR分解为离散椭球(Discrete Prolate Spheroidal, DPS)子空间基系数的线性组合，在信道重构过程中，通过仅需缩放和移位操作的DPS基函数实现快速傅里叶逆变换恢复CIR，有效节省了硬件资源。进一步地，文献[69]采用了流水线框架实时传输投影系数，实现了长时间的信道模拟。

### 3.3 面向统计性信道模型的硬件孪生

面向统计性信道模型的硬件孪生技术通过模拟信号传播过程中的时延、幅度及相位等特性的变化，来复现无线信道对信号传播的影响。该孪生技术依据统计性信道模型的参数计算思想，在硬件平台上利用时延模块和信道衰落因子生成模块实现时延和符合特定概率分布的衰落，整体实现架构如图4所示。

面向统计模型的信道硬件孪生技术在模拟过程中，信道模拟精度取决于时延和衰落因子的实现精度。时延模拟包括长距离传播产生的绝对时延和不同多径间的相对时延。绝对时延通常通过硬件平台上的大容量存储单元来实现，例如文献[70]中使用片外存储RAM实现信道的长时延模拟。相对时延则依赖寄存器等片内存储单元，但由于硬件采样时钟分辨率有限，难以精确描述多径间的微小时延差。为提高精度，文献[71]利用多相滤波器，将低精度的整数时延转换为高精度的分数时延。为减少不同时延值导致的存储资源开销，文献[72]采用了滤波器系数固定的Farrow结构滤波器，进一步优化了多相滤波器的存储效率。

在衰落因子产生方面，常用方法包括成形滤波法[73]、自回归法[74]和谐波叠加法[75–81]等。其中，谐

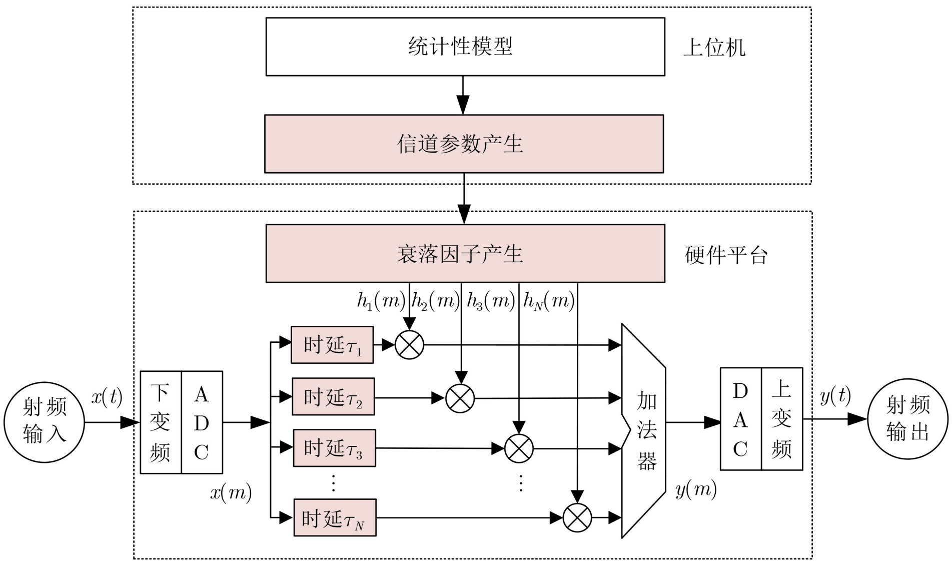

图 4 面向统计性信道模型的硬件孪生架构

波叠加法基于中心极限定理，通过多个谐波分量的叠加来模拟产生有色高斯随机过程，该方法具有实现简单且资源消耗少的优势，已被广泛应用于信道模拟器[75,76]。为适应非均匀散射场景，文献[77,78]将谐波叠加扩展至复数域，文献[79–81]则通过积分形式的相位替代乘积形式，确保输出相位的连续性，更好地适应非平稳信道的模拟需求。此外，为了准确复现信道特性，上位机需要产生符合一定统计特性的信道参数，其中多普勒频率参数尤为关键。目前主流的取值方法包括等面积法[82]、等功率法[83]、黎曼和法[84]和LP范数法[85]等。例如，文献[82]提出的等面积法将频谱分为等面积区域，以确定频点位置，实现较准确的功率谱密度；文献[83]则在等功率法的基础上引入不对称随机角偏移，以提高采样效率与衰落模拟精度；文献[84]通过黎曼和法分解入射角的概率密度函数，使自相关函数更贴合实际；文献[85]提出的LP范数法则通过匹配模型自相关函数与理论自相关函数，确定多普勒频率的取值。

除了精确的信道参数取值之外，硬件资源消耗和实时性也是信道硬件孪生面临的重要挑战。谐波叠加法需要生成大量的正余弦信号，常用的查找表法(Look-Up Table, LUT)通过预存相位表产生不同频率的正余弦信号，尽管实现简单但消耗存储资源较大[86]。为降低资源消耗，文献[87]引入了坐标旋转数字计算机(Coordinate Rotating Digital Computer, CORDIC)算法，通过旋转和平移操作逼近正余弦值，从而减少存储需求，但旋转过程带来了输出延迟。为了改进CORDIC算法，文献[88,89]分别通过角度折叠、角度记录及流水线架构等方法降低了计算复杂度和延迟。此外，文献[90,91]通过迭代法利用当前时刻的正余弦值推导下一时刻对应值，实现低资源的实时正余弦信号生成；文献[92]则提出前导零计数移位和算法转换法，将大位宽信号分解为小位宽分段线性函数，有效减少了硬件资源消耗。

### 3.4 3种信道硬件孪生技术分析比较

3种信道硬件孪生技术在模拟信道的真实性、灵活性、可扩展性、易实现性和仿真时长方面各有优劣势，各者的性能对比如表2所示。具体而言，面向实测信道数据的硬件孪生技术能够最大限度保留真实传播环境中的多径衰落、多普勒频移等复杂特性，具有实现简单、真实性高的显著优势。然而，由于其依赖于特定环境下的数据，其灵活性和扩展性较弱，难以适应其他场景。此外，信道复现时长受限于数据采集与存储量，满足长时间仿真的需求往往需高成本的大规模数据采集和存储模块。

面向确定性信道模型的硬件孪生技术灵活性较高，可通过上位机配置不同传播场景，且可以通过扩展硬件支持大规模网络验证。然而，其真实性依赖于信道模型仿真精度，在特定场景复现效果稍逊于面向实测信道数据的孪生技术。此外，该技术仍需存储大量滤波器抽头系数，虽然数据量少于实测数据，但信道仿真时长同样受到硬件存储资源的限制。

面向统计性信道模型的硬件孪生技术实现相对复杂，但灵活性和扩展性优越，能够通过参数调整适应多种场景，并支持模块化优化和扩展，以满足更复杂的模拟需求。然而，统计模型仅反映区域性信道的统计特性，在特定场景的真实性较低。此外，该技术可以基于信道参数持续生成特定分布的信道衰落，适合长时间信道仿真需求。

## 4 信道硬件孪生技术发展趋势与展望

### 4.1 未来发展趋势

(1)基于生成式网络的信道硬件孪生技术：面向实测信道数据的硬件孪生技术能够真实反映实际传播环境中的信道特性，尤其在未探明信道特性的场景中具有较高的复现精度。然而，该方法的复播时间受限于测量数据的时长，且由于通信环境的复杂性及测量过程的高昂成本，其应用受到较大限制。深度学习技术，如生成式网络(Generative Adversarial Network, GAN)，虽计算资源消耗较高，但其数据效率优势显著，能够在采集数据有限的情况下，通过学习信道内在特征生成长时间的信道数据，在较少的数据资源下复现复杂信道特性，为数据受限的场景提供更灵活的解决方案[93]。因此，数据驱动的信道孪生技术有效弥补了基于实测信道数据的硬件孪生技术在复播时长上的局限性，将成为未来复杂通信环境中信道模拟的重要研究方向。

表 2 3种信道硬件孪生技术性能比对

| | 真实性 | 灵活性 | 可扩展性 | 易实现性 | 仿真时长 |
|---|---|---|---|---|---|
| 面向实测信道数据的信道孪生 | ★★★ | ★ | ★ | ★★★ | ★ |
| 面向确定性信道模型的信道孪生 | ★★ | ★★★ | ★★ | ★★ | ★★ |
| 面向统计性信道模型的信道孪生 | ★ | ★★★ | ★★★ | ★ | ★★★ |

注：★越多表示该项性能越好；**真实性**：对真实传播场景的复现能力；**灵活性**：是否支持多场景仿真；**可扩展性**：是否支持根据需求进行硬件升级或扩展；**易实现性**：实现难度和资源需求；**仿真时长**：相同资源下，可支持的信道仿真的时长

(2)基于环境感知的信道硬件孪生技术：面向确定性信道模型的硬件孪生技术能够准确描述特定通信场景下的信道特性，尤其适用于对物理传播环境有详细先验信息的情况。然而，由于其依赖于离线的高精度环境建模，该方法实时性较差，难以在动态场景中快速响应环境变化，限制了其在复杂通信环境中的应用。在未来，通信网络将具备强大的环境感知和计算能力，结合精确的三维地图，可以通过实时快速感知对物理传播环境进行动态重构，从而实现对信道特性的高精度模拟与预测[94]。因此，基于环境感知的信道孪生技术能够有效弥补在实时性和动态适应性方面的不足，成为未来动态通信环境信道模拟的重要研究方向。

(3)基于迁移学习的信道硬件孪生技术：面向统计性信道模型的孪生技术可以通过大量测量数据进行统计分析，从而描述区域性的信道传播特性，并且能够通过调整模型参数统计特性来模拟不同场景中的信道特性。然而，该方法严重依赖已有的测量数据，一旦通信环境发生较大变化(如场景改变)，需重新进行数据采集和分析，模型更新成本和时间成本较高。迁移学习能够挖掘不同传播场景间的共性特征，并将现有模型的知识迁移到新场景中，从而在通信环境发生变化时，无需大量新数据即可快速调整模型[95]。此外，迁移学习还可以有效降低模型更新的成本，并提高信道模拟的适应性。因此，基于迁移学习的信道孪生技术在多场景切换的信道模拟方面具有重要的研究价值。

### 4.2 应用场景展望

(1)通信系统动态优化：随着6G网络对超高频段、XL-MIMO和动态多场景通信等的需求增加，无线信道模拟器将在新体制、新技术和新算法的动态设计优化中起到至关重要的作用。通过高精度的信道仿真与实时环境感知功能，信道模拟器能够快速复现不同场景(如高速车辆、无人机、卫星等)的动态信道变化，支持自适应波束成形、动态频谱管理以及多场景切换策略的测试与验证。未来，随着网络运营的智能化，信道模拟器将成为支持6G网络优化、智能决策和自动故障恢复的重要工具，使6G网络能够在复杂场景中更加灵活和高效地工作。

(2)通信网络规划设计：未来通信网络将面对更加复杂多变的部署场景(如城市、郊区、海上及空中等)，对网络的规划和设计提出了更高的要求。无线信道模拟器能够通过高精度的场景复现与多维度的信道分析，在不同部署场景下验证网络架构和传输方案的性能。利用环境感知和数字孪生技术，信道模拟器能够对各种场景进行快速重构与实时预测，从而帮助研究者在网络设计阶段提前评估不同部署策略的可行性与性能表现。通过该技术，通信网络的规划设计将更加精准，能够更好地满足未来异构网络的广覆盖与高可靠性需求。

(3)电磁设备测试评估：随着通信逐渐进入更高频段(如毫米波和太赫兹波)和新型设备(如智能反射面和可重构超表面等)的研发，无线信道模拟器将在电磁设备的研发和测试中扮演重要角色。特别地，能够在实验室条件下有效评估各种传播环境中的设备性能，包括新型天线、智能反射面及可重构通信硬件平台等。此外，通过建立统一的信道模拟标准，设备制造商、网络运营商和科研机构可以在统一的模拟环境中共享数据与模型，共同验证新的设备、协议和通信技术，从而加速技术的研发和成熟。

## 5 结束语

无线信道硬件孪生技术是评估和优化通信系统及设备性能的重要手段，在优化实时通信性能、提升网络部署效率和缩短设备研发周期等方面具有重要意义。本文面向未来大带宽、高动态及大规模通信场景的信道孪生需求，分析了信道硬件孪生技术的主要挑战，首次从信道数据来源、模型类型和实现架构等角度对现有技术进行了系统的分析，归纳了面向实测信道数据、确定性信道模型及统计性信道模型的3类硬件孪生方法，并比较了它们在真实性、灵活性及可扩展性等方面的优缺点，为复杂通信环境下的无线信道模拟复现提供了重要参考。最后，本文探讨了无线信道硬件孪生技术的未来发展趋势与应用场景，通过结合生成式网络、环境感知和迁移学习等新兴技术，以提升信道孪生效率与灵活性，更好地满足未来通信系统对性能验证的需求，推动通信技术的创新发展。

## 参 考 文 献


[1] LIU Ting, GUAN Ke, HE Danping, *et al*. 6G integrated sensing and communications channel modeling: Challenges and opportunities[J]. *IEEE Vehicular Technology Magazine*, 2024, 19(2): 31–40. doi: 10.1109/MVT.2024.3373930.

[2] WANG Heng, ZHANG Jianhua, NIE Gaofeng, *et al*. Digital twin channel for 6G: Concepts, architectures and potential applications[J]. *IEEE Communications Magazine*, 2025, 63(3): 24–30. doi: 10.1109/MCOM.001.2400213.

[3] LI Junling, WANG Chengxiang, HUANG Chen, *et al*. Digital twin online channel modeling: Challenges, principles, and applications[J]. *IEEE Vehicular Technology Magazine*, 2025, 20(1): 94–103. doi: 10.1109/MVT.2025.3527729.

[4] KIHERO A B, KARABACAK M, and ARSLAN H.

Emulation techniques for small scale fading aspects by using reverberation chamber[J]. *IEEE Transactions on Antennas and Propagation*, 2019, 67(2): 1246–1258. doi: 10.1109/TAP.2018.2883571.

[5] HATA M and NAGATSU T. Mobile location using signal strength measurements in a cellular system[J]. *IEEE Transactions on Vehicular Technology*, 1980, 29(2): 245–252. doi: 10.1109/T-VT.1980.23848.

[6] FAILLI M. Digital land mobile radio communications[EB/OL]. https://op.europa.eu/en/publication-detail/-/publication/61fc77e7-bca2-4229-8eb4-77741f0d2ab2, 1989.

[7] PODDAR H, JU Shihao, SHAKYA D, *et al*. A tutorial on NYUSIM: Sub-terahertz and millimeter-wave channel simulator for 5G, 6G, and beyond[J]. *IEEE Communications Surveys & Tutorials*, 2024, 26(2): 824–857. doi: 10.1109/COMST.2023.3344671.

[8] FRAUNHOFER HHI. QuaDRiGa channel model[EB/OL]. https://quadriga-channel-model.de, 2023.

[9] TARBOUSH S, SARIEDDEEN H, CHEN Hui, *et al*. TeraMIMO: A channel simulator for wideband ultra-massive MIMO terahertz communications[J]. *IEEE Transactions on Vehicular Technology*, 2021, 70(12): 12325–12341. doi: 10.1109/TVT.2021.3123131.

[10] BELZARENA P. PyWiCh: Python wireless channel simulator[C]. 2022 IEEE Latin-American Conference on Communications, Rio de Janeiro, Brazil, 2022: 1–6. doi: 10.1109/LATINCOM56090.2022.10000470.

[11] ALKHATEEB A. DeepMIMO: A generic deep learning dataset for millimeter wave and massive MIMO applications[EB/OL]. https://arxiv.org/abs/1902.06435, 2019.

[12] BUPT-ARTT Lab, IMT-2030 THz channel model platform[EB/OL]. http://www.zjhlab.net/publications/buptcmg-imt2030_thz-channel-model-platform, 2023.

[13] BJTU APC Lab, CloudRT ray-tracing simulation platform[EB/OL]. http://www.raytracer.cloud/, 2021.

[14] WANG Chengxiang, LV Zhen, CHEN Yunfei, *et al*. A complete study of space-time-frequency statistical properties of the 6G pervasive channel model[J]. *IEEE Transactions on Communications*, 2023, 71(12): 7273–7287. doi: 10.1109/TCOMM.2023.3307144.

[15] BONATI L, JOHARI P, POLESE M, *et al*. Colosseum: Large-scale wireless experimentation through hardware-in-the-loop network emulation[C]. 2021 IEEE International Symposium on Dynamic Spectrum Access Networks, Los Angeles, USA, 2021: 105–113. doi: 10.1109/DySPAN53946.2021.9677430.

[16] DAKIĆ A, RAINER B, HOFER M, *et al*. Hardware-in-the-loop framework for testing wireless V2X communication[C]. 2023 IEEE Wireless Communications and Networking Conference, Glasgow, UK, 2023: 1–6. doi: 10.1109/WCNC55385.2023.10118673.

[17] ZHU Qiuming, ZHAO Zikun, MAO Kai, *et al*. A real-time hardware emulator for 3D non-stationary U2V channels[J]. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 2021, 68(9): 3951–3964. doi: 10.1109/TCSI.2021.3087777.

[18] KEYSIGHT Technologies. F8800A PROPSIM F64 channel emulator[EB/OL]. https://www.keysight.com/us/en/product/F8800A, 2023.

[19] 坤恒顺维. KSW-WNS04无线信道仿真仪[EB/OL]. https://www.ksw-tech.com/products/ksw-wns04-wireless-channel-simulator.html, 2024.

KSW Technologies Co. ,Ltd. KSW-WNS04 Wireless Channel Simulator[EB/OL]. https://www.ksw-tech.com/products/ksw-wns04-wireless-channel-simulator.html, 2024.

[20] Spirent Communications. Spirent vertex channel emulator[EB/OL]. https://www.spirent.com/assets/u/spirent_vertex_channel_emulator_datasheet, 2024.

[21] ROHDE&SCHWARZ. R&S®SMW200A vector signal generator[EB/OL]. https://www.rohde-schwarz.com/us/products/test-and-measurement/vector-signal-generators/rs-smw200a-vector-signal-generator_63493-38656.html, 2024.

[22] JI Yilin and FAN Wei. Enabling high-fidelity ultra-wideband radio channel emulation: Band-stitching and digital predistortion concepts[J]. *IEEE Open Journal of Antennas and Propagation*, 2022, 3: 932–939. doi: 10.1109/OJAP.2022.3198287.

[23] GHOSH A and KIM M. THz channel sounding and modeling techniques: An overview[J]. *IEEE Access*, 2023, 11: 17823–17856. doi: 10.1109/ACCESS.2023.3246161.

[24] FAN Wei, KYÖSTI P, HENTILÄ L, *et al*. A flexible millimeter-wave radio channel emulator design with experimental validations[J]. *IEEE Transactions on Antennas and Propagation*, 2018, 66(11): 6446–6451. doi: 10.1109/TAP.2018.2864339.

[25] CAO Jue, TILA F, and NIX A. Design and implementation of a wideband channel emulation platform for 5G mmWave vehicular communication[J]. *IET Communications*, 2020, 14(14): 2369–2376. doi: 10.1049/iet-com.2019.1016.

[26] JI Yilin, FAN Wei, and PEDERSEN G. Wideband radio channel emulation using band-stitching schemes[C]. 2020 14th European Conference on Antennas and Propagation, Copenhagen, Denmark, 2020: 1–5. doi: 10.23919/EuCAP48036.2020.9135788.

[27] ZHANG Fengchun, BENGTSON M F, KYÖSTI P, *et al*. Dynamic sub-THZ radio channel emulation: Principle, challenges, and experimental validation[J]. *IEEE Wireless Communications*, 2024, 31(1): 10–16. doi: 10.1109/MWC.001.2300286.

[28] FENG Ruirui, MAO Kai, ZHU Qiuming, *et al*. Real-time

hardware emulation of frequency non-stationary UWB channels with continuous frequency response[C]. 2022 IEEE 22nd International Conference on Communication Technology, Nanjing, China, 2022: 999–1003. doi: 10.1109/ICCT56141.2022.10072872.

[29] 朱秋明, 倪浩然, 华博宇, 等. 无人机毫米波信道测量与建模研究综述[J]. 移动通信, 2022, 46(12): 1–11. doi: 10.3969/j.issn.1006-1010.20221114-0001.

ZHU Qiuming, NI Haoran, HUA Boyu, *et al*. A survey of UAV millimeter-wave channel measurement and modeling[J]. *Mobile Communications*, 2022, 46(12): 1–11. doi: 10.3969/j.issn.1006-1010.20221114-0001.

[30] 张在琛, 江浩. 智能超表面使能无人机高能效通信信道建模与传输机理分析[J]. 电子学报, 2023, 51(10): 2623–2634. doi: 10.12263/DZXB.20221352.

ZHANG Zaichen and JIANG Hao. Channel modeling and characteristics analysis for high energy-efficient RIS-Assisted UAV communications[J]. *Acta Electronica Sinica*, 2023, 51(10): 2623–2634. doi: 10.12263/DZXB.20221352.

[31] MAO Kai, ZHU Qiuming, WANG Chengxiang, *et al*. A survey on channel sounding technologies and measurements for UAV-assisted communications[J]. *IEEE Transactions on Instrumentation and Measurement*, 2024, 73: 8004624. doi: 10.1109/TIM.2024.3436128.

[32] HOFER M, XU Zhinan, VLASTARAS D, *et al*. Validation of a real-time geometry-based stochastic channel model for vehicular scenarios[C]. 2018 IEEE 87th Vehicular Technology Conference, Porto, Portugal, 2018: 1–5. doi: 10.1109/VTCSpring.2018.8417476.

[33] ZHU Qiuming, LIU Xinglin, YIN Xuefeng, *et al*. A novel simulator of nonstationary random MIMO channels in Rayleigh fading scenarios[J]. *International Journal of Antennas and Propagation*, 2016, 2016: 3492591. doi: 10.1155/2016/3492591.

[34] 李浩, 朱秋明, 陈应兵, 等. 非平稳信道衰落FPGA实时模拟方法[J]. 信号处理, 2018, 34(3): 368–375. doi: 10.16798/j.issn.1003-0530.2018.03.014.

LI Hao, ZHU Qiuming, CHEN Yingbing, *et al*. A real-time FPGA-based emulation method for no-stationary channel fading[J]. *Journal of Signal Processing*, 2018, 34(3): 368–375. doi: 10.16798/j.issn.1003-0530.2018.03.014.

[35] CHAUDHARI A, SQUIRES D, and TILGHMAN P. Colosseum: A battleground for AI let loose on the RF spectrum[J]. *Microwave Journal*, 2018, 61(9): 22–36.

[36] HUANG Pengda, TONNEMACHER M J, DU Yongjiu, *et al*. Towards massive MIMO channel emulation: Channel accuracy versus implementation resources[J]. *IEEE Transactions on Vehicular Technology*, 2020, 69(5): 4635–4651. doi: 10.1109/TVT.2020.2980583.

[37] HUANG Duoxian, XIN Lijian, HUANG Jie, *et al*. Adaptive non-stationary vehicle-to-vehicle MIMO channel simulator and emulator[C]. 2023 IEEE Wireless Communications and Networking Conference, Glasgow, UK, 2023: 1–6. doi: 10.1109/WCNC55385.2023.10119045.

[38] VAN TIEN T, TIEN T M, and KHAI L D. Hardware implementation of a MIMO channel emulator for high speed WLAN 802.11 ac[C]. 2018 5th NAFOSTED Conference on Information and Computer Science, Ho Chi Minh City, Vietnam, 2018: 183–188. doi: 10.1109/NICS.2018.8606847.

[39] FANG Sheng, MAO Tongbao, HUA Boyu, *et al*. A scalable spatial–temporal correlated non-stationary channel fading generation method[J]. *Electronics*, 2023, 12(19): 4132. doi: 10.3390/electronics12194132.

[40] CHEN Yanning, LIU Fang, GAO Jie, *et al*. Research on electromagnetic environment characteristic acquisition system for industrial chips[J]. *Electronics*, 2024, 13(10): 1963. doi: 10.3390/electronics13101963.

[41] XU Yuan, WU Jintie, LIANG Wei, *et al*. The development of high performance GNSS RF record & playback system[C]. 2017 International Workshop on Electromagnetics: Applications and Student Innovation Competition, London, UK, 2017: 74–78. doi: 10.1109/iWEM.2017.7968789.

[42] CONSOLI A and YOSSEF Y B. High precision record & playback system for the analysis of wide-band GNSS signals[C]. 2019 European Navigation Conference, Warsaw, Poland, 2019: 1–5. doi: 10.1109/EURONAV.2019.8714139.

[43] ZHAO Yingxiao, SU Yang, HUANG Rui, *et al*. Design and implementation of a radar waveform playback system for real-time digital signal processing test[C]. 2017 Sixth Asia-Pacific Conference on Antennas and Propagation, Xi'an, China, 2017: 1–3. doi: 10.1109/APCAP.2017.8420895.

[44] MATHUR N and LAKSHMI B. High throughput arbitrary sample rate converter for software radios[C]. 2014 International Conference on Control, Instrumentation, Communication and Computational Technologies, Kanyakumari, India, 2014: 1121–1123. doi: 10.1109/ICCICCT.2014.6993129.

[45] ZHAO Wenhao, TIAN Shulin, LIU Ke, *et al*. Low spurious waveform synthesis based on digital resampling[C]. 2021 IEEE 15th International Conference on Electronic Measurement & Instruments, Nanjing, China, 2021: 276–280. doi: 10.1109/ICEMI52946.2021.9679594.

[46] ZHAO Yingxiao, YOU Hongliang, and ZHANG Yue. An FPGA-based direct sampling and digital processing system for wideband and narrowband radar signal[J]. *Journal of Physics: Conference Series*, 2020, 1624(3): 032029. doi: 10.1088/1742-6596/1624/3/032029.

[47] JENSERUD T and OTNES R. Reverberation tail in power delay profiles: Effects and modeling[C]. 2013 MTS/IEEE OCEANS-Bergen, Bergen, Norway, 2013: 1–10. doi: 10.1109/OCEANS-Bergen.2013.6608063.

[48] SOCHELEAU F X, LAOT C, and PASSERIEUX J M. Parametric replay-based simulation of underwater acoustic communication channels[J]. *IEEE Journal of Oceanic Engineering*, 2015, 40(4): 796–806. doi: 10.1109/JOE.2015.2458211.

[49] OTNES R, VAN WALREE P A, and JENSERUD T. Validation of replay-based underwater acoustic communication channel simulation[J]. *IEEE Journal of Oceanic Engineering*, 2013, 38(4): 689–700. doi: 10.1109/JOE.2013.2262743.

[50] ISUKAPALLI Y, SONG H C, and HODGKISS W S. Stochastic channel simulator based on local scattering functions[J]. *The Journal of the Acoustical Society of America*, 2011, 130(4): EL200–EL205. doi: 10.1121/1.3633688.

[51] SOCHELEAU F X, LAOT C, and PASSERIEUX J M. Stochastic replay of non-WSSUS underwater acoustic communication channels recorded at sea[J]. *IEEE Transactions on Signal Processing*, 2011, 59(10): 4838–4849. doi: 10.1109/TSP.2011.2160057.

[52] YANG S, DEANE G B, PREISIG J C, *et al*. On the reusability of postexperimental field data for underwater acoustic communications R&D[J]. *IEEE Journal of Oceanic Engineering*, 2019, 44(4): 912–931. doi: 10.1109/JOE.2019.2925921.

[53] YANG S and SINGER A C. Optimal replay-based channel simulation via dithering methods[C]. 2019 53rd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, USA, 2019: 957–963. doi: 10.1109/IEEECONF44664.2019.9049034.

[54] OTNES R, VAN WALREE P A, BUEN H, *et al*. Underwater acoustic network simulation with lookup tables from physical-layer replay[J]. *IEEE Journal of Oceanic Engineering*, 2015, 40(4): 822–840. doi: 10.1109/JOE.2015.2471736.

[55] RUSCA R, RAVIGLIONE F, CASETTI C, *et al*. Mobile RF scenario design for massive-scale wireless channel emulators[C]. 2023 Joint European Conference on Networks and Communications & 6G Summit, Gothenburg, Sweden, 2023: 675–680. doi: 10.1109/EuCNC/6GSummit58263.2023.10188319.

[56] VILLA D, TEHRANI-MOAYYED M, ROBINSON C P, *et al*. Colosseum as a digital twin: Bridging real-world experimentation and wireless network emulation[J]. *IEEE Transactions on Mobile Computing*, 2024, 23(10): 9150–9166. doi: 10.1109/TMC.2024.3359596.

[57] GHIAASI G, ASHURY M, VLASTARAS D, *et al*. Real-time vehicular channel emulator for future conformance tests of wireless ITS modems[C]. 2016 10th European Conference on Antennas and Propagation, Davos, Switzerland, 2016: 1–5. doi: 10.1109/EuCAP.2016.7481226.

[58] CHAUDHARI A and BRAUN M. A scalable FPGA architecture for flexible, large-scale, real-time RF channel emulation[C]. 2018 13th International Symposium on Reconfigurable Communication-centric Systems-on-Chip, Lille, France, 2018: 1–8. doi: 10.1109/ReCoSoC.2018.8449390.

[59] ZHOU Shun, OU Gang, and TANG Xiaomei. Satellite navigation multipath channel sparse reconstruction scheme applied in performance evaluation of constellation channel emulation[C]. 2021 13th International Symposium on Antennas, Propagation and EM Theory, Zhuhai, China, 2021: 01–03. doi: 10.1109/ISAPE54070.2021.9753259.

[60] TEHRANI-MOAYYED M, BONATI L, JOHARI P, *et al*. Creating RF scenarios for large-scale, real-time wireless channel emulators[C]. 2021 19th Mediterranean Communication and Computer Networking Conference, Ibiza, Spain, 2021: 1–8. doi: 10.1109/MedComNet52149.2021.9501275.

[61] MBUGUA A W, CHEN Yun, and FAN Wei. On simplification of ray tracing channels in radio channel emulators for device testing[C]. 2021 15th European Conference on Antennas and Propagation, Dusseldorf, Germany, 2021: 1–5. doi: 10.23919/EuCAP51087.2021.9411504.

[62] MBUGUA A W, CHEN Yun, and FAN Wei. Radio channel emulation for virtual drive testing with site-specific channels[C]. 2022 16th European Conference on Antennas and Propagation, Madrid, Spain, 2022: 1–5. doi: 10.23919/EuCAP53622.2022.9769382.

[63] MBUGUA A W, CHEN Yun, RASCHKOWSKI L, *et al*. Efficient preprocessing of site-specific radio channels for virtual drive testing in hardware emulators[J]. *IEEE Transactions on Aerospace and Electronic Systems*, 2023, 59(2): 1787–1799. doi: 10.1109/TAES.2022.3205289.

[64] GHIAASI G, BLAZEK T, ASHURY M, *et al*. Real‐time emulation of nonstationary channels in safety‐relevant vehicular scenarios[J]. *Wireless Communications and Mobile Computing*, 2018, 2018: 2423837. doi: 10.1155/2018/2423837.

[65] HOFER M, BERNADÓ L, RAINER B, *et al*. Evaluation of vehicle-in-the-loop tests for wireless V2X communication[C]. 2019 IEEE 90th Vehicular Technology Conference, Honolulu, USA, 2019: 1–5. doi: 10.1109/VTCFall.2019.8891080.

[66] BARCKLOW D R, BLOCH L E, SWEENEY S W, *et al*. Radio frequency emulation system for the defense advanced research projects agency spectrum collaboration challenge[J]. *Johns Hopkins APL Technical Digest*, 2019, 35(1): 69–78.

[67] KALTENBERGER F, ZEMEN T, and UEBERHUBER C W. Low-complexity geometry-based MIMO channel

simulation[J]. *EURASIP Journal on Advances in Signal Processing*, 2007, 2007: 095281. doi: 10.1155/2007/95281.

[68] HOFER M, XU Zhinan, VLASTARAS D, *et al*. Real-time geometry-based wireless channel emulation[J]. *IEEE Transactions on Vehicular Technology*, 2019, 68(2): 1631–1645. doi: 10.1109/TVT.2018.2888914.

[69] DAKIĆ A, HOFER M, RAINER B, *et al*. Real-time vehicular wireless system-level simulation[J]. *IEEE Access*, 2021, 9: 23202–23217. doi: 10.1109/ACCESS.2021.3055978.

[70] ZHANG Dongyang, MAO Kai, YANG Yang, *et al*. Implementation of non-stationary channel emulator based on USRP[C]. 5th International Conference on Machine Learning and Intelligent Communications, Shenzhen, China, 2021, 342: 437–446. doi: 10.1007/978-3-030-66785-6_48.

[71] 黄文清, 李伟东, 郭放, 等. 基于轨迹的车对车无线信道建模及硬件模拟[J]. 电子测量与仪器学报, 2019, 33(8): 55–62. doi: 10.13382/j.jemi.B1902193.

HUANG Wenqing, LI Weidong, GUO Fang, *et al*. Channel modeling and hardware emulation for the trajectories based vehicle-to-vehicle channels[J]. *Journal of Electronic Measurement and Instrumentation*, 2019, 33(8): 55–62. doi: 10.13382/j.jemi.B1902193.

[72] CHEN Y M and CHEN Chuncheng. Design of farrow structured variable fractional delay filter for time-varying LEO communication channel emulator with SRRC communication waveforms[J]. *IEEE Access*, 2024, 12: 122229–122238. doi: 10.1109/ACCESS.2024.3452496.

[73] YOUNG D J and BEAULIEU N C. The generation of correlated Rayleigh random variates by inverse discrete Fourier transform[J]. *IEEE Transactions on Communications*, 2000, 48(7): 1114–1127. doi: 10.1109/26.855519.

[74] BADDOUR K E and BEAULIEU N C. Autoregressive modeling for fading channel simulation[J]. *IEEE Transactions on Wireless Communications*, 2005, 4(4): 1650–1662. doi: 10.1109/TWC.2005.850327.

[75] ALIMOHAMMAD A and COCKBURN B F. A reconfigurable SOS-based Rayleigh fading channel simulator[C]. IEEE Workshop on Signal Processing Systems Design and Implementation, Banff, Canada, 2006: 39–44. doi: 10.1109/SIPS.2006.352552.

[76] YUAN Yi, WANG Chengxiang, CHENG Xiang, *et al*. Novel 3D geometry-based stochastic models for non-isotropic MIMO vehicle-to-vehicle channels[J]. *IEEE Transactions on Wireless Communications*, 2014, 13(1): 298–309. doi: 10.1109/TWC.2013.120313.130434.

[77] GUTIÉRREZ C A and PATZOLD M. The design of sum-of-cisoids Rayleigh fading channel simulators assuming non-isotropic scattering conditions[J]. *IEEE Transactions on Wireless Communications*, 2010, 9(4): 1308–1314. doi: 10.1109/TWC.2010.04.091198.

[78] WANG Weimin, WANG Heng, WU Yongle, *et al*. Novel deterministic angular sampling methods for 3D channel models[J]. *IEEE Communications Letters*, 2021, 25(6): 1756–1760. doi: 10.1109/LCOMM.2021.3061735.

[79] ZHU Qiuming, HUANG Wei, MAO Kai, *et al*. A flexible FPGA-based channel emulator for non-stationary MIMO fading channels[J]. *Applied Sciences*, 2020, 10(12): 4161. doi: 10.3390/app10124161.

[80] LIU Xinglin, ZHU Qiuming, CHEN Xiaomin, *et al*. A new simulation model for non-stationary fading channel[C]. 2016 3rd International Conference on Electronic Design, Phuket, Thailand, 2016: 66–69. doi: 10.1109/ICED.2016.7804608.

[81] ZHU Qiuming, LI Hao, FU Yu, *et al*. A novel 3D non-stationary wireless MIMO channel simulator and hardware emulator[J]. *IEEE Transactions on Communications*, 2018, 66(9): 3865–3878. doi: 10.1109/TCOMM.2018.2824817.

[82] GUTIÉRREZ C A and PĂTZOLD M. The generalized method of equal areas for the design of sum-of-cisoids simulators for mobile Rayleigh fading channels with arbitrary Doppler spectra[J]. *Wireless Communications and Mobile Computing*, 2013, 13(10): 951–966. doi: 10.1002/wcm.1154.

[83] ZHANG Yuxiang, YUAN Zhiqiang, TIAN Lei, *et al*. A novel random angular sampling method for spatial and temporal channel emulation[J]. *IEEE Wireless Communications Letters*, 2019, 8(5): 1381–1385. doi: 10.1109/LWC.2019.2918787.

[84] GUTIÉRREZ C A, FABÍAN-RODRÍGUEZ R A, CASTILLO-SORIA F R, *et al*. SOC-based simulation of 3D MIMO mobile-to-mobile fading channels: A Riemann sum approach[J]. *IEEE Open Journal of Vehicular Technology*, 2024, 5: 1–20. doi: 10.1109/OJVT.2023.3331534.

[85] PĂTZOLD M and YOUSSEF N. Modelling and simulation of direction-selective and frequency-selective mobile radio channels[J]. *AEU - International Journal of Electronics and Communications*, 2001, 55(6): 433–442. doi: 10.1078/1434-8411-54100064.

[86] DONG Shuli, ZHANG Taotao, and WANG Yan. A real-time simulation design of multi-path fading channel based on SOS method[C]. 2019 IEEE 4th Advanced Information Technology, Electronic and Automation Control Conference, Chengdu, China, 2019: 2550–2554. doi: 10.1109/IAEAC47372.2019.8997884.

[87] HUANG Duoxian, XIN Lijian, HUANG Jie, *et al*. A non-stationary channel emulator for 6G THz wireless channels[C]. 2023 International Conference on Wireless Communications and Signal Processing, Hangzhou, China, 2023: 563–568. doi: 10.1109/WCSP58612.2023.10405337.

[88] ZHAO Zikun, ZHU Qiuming, MAO Kai, *et al*. An efficient

hardware generator for massive non-stationary fading channels[C]. 2020 IEEE Globecom Workshops, Taipei, China, 2020: 1–6. doi: 10.1109/GCWkshps50303.2020.9367588.

[89] FANG Chen, MAO Kai, FANG Sheng, *et al*. CORDIC-based general multiple fading generator for wireless channel digital twin[J]. *Sensors*, 2023, 23(5): 2712. doi: 10.3390/s23052712.

[90] 赵子坤, 房晨, 陈小敏, 等. 面向5G/6G大规模MIMO信道实时模拟研究[J]. 微波学报, 2022, 38(1): 30–35,40. doi: 10.14183/j.cnki.1005-6122.202201007.

ZHAO Zikun, FANG Chen, CHEN Xiaomin, *et al*. A real-time emulation research on 5G/6G massive MIMO channels[J]. *Journal of Microwaves*, 2022, 38(1): 30–35,40. doi: 10.14183/j.cnki.1005-6122.202201007.

[91] YANG Yang, LI Tingpeng, CHEN Xiaomin, *et al*. Real-time ray-based channel generation and emulation for UAV communications[J]. *Chinese Journal of Aeronautics*, 2022, 35(9): 106–116. doi: 10.1016/j.cja.2021.12.008.

[92] PAPALAMPROU I, ARMENIAKOS G, STRATAKOS I, *et al*. Flexible real-time emulation of fading channels on SoC-FPGA devices[C]. 2024 Panhellenic Conference on Electronics & Telecommunications, Thessaloniki, Greece, 2024: 1–6. doi: 10.1109/PACET60398.2024.10497075.

[93] XIAO Han, TIAN Wenqiang, LIU Wendong, *et al*. ChannelGAN: Deep learning-based channel modeling and generating[J]. *IEEE Wireless Communications Letters*, 2022, 11(3): 650–654. doi: 10.1109/LWC.2021.3140102.

[94] ALKHATEEB A, JIANG Shuaifeng, and CHARAN G. Real-time digital twins: Vision and research directions for 6G and beyond[J]. *IEEE Communications Magazine*, 2023, 61(11): 128–134. doi: 10.1109/MCOM.001.2200866.

[95] MAO Kai, ZHU Qiuming, SONG Maozhong, *et al*. Machine-learning-based 3-D channel modeling for U2V mmWave communications[J]. *IEEE Internet of Things Journal*, 2022, 9(18): 17592–17607. doi: 10.1109/JIOT.2022.3155773.

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# Advances and Challenges in Wireless Channel Hardware Twin

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**Abstract**:

**Significance** Wireless channel characteristics are key determinants of communication system performance and reliability. Channel twin technology—defined as the physical or digital reproduction of channel distortion effects—has become essential for system testing and validation. Digital twin approaches are favored for their flexibility and efficiency, and hardware-based platforms (i.e., channel emulators, CEs) are widely used for large-scale performance evaluation. However, as networks advance toward Terahertz (THz) bands, extremely large-scale massive Multiple-Input Multiple-Output (XL-MIMO) systems (e.g., 1024-antenna arrays), and integrated air-space-ground-sea communications, three key limitations remain: (1) Inability to support real-time processing for ultra-wide bandwidths over 10 GHz; (2) Inadequate dynamic emulation accuracy for non-stationary channels under high mobility; and (3) Insufficient hardware resources for simulating over $10^6$ concurrent channels in XL-MIMO architectures. This study reviews state-of-the-art hardware twin technologies, identifies critical technical bottlenecks, and outlines future directions for next-generation channel emulation platforms.

**Progress** Existing channel hardware twin technologies can be categorized into three paradigms based on channel data sources, model types, and implementation architectures. First, measured data-driven twin technology uses real-world propagation data to enable high-fidelity emulation. Signal replay reproduces specific

electromagnetic environments by replaying recorded signals. Although this approach preserves scene-specific authenticity, it lacks flexibility due to dependence on measured datasets and storage constraints. Channel Impulse Response (CIR) replay extracts propagation characteristics from measurement data, making it applicable to unmodeled environments such as underwater acoustics. However, its accuracy depends on precise channel estimation and is limited by data sampling resolution and storage capacity. Second, deterministic model-driven twin technology generates CIR using Finite Impulse Response (FIR) filters by synthesizing multipath delays and fading coefficients for predefined scenarios. Techniques such as sparse filtering and subspace projection optimize the trade-off between accuracy and hardware efficiency. For example, current large-scale emulators support 256×256 MIMO systems with 512-tap FIR filters, requiring only four active taps. Nonetheless, limited clock resolution introduces phase distortion in the frequency response, reducing fidelity in high-frequency terahertz applications. Third, statistical model-driven twin technology emulates time-varying channel behavior by generating fading and delay profiles based on probability distributions. The sum-of-sinusoids method is widely employed due to its simplicity and low computational demand, while enhanced implementations—such as the coordinate rotating digital computer algorithm—minimize storage requirements for sinusoid generation. This paradigm offers strong scalability but sacrifices scenario-specific fidelity, limiting its ability to reproduce certain channel characteristics accurately. A comparative analysis across fidelity, flexibility, scalability, and implementation complexity shows that measured data-driven methods are best suited for reproducing real-world environments; deterministic models support configurable scenario design for known settings; and statistical models facilitate efficient emulation of large-scale networks. Each approach balances distinct advantages against inherent limitations.

**Prospects** Future developments in channel hardware twin technologies are expected to integrate emerging innovations to overcome current limitations: (1) Deep learning techniques—such as generative adversarial networks—can learn from limited measured channel data to synthesize channel characteristics, reducing dependence on extensive datasets in measured data-driven approaches. (2) The environment-aware capabilities of next-generation communication networks enable dynamic reconstruction of propagation environments, addressing the lack of real-time adaptability in deterministic model-driven technologies. (3) Transfer learning enables the migration of knowledge across propagation scenarios, improving the cross-scenario generalization of statistical model-driven emulation without requiring large amounts of measured data. Future applications of channel hardware twin technologies are expected to advance in three primary directions: (1) real-time optimization of communication systems; (2) network planning and design; and (3) testing and evaluation of electromagnetic devices. Through the integration of deep learning and environmental sensing, hardware twin platforms will support intelligent, self-adaptive communication systems capable of meeting the increasing complexity of future network demands.

**Conclusions** This review synthesizes recent progress in channel hardware twin technologies and addresses critical challenges posed by future communication scenarios characterized by ultra-wide bandwidths, high channel dynamics, and large-scale networking. Key issues include high-frequency wideband signal processing, emulation of non-stationary dynamic environments, and scalability to large multi-branch network architectures. A classification framework is proposed, categorizing existing hardware twin approaches into three paradigms—measured data-driven, deterministic model-driven, and statistical model-driven—based on data sources, modeling strategies, and implementation architectures. A comparative analysis of these paradigms evaluates their relative strengths and limitations in terms of authenticity, flexibility, scalability, and emulation duration, providing guidance for selecting appropriate emulation strategies in complex environments. Furthermore, this study explores the integration of emerging technologies such as generative networks, environmental sensing, and transfer learning to support data-efficient generation, dynamic scenario adaptation, and cross-scene generalization. These advancements are expected to enhance the efficiency and adaptability of channel hardware twins, enabling them to meet the stringent requirements of future communication systems in performance validation, network design, and device testing. This work offers a foundation for advancing innovation in channel hardware twin technologies and accelerating the development of next-generation wireless networks.

**Key words**: Wireless channel; Digital twin; Channel hardware twin; Channel characteristics; Communication performance testing