Creating Digital Twins of RF Systems

Span the “accuracy gap” with MBSE and PathWave System Design

Model-based systems engineering (MBSE) is a systems engineering methodology that focuses on creating and exploiting domain models as the primary means of information exchange. Most model-based approaches address four system engineering domains: requirements, architecture (or structure), behavior, and verification/validation. MBSE tools tie these domains together virtually using a digital modeling language, leaving document-centric approaches behind.

The “digital twin” concept hopes to convert most if not all physical system engineering activities into virtual ones. Digital twins have high value where staging physical testing is hard, and real-world effects are difficult to reproduce – like in 5G, radar, satellite, and other RF system scenarios. A digital twin extends MBSE, which has engineering benefits even if math-based models only approximate behavior of physical prototypes. To reduce costs and risks, a digital twin must bring engineers into a virtual space that accurately reflects a physical system’s behavior over its life cycle.

But often, earlier virtual simulations can’t match later physical measurements. Development time and cost gains may be offset by redesign and retest losses. This accuracy gap invalidates a digital twin, sending engineering back to the physical world.

Real-world effects expose an accuracy gap in most math-based RF system simulation. What if MBSE could span that gap, with accuracy needed for digital twins of complex RF systems? PathWave System Design, developed by Keysight RF measurement science experts, turns MBSE inside-out and puts RF system digital twins in reach. PathWave System Design:

- Gives RF system architects choice in their workflow – without imposing SysML
- Offers robust real-world RF model libraries with proven Keysight and third-party IP
- Provides ‘best-in-class’ multi-domain simulation speed with near-circuit level fidelity
- Captures world-class Keysight measurement science and feeds back observations
- Integrates with other modeling, scenario planning, and MBSE tools and workflows
MBSE results hinge on the models inside

A big challenge for complex systems is requirements traceability – making sure requirements are documented, understood, and addressed appropriately. To deal with that, the document-centric engineering approach was born, with teams spending major efforts in deciphering requirements, determining ownership, and ensuring responses. System architecture created a structure passed to detailed design teams, then designs passed to verification and validation teams.

Typically, the tools used by each of these disciplines have been very different. The hope is that each discipline does a thorough job, and requirements flow through the system design all the way to verification and validation. As systems grow in complexity, and diverse subsystems have less and less visibility to other subsystems, the idea behind human-based traceability becomes tenuous.

Enter MBSE. The thought is pulling all the domains together into one system model solves several problems. Requirements are visible system wide. Architectural structure ties to specific requirements. A behavioral model implements each structure element. Verification and validation activities exercise models within operational parameters, comparing results to requirements.¹

MBSE isn’t a single process – it’s flexible, and can adapt for many complex systems. MBSE tools set up a design environment where teams define their workflow and enter models. Often a system modeling language like SysML is used for capturing each of the four domains in abstract terms for concise viewing.

Abstraction is good, up to a point. Successful MBSE means someone with extensive domain knowledge must create high-fidelity behavioral models, with appropriate parameters. If they’re working in a generic modeling language, there may be a lot of work ahead translating years of domain knowledge into syntax. For RF designs, it may not even be possible to capture necessary details using basic modeling tools.

![Diagram of MBSE process](image)

**Figure 1.** An “accuracy gap” shows up when behavioral models lack fidelity

If driving MBSE forward from requirements through architecture runs up against big modeling challenges, can MBSE be turned inside-out, starting with proven behavioral models? That’s what the PathWave Systems Design team considered in the context of architecture, design, simulation, and verification.

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Turning MBSE inside-out for complex RF systems design

Using MBSE for RF system architecture has big implications. When it comes to any complex system, it’s difficult and prohibitively expensive, if not impossible, to physically recreate everything a system might see in the real world. Engineering in virtual space makes sense given other factors in RF system design:

- Requirements often arrive in the form of comprehensive industry specifications
- Scenarios are crucial, defining kinematic and interference effects on a system
- Behavioral models are complex, but definable using RF physics detail
- Parameters go hand-in-hand with observability and measurement science

MBSE holds the key to earlier and more accurate system capability prediction – but only if the models it uses have enough fidelity to support confidence in simulation results. In modeling a complex RF system, reducing complexity through abstraction works against accuracy. The goal should be packaging complexity in models that are easier to use in architectural frameworks, without sacrificing fidelity.  

PathWave System Design effectively turns MBSE inside-out. It starts with high-fidelity RF models, surrounding them with an easy-to-use system architecture simulation workflow. Robust models and powerful simulation capability empowers system architects who may not be experts in RF characteristics, but who can understand how RF processing blocks fit together. PathWave System Design enables these key engineering efforts for achieving high-performance system designs:

- Creating virtual prototypes of systems quickly, and optimizing subsystems and algorithms
- Testing and evaluating complex mission scenarios digitally, including rapid dynamic changes
- Integrating effects of increasingly congested electromagnetic spectrum through high-level environment scenarios

Figure 2. Digital modeling provides earlier confidence in system performance (Kolonay, AFRL)

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Digital twins should start good, get better

What makes up a “digital twin”? The conversation starts at concepts aligned with MBSE. “Shift-left” is a broadly accepted practice, using simulations or virtual prototypes to uncover faults earlier in a design cycle, reducing costs of remedies. “Single source of truth” is another popular idea, one place where everyone working on a system sees everything needed for both virtual and physical system design.

These premises are both necessary, but not sufficient in defining a digital twin. Limiting its definition to a digital simulation or a virtual prototype of a system undervalues its potential. A more interesting definition stretches in a new direction – a virtual space modeling both a system and its surrounding environment. Adding one more dimension makes a digital twin a breakthrough concept:

“A digital twin is a virtual instance of a physical system continually updated with the latter’s performance, maintenance, and health status data throughout the physical system’s life cycle.”

Time weighs heavily on electromechanical systems, with degradation, repairs, and upgrades. Electronic systems can typically decouple functional performance from reliability. For either type of system, performance assessment in a variety of operational situations is a prime use case for a digital twin. The above definition continues with a point making the distinction vibrantly clear:

“While virtual models tend to be generic representations of a system, part, or family of parts, the digital twin represents an instance.”

Generic may seem harshly overstated. System engineers often use spreadsheets for fast estimates, or lightweight math-based modeling to speed up simulations. Quick answers show if a system architecture is heading the right way. Yet, surprises may lurk as designers fill in details and see actual results.

Simplified math may only approximate behavior under normal conditions, missing real-world effects and interactions. Also, there may be no feedback path from physical measurements around a system, or the data obtained is mismatched to modeling parameters, leaving simulation updates to trial and error.

Dynamic environments can have dramatic effects on complex RF system performance. An instance – virtual “truth” about the current state of the physical system – should start out good and get better, closing any accuracy gap. Moving engineering efforts to virtual space calls for a digital twin sitting on three pillars:

• A virtual prototype built around high-fidelity models in a functional framework,
• Simulations providing stimuli and observability matching real-world operational conditions,
• Updates to models and simulations based on feedback from measurements on a physical twin.

PathWave System Design goes beyond math-based modeling and “shift-left” thinking. Its robust component models incorporate real-world effects and leverage Keysight measurement science, aligning parameters so physical twin measurements feed back to virtual models precisely. Libraries provide pre-built and verified reference designs for complex RF specifications along with simulation stimuli. High-level integration adds scenario and mission planning information for real-world environmental conditions.

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Multi-domain modeling and simulation unlocks near-circuit-level accuracy

Replacing real-world activities with a digital twin requires accuracy from the start. PathWave System Design brings RF-aware multi-domain modeling and simulation to the first two pillars of a digital twin.

Off-the-shelf and extensible behavioral models

Over 300 simulation blocks come standard, all with high fidelity RF characterization built in:

- Effects such as non-linearity, spurs, phase noise, impedance, and more
- Advanced modeling such as X-parameters and fast circuit envelope techniques
- Stimuli including pre-built, verified waveforms and vector modulation analysis

Open interfaces allow building models from datasheets using Sys-parameters, S- and X-parameters, and libraries are available from vendors like Analog Devices, Mini-Circuits, Qorvo, X-Microwave, and more.

Simulation with RF effects captured

**Time-domain simulation** in PathWave System Design captures modulation and time-varying behavior:

- Dataflow simulation addresses complex RF system scenarios such as adaptive modulation, system agility, and dynamic resource allocation.
- Multiple envelope dataflow handles higher-order harmonics and distortion for wideband designs.

**Frequency-domain simulation** brings more RF critical measurements and accurate modeling:

- Spectrasys, a block-level RF simulator with unique technology for analyzing how harmonics and intermodulation propagate through systems.
- WhatIF frequency planning helps pinpoint optimum intermediate frequencies.
- EM Link captures layout and enclosure coupling effects starting early in the system design process, sharing data with layout tools, and highlighting parasitic issues automatically. Teams can explore system and physical design simultaneously with higher RF fidelity.

**Cross-domain simulation** extends PathWave System Design capability with unique analyses:

- RF Link allows time-domain simulations to use frequency-domain blocks with RF impairments directly from Spectrasys.
- With RF Link, simulations can capture stages of up- or down-conversion, spectral inversion, thermal and phase noise, frequency/power dependence, and more.

![Figure 3. Modulation performance analysis in PathWave System Design](Image)
**Measurement science connects real-world specifications**

The third pillar of a digital twin – updating its performance modeling with measurements from a physical twin – completes the transformation of a virtual prototype into an instance of a physical system. Two aspects of Keysight measurement science factor into unrivaled capability for RF system digital twins.

Architecting a functional structure for a system like 5G NR, radar and EW, wireless connectivity, digital modems, and other advanced RF systems usually turns out to straightforward, especially considering PathWave System Design has optional reference libraries for these applications. Design teams can pull in specification-compliant blocks and add their own MATLAB®, C++, or HDL code to complete their system.

What’s not straightforward is the first aspect - the stimuli required to fully exercise those blocks. Without verified complex waveforms for RF system specifications, assessing performance and test coverage turns into a lengthy and sometimes risky guessing game.

The second aspect is the analysis. Vector modulation analysis is complex, requiring state-of-the-art instrumentation for accurate results and powerful visualization in determining problems.

That’s where Keysight measurement science makes its impact. The same knowledge that Keysight uses to design its instrumentation connects with PathWave System Design. Teams can use the same stimulus in both simulation and physical lab testing. Results from physical twin measurements can be brought back into modeling for enhancements and further analysis.

For example, a Keysight PNA Vector Network Analyzer offers an efficient way to create and enhance component behavioral models. Its measurement capability includes two-tone X-parameter measurements, noise figure, gain compression, intermodulation, and harmonic distortion.

The Keysight PathWave Vector Signal Analyzer (VSA) handles modulation including FM linear chirp frequency hopping, pulsed RF, and FMCW. It also provides demodulation and error vector measurements of 5G NR signals, as well as capabilities in carrier aggregation, higher-order MIMO, and constellation signal quality analysis.

These and other advanced measurement capabilities connect directly with PathWave System Design, eliminating guesswork and estimation and increasing model fidelity. As specifications evolve, Keysight measurement science continues growing.
Bringing real-world environments into the digital twin

Complex RF systems fit into intricate real-world environments. Platforms move and reorient, changing RF propagation and interference. A system that functions well in a fixed location may display problems when kinematics are introduced. One location may be trouble-free, while another presents nearby RF emitters causing issues. In three-dimensional space, problems may come and go as paths cross temporarily.

On many projects, there are teams of less-RF-centric system engineers and planners working on modeling these environmental scenarios. Instead of forcing these teams into an all-new workflow or creating a discontinuity between their work and that of RF design teams, PathWave System Design extends RF system engineering capability with integration of popular tools for mission and scenario planning, requirements management, and high-level system modeling.

Teams can drill down into part of a design, reducing world-level complexity while simulating with higher RF fidelity using PathWave System Design, then share results improving accuracy system-wide. Direct integrations with PathWave System Design include:

- Digital mission engineers working in STK from AGI, an Ansys company, can directly connect accurate models of platform motion and antenna orientation with multi-domain RF simulations.
- Electromagnetic (EM) propagation and channel models created in Wireless InSite® can also directly connect with multi-domain RF simulations.

PathWave System Design has been developed from its beginning as an open framework for integration. A flexible application programming interface (API) allows other MBSE tools to tie information into PathWave System Design workflows.

- Requirements tools including Engineering Requirements Management DOORS® and others.
- System modeling tools such as Engineering Systems Design Rhapsody®, Cameo Systems Modeler™, and ModelCenter®.

With these integrations, scenarios difficult to stage in the physical world can be evaluated quickly in the virtual world, using the digital twin as a proving ground knowing its behavior mirrors the physical twin.

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Put digital twins in reach using built-in RF modeling excellence

PathWave System Design goes beyond math-based modeling with a complete RF-aware design workflow, plus decades of Keysight measurement science in RF instrumentation, ready for any system architect. Component libraries are available from Analog Devices, Mini-Circuits, Qorvo, X-Microwave, and others, and open interfaces allow building new models from datasheets. It's the most advanced solution for creating accurate, useful digital twins of complex RF systems.

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