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Preface

With the rapid development of radio frequency (RF) and microwave technologies, there is an increasing need for co-simulations of microwave circuits and high-frequency electromagnetic fields (HFEMFs). This is particularly prevalent in the fields of modern wireless communications and radar systems, where the complexity of microwave devices and antenna structures is continuously rising. Consequently, researchers and designers must not only contemplate the designs of circuit level, but also take into account the impact of electromagnetic fields, and the co-simulations of microwave circuits and HFEMFs have become an inevitable choice. This book aims to offer readers a comprehensive guide to the co-simulations of RF and microwave circuits incorporated with the HFEMFs. Over the past few decades, we have observed the evolution of numerous kinds of powerful simulation software for microwave circuits and HFEMFs. Among these, Advanced Design System (ADS) and High-Frequency Structure Simulator (HFSS) are undoubtedly the two software tools which have been most prevalently used and widely acknowledged. However, these two tools emphasize different functions and application fields, rendering them incapable of fully meeting the needs of some application scenarios. Therefore, it is imperative to develop the co-simulations method based on the ADS and HFSS for microwave circuits and HFEMFs. This book endeavors to present a comprehensive introduction to the concepts, principles, methods, implementations, and applications of co-simulations based on those software tools. It will offer detailed explanations and abundant examples to help readers better understand the related knowledge and provide useful references for practical engineering applications. Also, this book presents some interesting discussions on the further development and applications of co-simulations and relevant software tools in electronic designs, including their features, practical operations, and optimization skills. The book consists of eight chapters and each chapter focuses on an individual topic.

Chapter 1 mainly introduces the background related to the co-simulations of microwave circuits and HFEMFs. We start with presenting an overview of the well-known simulation software tools, ADS and HFSS, facilitating a preliminary understanding on them for readers. This is followed by a detailed discussion on the ADS, highlighting its development history and its significant position in the field of microwave circuit designs. We then explore the main features of ADS, including its robust design functions and extensive library resources. We also present typical application cases to better demonstrate the advantages of ADS in practical engineering applications. Subsequently, we introduce the HFSS by detailing its development route from an inception to becoming an industry leader of electromagnetic simulation software tools. We provide a guidance on using the HFSS to model and simulate complex three-dimensional structures and discuss its key technologies. Also, we showcase typical applications in the area of HFEMFs to illustrate the robust performance of HFSS in practical scenarios. The latter half of this chapter focuses on the software tools for the co-simulations with the ADS and HFSS, and provide researchers and engineers with more efficient ways of addressing practical issues. The advantages of co-simulations for microwave circuits and HFEMFs, such as improved simulation accuracies and reduced design cycles, are discussed. Finally, we offer a prospect for the co-simulations of microwave circuits and HFEMFs and provide useful insights for readers concerning with technological advancements and application expansions.

Chapter 2 addresses the simulation technologies for HFEMFs. We first discuss the definitions, applications, and developments of HFEMF simulations and then delve into their underlying principles, including Maxwell's equations and numerical methods of solving them. We then analyze the potential errors that could occur during the simulations and provide corresponding solutions. Also, we illustrate the applications of ADS and HFSS for HFEMF simulations, including their respective tools, modeling techniques, and simulation steps and guides. Finally, we focus on the definitions, principles, and implementation methods of co-simulations in detail and introduce different kinds of software for the co-simulations with the ADS and HFSS. In order to give readers a better understanding, the specific implementation process of HFSS and co-simulations designs through examples is provided. This will also allow readers to recognize the value and necessity of HFEMF simulations in practical applications. In addition, an overview on the future of HFEMF simulation technologies is given, including the model refinement, computational efficiency, artificial intelligence, interdisciplinary cooperation, and standardization.

In Chap. 3, we discuss the basic principles and applications of simulation technologies for microwave circuits. Starting with an introduction to the fundamental concepts of microwave circuits, we first emphasize the significance and centrality of simulations for optimally designing microwave circuits. We then narrate the involved principles of simulations for microwave circuits, including electromagnetic equations, transmission line theory, equivalent circuit models, finite element method, finite difference time-domain method, and error analysis and compensation methods. We also explore the applications of ADS and HFSS for the low-frequency simulations of microwave circuits and provide detailed insights into their functions and settings. Finally, the co-simulations are discussed and practical examples are provided to demonstrate how to use the Layout and rFactor Pro (rFpro) to accurately simulate microwave integrated circuits.

Chapter 4 concentrates on the basic concepts, principles, and applications of simulation technologies for antenna designs. The importance and role of simulations for antenna designs are first described and the basic simulation workflow is then provided. Also, the involved working principles of antennas in simulations are addressed, including the basic theory, radiation characteristics, electromagnetic fields, optimization algorithms, and error analysis and calibration. In addition, the applications of ADS and HFSS to the simulations of antenna designs are discussed separately and the software tools for the co-simulations of antenna designs with the ADS and HFSS are introduced, including the Computer Simulation Technology (CST) Studio Suite, WIPL-D (WI stands for wires, PL stands for plates, and D stands for dielectrics), X Finite Difference Time Domain (XFdtd), Antenna Magus, and EM Consulting & Software (EMCoS) Antenna VirtualLab. This chapter comes to an end by discussing the prospect of simulation technologies for antenna designs and explaining how to use the HFSS and Ansys Circuit for co-simulating antenna designs.

Chapter 5 highlights the simulation technologies for the analyses and designs of electromagnetic compatibility (EMC), ranging from fundamental principles to practical applications. The definitions and classifications for the EMC are first given so that readers can preliminarily recognize the EMC in simulations. The simulation functions of ADS and HFSS for EMC analyses and designs are then introduced in detail. We also narrate a variety of simulation software that can be incorporated with the ADS and HFSS for the co-simulations of EMC analyses and designs, including CST Studio, Applied Wave Research (AWR) Microwave office, Simbeor, Ansys SIwave, Altium Designer, and HyperLynx. The optimization methods and techniques are very essential for EMC analyses and designs, so we discuss various optimization strategies and involved challenges as well. To help readers better understand, we demonstrate the EMC co-simulations based on the CST Studio Suite and ADS through practical examples. This chapter is finished by discussing the future of simulation technologies on EMC analyses and designs.

In Chap. 6, we focus on the thermal simulations and their influences on electromagnetic simulations. We first introduce the definitions, classifications, principles, implementations, and applications of thermal simulations so as to familiarize readers with this topic. We then delve into the principles of thermal simulations, which include the heat conduction equation, boundary and initial conditions, heat source modeling, meshing, and solution algorithms. With the knowledge, we address the co-simulations or the interaction between thermal simulations and electromagnetic simulations and their mutual impacts. Also, different kinds of software that can co-simulate with the ADS and HFSS are described, respectively, including the FloTHERM and Icepak. Finally, we present a co-simulations example for illustrating the simulation of electromagnetic loss of a circulator in the HFSS and the electrothermal simulation with a two-way coupling in the Icepak. The illustration can help readers strength their understanding on the thermal-electromagnetic simulations and their influences on analyses and designs.

Chapter 7 presents structural simulations and their incorporations with electromagnetic simulations. A comprehensive overview is provided about the backgrounds, principles, implementations, applications, challenges, and development trends of structural simulations, which can help readers form a holistic understanding on them. The principles of structural simulations are further explained in detail, including stress and strain analyses, material models and mechanical properties, boundary conditions and loads, meshing and solving algorithms, as well as analyses and verifications of results. We also elaborate the requirement, method, framework, process, data transfer, and interface of implementation for structural co-simulations. Furthermore, different kinds of software which can be used to co-simulate with the ADS and HFSS are introduced, including SIMULIA Abaqus and MacNeal-Schwendler Corporation (MSC) Software for the ADS, and Ansys Mechanical, COMSOL Multiphysics, and Ansys Multiphysics for the HFSS. Finally, through the examples of static simulations with the Hypermesh and Ansys Mechanical, we explain the pre-processing, solution, and post-processing stages of the simulations which can help readers understand the incorporation of structural simulations with electromagnetic simulations.

Chapter 8 narrates the automation interfaces and scripting program methods for simulations. It begins with an introduction to the Advanced Extension Language (AEL) interface in the ADS, including the basic concepts, writing, loading, and running of AEL scripts. We then present the Python Data Link (PDL) in the ADS, including its basic concepts and architecture. Also, we illustrate the data transfer method, processing method of ADS simulation results in the MATLAB, and optimization method for the ADS-MATLAB interfaces. For the HFSS, we first discuss the application of VBScript in the HFSS, including the call of VBS, frequency sweep control using the VBS, revision of model parameters, and post-processing operations. We then look into the IronPython scripting method in the HFSS, including the introduction to the IronPython, basic method of writing HFSS automation scripts, and advanced automation design method. Finally, we address the Application Programming Interface (API) based on the MATLAB and HFSS, including the overview of API, framework, and MATLAB-control file writing method. All introductions are accompanied with practical examples to help understand. Readers can well grasp the knowledge and skills of the automation interfaces and script program methods based on those kinds of software by reading this chapter.

Shanghai, China
April 2023

Mei Song Tong

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Contents

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Transactions on Components, Packaging and Manufacturing Technology, *International Journal of Numerical Modeling: Electronic Networks, Devices and Fields*, *Progress in Electromagnetics Research*, and *Journal of Electromagnetic Waves and Applications*. He also frequently served as a session organizer/chair, technical program committee member/chair, and general chair for some prestigious international conferences. He was the recipient of a Visiting Professorship Award from Kyoto University, Japan, in 2012 and from University of Hong Kong, China, in 2013. He advised and co-authored 12 papers that received the Best Student Paper Award from different international conferences. He was the recipient of the Travel Fellowship Award of USNC/URSI for the 31th General Assembly and Scientific Symposium (GASS) in 2014, Award for the Advance of Science and Technology of Shanghai Municipal Government in 2015, Fellowship Award of JSPS in 2016, Innovation Award of Universities' Achievements of Ministry of Education of China in 2017, Innovation Achievement Award of Industry-Academia-Research Collaboration of China in 2019, "Jinqiao" Award of Technology Market Association of China in 2020, Carl Friedrich von Siemens Research Award of the Alexander von Humboldt Foundation of Germany in 2023, and Technical Achievement Award of Applied Computational Electromagnetics Society (USA) in 2024. In 2018, he was selected as the Distinguished Lecturer (DL) of IEEE Antennas and Propagation Society for 2019–2022.

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Chapter 1
Introduction to Co-simulations of Microwave Circuits and High-Frequency Electromagnetic Fields

1.1 Introduction

With the rapid development in the areas of wireless communications [1–3], radar [4–6], navigation [7–9], and medical imaging [10–12], etc., there is a growing recognition on the significance of simulations for microwave circuits and high-frequency electromagnetic fields (HFEMFs). The simulations of HFEMFs involve the numerical modeling/simulation and analysis of physical wave behaviors such as propagation, scattering, and radiation of high-frequency electromagnetic waves [13]. On the other hand, the simulations of microwave circuits refer to the numerical modeling/simulation and analysis/optimization for the design of microwave circuits [14]. These simulations need to individually meet the requirements on accuracy and efficiency, and more importantly, their co-simulations are also required for many applications in order to realize diverse functions.

The co-simulation is a method that integrates multiple simulation, combining simulation models and tools from different domains to evaluate the behavior and performance of complex systems [15]. Its significance lies not only in improving the accuracy and credibility of simulations but also in fostering cross-fertilization and collaborative innovation across different fields [15, 16]. Co-simulation enables quick assessment of system feasibility and risks, optimization of system design and performance, and enhancement of decision-making based on scientific evidences. Additionally, co-simulation provides a support for system implementation and operation, reducing the risk of failures and errors, and improving system reliability and safety. Hence, co-simulation finds wide-ranging applications and promising prospects in military, aerospace, transportation, and healthcare fields [15–20].

To facilitate the co-simulations for microwave circuits and HFEMFs, the two well-known software tools have been widely used, i.e., Advanced Design System (ADS) [21, 22] and High-Frequency Structure Simulator (HFSS) [23] as shown in Fig. 1.1, and they are the main focus of this book. The ADS is a kind of circuit simulation software based on Electronic Design Automation (EDA) that can enable

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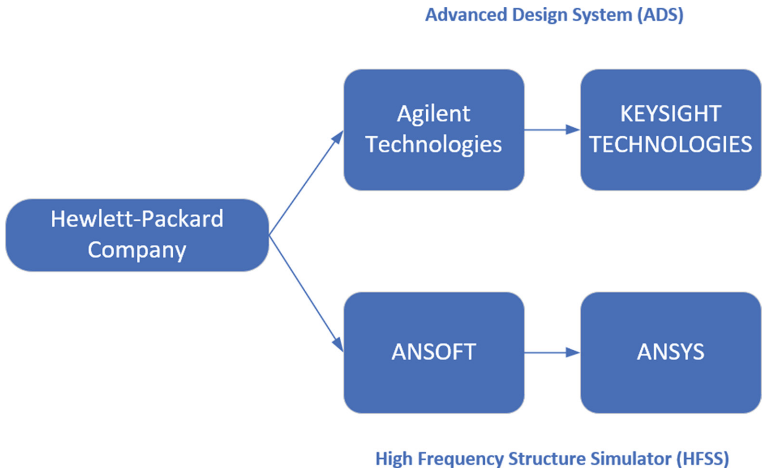

Fig. 1.1 Distinct developmental branches of ADS and HFSS: Tracing the evolution from Hewlett-Packard Company to Agilent Technologies and KEYSIGHT Technologies, and from ANSOFT to ANSYS

the simulations for microwave and RF circuits, among other functions [24]. It offers powerful simulation and analysis capabilities, user-friendly interfaces, and broad application areas. On the other hand, the HFSS is a simulation tool for HFEMFs and has been widely utilized for the modeling/simulations of antennas, electronic packaging, electromagnetic compatibility, radar imaging, etc. [25]. It can provide high-precision simulations of electromagnetic waves, advanced post-processing and analyses, and support co-simulations with other softwares [26, 27].

For co-simulations, both the ADS and HFSS possess unique advantages and application scopes. The ADS excels in microwave circuit simulations, offering diverse simulation functions that enable fast and accurate simulations and optimization for microwave circuits [24, 28]. The HFSS, on the other hand, stands out in electromagnetic field simulations, providing high-precision and high-efficiency simulation capabilities to deliver comprehensive and accurate analyses for complex electromagnetic problems [26, 27, 29, 30].

In addition to the co-simulation capabilities provided by the ADS and HFSS themselves, there are several other kinds of software available that can be integrated with them to expand the range of simulation applications. For instance, the softwares Genesys [31] and CST Studio Suite [32] can be used for the co-simulations of microwave circuits [33]. Similarly, the softwares COMSOL Multiphysics [34] and Designer [35] can be employed for the co-simulations of electromagnetic fields [36, 37]. These software tools can be utilized not only in conjunction with the ADS and HFSS but also with other softwares to cater to the simulation needs of diverse fields.

During the actual co-simulation processes, it is essential to understand and address the data formats and interfaces between different kinds of software. For example, in the co-simulations between the ADS and HFSS, the circuit designs and simulations are conducted using EMPro or Layout software within the ADS. Subsequently, the design results are imported into the HFSS for electromagnetic simulations and analyses. In this process, the data interface between the two kinds of software needs to be properly configured and debugged to ensure accurate data transmission and reliable simulation results. Besides, the interface debugging, optimization, and adjustment of the simulation models and parameters must satisfy the requirements of co-simulations. For instance, in the antenna design and analysis, the parameters such as antenna geometry, material properties, and radiation direction must be finely tuned and optimized to enhance the accuracy and reliability of the simulation results. Finally, the co-simulation results need to be thoroughly analyzed and evaluated to validate the reliability and accuracy of the simulation models and parameters. This involves the comparison and analysis of the simulation results to identify and rectify sources of errors, as well as to determine areas for improvement. Furthermore, the visualization and report of the simulation results are crucial for effectively presenting the findings and conclusions of the analyses.

The co-simulation is an essential part for microwave circuits and HFEMFs, as it can enhance the reliability and accuracy of the circuits with fields. This book aims to introduce the fundamental principles and applications of ADS and HFSS, along with various kinds of software that can facilitate co-simulations. It will also explore the advantages and application scenarios of co-simulations so that readers can gain a better understanding for the applications associated with this approach.

1.2 Overview of Advanced Design System (ADS)

Since the 1970s, the EDA has been extensively utilized in the field of microwave circuit designs [39]. The EDA-based simulation tools have played a crucial role in achieving accurate and efficient designs of microwave circuits [40–42]. Among various EDA software options, the ADS stands out as a highly popular and widely used choice for the simulation and optimization of microwave circuits. Developed by Keysight [43], Inc., the ADS has undergone numerous updates and iterations since its initial release, and continuously enhanced its simulation functions and performances. Over time, it has evolved into a comprehensive and versatile EDA software platform with applications across multiple disciplines. This section provides a comprehensive overview for the ADS, including its historical development, key functions, and notable features.

1.2.1 Development History of ADS

Advanced Design System (ADS) is a kind of premier software developed by PathWave Design, a division of Keysight Technologies, that specializes in electronic circuit design, simulation, and automation. It offers a comprehensive environment for designing RF electronic systems, including wireless networks, mobile phones, satellite communications, high-speed data links, and radar systems. The software

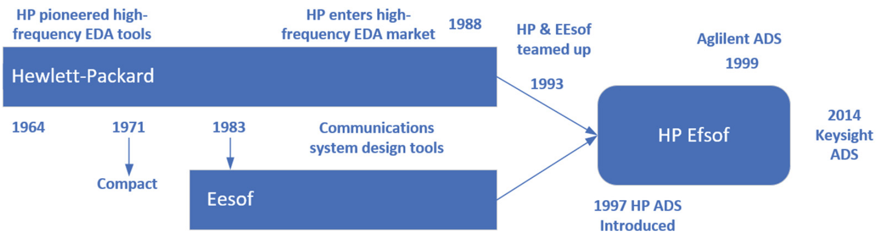

Fig. 1.2 Chronological evolution of Keysight ADS: It begins with Hewlett-Packard in 1964, marking the company's pioneering of high-frequency EDA tools, and follows through various milestones such as the entry into the high-frequency EDA market in 1988, the partnership with EEsof in 1993, and the introduction of HP ADS in 1997. The timeline continues with the evolution to Agilent ADS in 1999 and culminates with Keysight ADS in 2014

initially emerged in 1985 as Microwave Design System (MDS) and was later enhanced and rebranded as ADS in 2016, introducing improvements in speed, performance, and design flexibility [22]. ADS supports designers throughout the entire design process, from schematic capture, design rule checking, and layout, to electromagnetic field (EMF) simulation, and time- and frequency-domain circuit simulation. This enables designers to effortlessly characterize and optimize RF designs without the need to switch between different tools or systems.

In Fig. 1.2, it can be observed that the origins of Advanced Design Software (ADS) can be traced back to the 1970s. During that time, microwave circuit design and simulation heavily relied on manual calculations, experimentation, and hand-drawn diagrams by electronic engineers. However, these methods were time-consuming, labor-intensive, and prone to errors and inaccuracies. Consequently, the exploration of computer-aided design and simulation for microwave circuits began to improve efficiency and accuracy.

Starting in the mid-1970s, several commercial computer programs for microwave circuit design became available. Examples of such software packages include SUPER COMPACT (developed by Compact Software, Inc. in 2000) and TOUCHSTONE (from EEsof, Inc. in 1997). However, due to the limited computational power and storage capacity of computers during that era, these programs could only handle relatively simple circuits and fell short in meeting the simulation demands of complex circuits. As computer technology continued to advance, more microwave circuit simulation software was developed, gradually becoming an indispensable tool for microwave circuit design.

During the early stages of microwave circuit simulation software, numerical methods like the finite element method and finite difference method were primarily utilized for electromagnetic field simulation. Prominent examples of these software packages include HFSS by Ansoft and Sonnet. While these programs offered high-precision simulation capabilities, their efficiency was relatively low and could not satisfy real-time simulation requirements. As computer hardware performance continuously improved, microwave circuit simulation software began to evolve toward high efficiency and multifunctionality. For instance, in the 1990s, the U.S. company Eagleware introduced a type of microwave circuit simulation software called Eagleware Genesys, which boasted high efficiency, precision, and user-friendliness, ultimately becoming a leading product in the market at that time. Furthermore, software offerings such as Mentor Graphics' HyperLynx and Agilent Technologies' ADS gradually gained prominence.

As we enter the twenty-first century, the field of microwave circuit simulation software is witnessing significant advancements in terms of scale, multi-domain capabilities, and intelligent functionalities [37]. One notable example is the evolution of ADS, which has transformed into a versatile EDA software platform catering to various domains such as microwave circuit simulation, RF circuits, digital signal processing, communication systems, and more. ADS now supports co-simulations with other software, enabling users to customize simulation and optimization processes through automated scripts and APIs. Over the years, ADS has undergone numerous updates and iterations to continuously enhance its simulation accuracy and efficiency, gradually evolving into a comprehensive EDA software platform for multiple disciplines. On July 6, 2022, Keysight introduced Keysight PathWave ADS 2023, the latest annual update of ADS, further empowering circuit designers with advanced electromagnetic (EM) simulation capabilities. PathWave ADS 2023 reaffirms its position as the industry's most comprehensive simulation software, offering a wide range of functionalities for RF and microwave, high-speed digital, and power electronics design. The 2023 version introduces new and improved features aimed at enhancing the productivity and usability of RF and microwave circuit and system designers [38].

Circuit Simulations

- Simplified remote and distributed simulation management with support for cloud-based high-performance computing (HPC).
- New Leti-UTSOI 102.6 transistor model for accurate analog and RF circuit design.
- Monte Carlo statistical controller now includes yield optimization.

Electro-thermal Simulations

- Customized multi-technology electro-thermal (ETH) processes are supported even if the layout and schematic levels do not match.
- PathWave ADS provides the industry's most accurate electro-thermal simulation, predicting the location and timing of harmful transient temperature spikes so that they can be fixed before hardware production.
- PathWave ADS' electro-thermal dynamic model generator enables transient electro-thermal simulations to be performed typically 10 times faster and up to 100 times faster to ensure thermal reliability of mission-critical and reputation-critical designs.

High-Performance Computing (HPC)

- EM and Circuit simulation acceleration through parallelized High-Performance Computing (HPC) with cost-effective, powerful, and high-capacity cloud-based hardware resources enable typical speedup from 5x to 20x.
- Parallel EM simulation (RFPro) parameter sweep.
- Even with a modest fivefold increase in speed, this translates to a saving of four days in a typical five-day workweek, allowing for a greater number of simulations in designing high-performance, tolerance-insensitive RF/MW components and substantially reducing the time-to-market.

High-Speed Digital (HSD) Design

Memory Designer

- Supports HBM3, LPDDR5x, IBIS-EMD models.
- IBIS 7.1 parser with custom IBIS file viewer.
- Multi-segment smart bus wire connection.
- Drag-n-drop multi-plots from Expression Manager.
- Improved CA/Data Bus Pre-layout builder editing.
- Cloud based High-Performance Computing (HPC).

SerDes Design

- New Ethernet AMI modeler
- USB AMI model for NZR modulation and Spread Spectrum Clocking (SSC).
- USB reference channel models.
- PCIe AMI model generation for Gen 6 with PAM4 modulation, DFE taps, and 6-lance reference channel with crosstalk.
- PAM6 modulation for Tx in Channel Simulator.
- SmartEye Probe for transient PAM4 simulation.
- Channel Operating Margin (COM) versions 3.4 and 3.7 added.
- Measured Data based model for TX Waveform AMI component in Rx package and external channel models.
- PowerSum crosstalk and ICR/ICN analysis in S-parameter Toolkit.

EM-SIPro/PIpro

- RapidScan support for trapezoidal conductor cross sections and improved coplanar ground detection.
- Python 3.10 update for SIPro, PIPro, RFPro, and PEPro.
- PIPro radiated emission in conducted EMI analysis.
- CEMI analysis on remote, cloud, and cluster compute nodes.
- Power Integrity conducted EMI Picotest SIC531 PCB example.
- Parameter sweeps, e.g., ambient temperature in PIPro-DC simulation.

EM Simulations

RFPro Platform

- OpenAccess component instance swept parameters.
- Opening complex designs, switching component roles and net re-extraction now faster and using less memory.
- Simulations mesh and ports now visible.
- Multi-port excitation in field visualization can be exported/imported via .csv or .json file.
- 3D component editing, measuring, and placement enhancements.
- Improved resource management for remote, cloud, and cluster simulations.
- Improved schematic interoperability between ADS and Virtuoso.

Momentum

- TSMC advanced IC process node features supported including width, thickness, resistivity, bias, multi-patterning colors, and damage K.
- Compliance with foundry recommendations for layout scaling and bias sequence.
- Ground loss correction no longer applied when substrate stack contains a semiconductor layer for better accuracy.

FEM

- Improved meshing for multi-technology designs.
- Improved accuracy for passive device modeling on silicon substrates.
- Gen 2 solver correctly handles temperature dependency of conductor with surface resistance.

HFSS Option

- HFSS simulation support in PathWave Design Cloud simulation service.

For more highlights of the ADS 2023 release update, please visit the official website of Keysight.

1.2.2 Main Functions of ADS

ADS (advanced design system) integrates the benefits of multiple simulation software, offering a diverse range of simulation methods. It encompasses various domains such as time and frequency, digital and analog, linear and nonlinear, high and low frequency, and noise analysis. Its capabilities span from analyzing small components to designing and simulating complex system-level configurations. ADS excels in simulating RF (radio frequency), analog, and digital signal processing (DSP) circuits simultaneously. Moreover, it enables the co-simulations of mixed circuits consisting of both digital and analog components (Fig. 1.3).

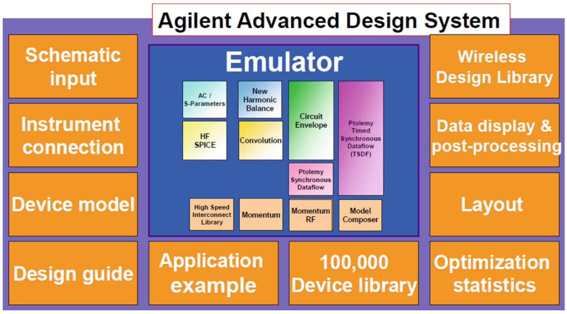

Fig. 1.3 Comprehensive overview of Agilent ADS: Core Components, Emulation Capabilities, and Design Resources

The primary functions of Advanced Design System (ADS) encompass circuit simulation, electromagnetic simulation, system simulation, and optimization design. The circuit simulation capability is fundamental and central to ADS, providing precise simulation and analysis for a wide range of microwave circuits. ADS supports the modeling and simulation of various components like transmission lines, filters, power dividers, mixers, amplifiers, catering to a wide array of circuit simulation needs. The main aspects of the circuit simulation functions in ADS are

- Circuit parameter extraction: ADS can autonomously extract various parameters, such as S-parameters, Y-parameters, and Z-parameters from the circuit's layout diagram and component model for further simulation and analysis.
- Circuit analysis: ADS performs different analyses like DC analysis, AC analysis, frequency-domain analysis, and time-domain analysis on circuits to evaluate their performance and stability.
- Circuit optimization: ADS optimizes various circuit parameters via automatic optimization algorithms, achieving optimal circuit design.
- Circuit layout design: ADS offers a variety of circuit layout design tools to rapidly construct and modify circuit layout diagrams according to varying design requirements.

Beyond circuit simulation, ADS also features robust electromagnetic simulation functions, enabling numerical simulation and analysis of complex electromagnetic field problems. These functions predominantly include

- Electromagnetic field analysis: ADS analyzes various electromagnetic field problems like propagation, radiation, and scattering.
- Electromagnetic field (EMF) optimization: ADS optimizes various EMF parameters through automatic optimization algorithms to achieve optimal EMF design.
- EMF radiation analysis: ADS performs EMF radiation analysis on structures like antennas, arrays to evaluate their radiation characteristics and performance.

- EMF scattering analysis: ADS conducts EMF scattering analysis on various scatterers to assess their scattering characteristics and performance.

Alongside circuit and electromagnetic simulation, ADS also boasts strong system simulation functions. This capability allows the integration of multiple microwave circuit and electromagnetic field simulation models into a system for system-level simulation and analysis. This, in turn, enables optimal design of circuits and systems to meet specific performance specifications. Here's a detailed account of ADS simulators and their functions frequently employed in RF and analog circuit design:

- DC Simulations: DC simulation is the foundation for all simulations, performing circuit topology checks as well as DC operating point scanning and analysis.
- AC Simulations: AC simulation derives small-signal transmission parameters like voltage gain, current gain, linear noise voltage, and current.
- S-parameter Simulations: S-parameter simulation treats the circuit as a four-port network, linearizes the circuit at the operating point, performs linear small-signal analysis, and analyzes various parameter values through its specific algorithm.
- Harmonic Balance Simulations: This simulation is ideal for dealing with the analysis of nonlinear circuits, focusing on the frequency-domain characteristics of the signal.
- Large-Signal S-parameter Simulations (Simulations-LSSP): This type of simulation performs large-signal S-parameter analysis and is instrumental when designing amplifiers.
- Gain Compression Simulations (XDB): Simulations-XDB is used to find user-defined gain compression points.
- Circuit Envelope Simulations: Circuit envelope emulator is a technology for communication systems that processes high-frequency modulated signals in the time and frequency domains.
- Transient Simulations: The Transient Simulator is a kind of traditional SPICE software, which is ideal for all analog and digital circuits but less efficient for high-frequency signals.

Each ADS emulator is designed to simulate a specific metric. Therefore, when simulating a complete circuit, it is crucial to employ multiple emulators to simulate all metrics. For microwave/RF circuit and system design, the most frequently used simulators are S-parameter Simulations, Circuit Envelope Simulations, and Harmonic Balance Simulations.

1.2.3 Characteristics of ADS

In the field of microwave circuit design, Advanced Design System (ADS) stands out as a kind of powerful simulation software. It offers a wide range of features and capabilities that enable engineers to effectively design, optimize, and analyze microwave circuits. This section provides a comprehensive overview of ADS, highlighting its key features and applications.

ADS boasts an extensive library of components and models specifically tailored for microwave circuit simulations. This comprehensive library includes various transmission lines, filters, power dividers, mixers, amplifiers, and more. With such diverse options, ADS can accommodate different simulation requirements. Additionally, ADS incorporates material libraries and device model libraries, such as Smith Chart, S-parameters, and Y-parameters. These libraries simplify the selection of appropriate components and models for specific simulations. Furthermore, ADS supports multiple scripting languages and custom APIs, empowering users to expand and customize the software's functionality. Scripting languages like Python, MATLAB, and Visual Basic enable programming and calculations during simulations, catering to diverse simulation needs. By allowing users to write custom functions and modules, ADS facilitates flexible and efficient simulation and analysis.

ADS offers a broad range of simulation functions, encompassing basic circuit simulation, electromagnetic simulation, system simulation, optimization design, and printed circuit board design, among others. The system simulation function enables the integration of multiple microwave circuit and electromagnetic field simulation models, facilitating system-level analysis. Moreover, ADS is scalable and compatible with other simulation and computer-aided-design (CAD) software, allowing co-simulations and data exchange. It seamlessly interfaces with CAD software such as Cadence Virtuoso, Mentor Graphics, and Altium Designer, enabling circuit and layout design and data transfer.

The graphical user interface (GUI) of ADS is user-friendly, featuring a simple and intuitive design that facilitates simulation and analysis tasks. The GUI adopts a modular approach, organizing different functional modules into categories for easy navigation. Users can swiftly locate and access the required modules and options. Furthermore, the GUI offers customizable toolbars and shortcut keys, empowering users to personalize their workflow according to their preferences.

Performance optimization is another notable aspect of ADS. It includes various techniques to enhance simulation efficiency and accuracy, based on specific requirements and computing resources. ADS supports multi-threaded computing and GPU acceleration, enabling faster and more accurate simulations. Performance monitoring and analysis tools allow users to assess and optimize the performance of simulation processes, ensuring optimal resource allocation and performance.

1.2.4 Application Scenarios of ADS

ADS is a kind of versatile software with a wide range of applications across various fields. It is particularly useful in RF and microwave communications, satellite communications, radar systems, satellite navigation, antenna design, and semiconductor device design and testing, among others. This comprehensive platform allows users to seamlessly integrate design, simulation, and testing processes within a single environment. It offers advanced features such as layout automation, optimization, high-frequency electromagnetic simulation, and system-level simulation. ADS provides diverse modeling and simulation methods, including linear and nonlinear circuit simulation, high-frequency electromagnetic simulation, system simulation, and digital signal processing simulation [44]. Users can create circuits using their own models or utilize the extensive built-in library of components and models. For instance, as the frequencies and speeds of printed circuit boards (PCBs) increase, ensuring signal and power integrity becomes increasingly critical. Transmission line losses can lead to device failures, necessitating accurate simulation of modeled alignments, vias, and interconnects. By employing custom IC designs and electromagnetic simulators, ADS helps improve high-speed link performance in PCB designs and facilitates power and signal integrity analysis. Moreover, ADS offers various automated tools such as PathWave EM Design (EMPro) and PathWave RFIC Design (GoldenGate). EMPro enables the analysis of 3D effects in components and accurately assesses electromagnetic phenomena. GoldenGate, on the other hand, is a kind of simulation software specifically designed for complex integrated circuits. During the early stages of RFIC design, it is crucial to monitor system IC specifications, such as error vector magnitude (EVM), through RF simulations. GoldenGate incorporates layout parasitic effects, complex modulated signals, and digital control circuits into its simulations. Additionally, PathWave RFIC Design allows simulations in both frequency and time domains and facilitates seamless design transfers between Cadence Virtuoso and Synopsys Custom Compiler. The design and optimization of microwave circuits within wireless communication systems directly impact system performance and reliability. ADS offers optimized design capabilities and system-level simulation functions to facilitate performance optimization of wireless communication systems. Radar systems are another major application domain for ADS. The design and optimization of microwave circuits significantly influence the performance and accuracy of radar systems. ADS supports various radar signal processing algorithms and circuit designs. In the field of space technology, microwave circuit design and simulation are crucial for spacecraft communication, navigation, and control. ADS encompasses a rich library of components and models, accommodating a broad range of space applications and standards such as GPS, satellite communications, and solar panels. Beyond these primary application areas, ADS finds utility in other domains as well. For example, the demand to enhance power device efficiency is driven by power supplies, solar inverters, and electric vehicles. ADS models modern materials and switch-mode power supplies to optimize power device designs for maximum efficiency. Moreover, ADS facilitates co-simulations with other CAD software and electromagnetic field (EMF) simulation software. This enables data exchange and collaboration between multiple software tools, enhancing simulation efficiency and accuracy.

1.3 Overview of High Frequency Structure Simulator (HFSS)

The HFSS is a kind of powerful software developed by ANSYS, Inc. specifically designed for high-frequency electromagnetic field simulations. Its primary purpose is to facilitate the design and analysis of various high-frequency electronic products such as antennas, RF and microwave components, high-speed interconnects, filters, connectors, IC components and packages, as well as printed circuit boards [45]. By utilizing the Finite Element Method (FEM), HFSS is capable of accurately solving complex electromagnetic field equations, enabling the simulation of the electromagnetic behavior of a wide range of high-frequency devices and circuits, including antennas, microstrip lines, waveguides, and filters, among others. With its exceptional accuracy, efficient solving speed, and user-friendly interface, HFSS has emerged as a vital tool [13, 45–47] in the field of high-frequency electromagnetic field simulation.

In the subsequent section, a comprehensive overview of HFSS will be presented, encompassing its historical development, key functionalities, and notable features.

1.3.1 Development History of HFSS

HFSS, which stands for High-Frequency Structure Simulator, was originally developed by Prof. Zoltan J. Cendes, at Carnegie Mellon University [48]. Professor Cendes focused on finite element-based electromagnetic calculations and founded Ansoft (short for Analysis Software) in 1984. Ansoft was later acquired by ANSYS in 2011, and HFSS became one of ANSYS' product offerings. Since then, with the support of ANSYS, HFSS has undergone continuous updates and enhancements, incorporating additional functionalities and features. These include advanced parametric modeling, automated design flow, and simulation acceleration, solidifying its position as a kind of leading software in high-frequency electromagnetic field simulation [46].

Initially, HFSS started as a two-dimensional electromagnetic field simulation tool primarily used for solving problems related to antennas and waveguides. As computer performance and software technology advanced, HFSS evolved into a three-dimensional EM field simulation software in the 1990s. Its usage expanded significantly within the microwave and millimeter wave fields. During its early development, HFSS prioritized enhancing simulation accuracy and solution speed to meet the growing demand for high-frequency EMF simulation. In the early 2000s, as the demand for microwave circuit design and optimization increased, HFSS began to incorporate circuit design and optimization capabilities. It introduced various optimization, such as automatic optimization, parameter scanning, and adaptive meshing, enabling the optimization of circuit parameters and achieving optimal design solutions. Additionally, HFSS introduced various component modeling, including