

ONE DAY SEMINAR

ON WAVES

WIRELESS ARCHITECTURES, VLSI AND EMBEDDED SYSEMS

**VLSI Next-Gen Innovation
Trends in Communication Systems**



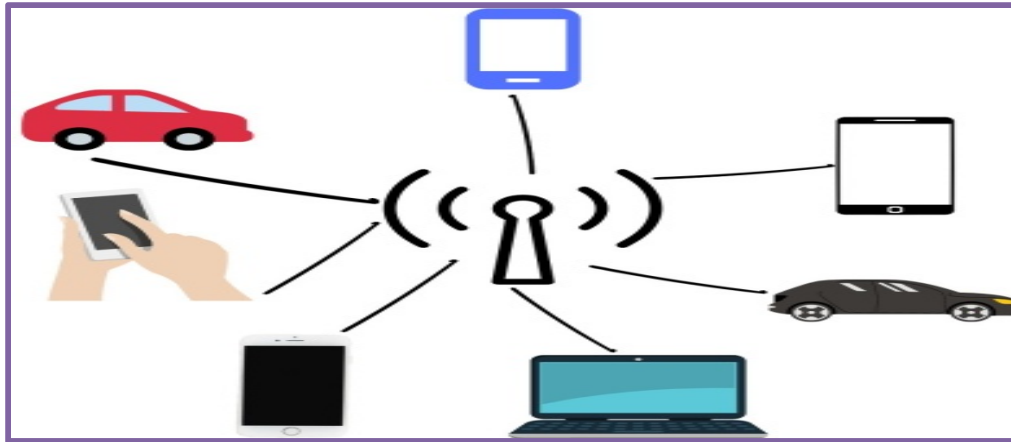
**PRESENTED
BY**

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UP STATE CENTER, LUCKNOW**

Wireless Communication



- 3D (i) Device (ii) Data (iii) Data Transfer
- Wireless communication emerged as a great facility for humans in the terms of **mobility** and **portability**, suppressing the dependency on physical means of communication.
- Following the path of Evolution in wireless communication, we have reached to the era (Mobile Communication)
- Where **5G exists** (Next-Generation)and progress is **towards 6G** (Future Communication Technology).

Waves (तरंगें) - पंचतत्व (Five Tatva)

1. **W - Water (जल/पानी):** यह शरीर में तरल पदार्थों, भावनाओं और प्रवाह का प्रतिनिधित्व करता है।
2. **A - Air (वायु):** यह श्वास, प्राणवायु और गति का प्रतिनिधित्व करता है।
3. **V - Vibration (आकाश/शून्य कंपन):** शास्त्रीय भौतिकी में, तरंगें अंतरिक्ष में ऊर्जा का कंपन है, जो सूक्ष्म रूप से आकाश (space) और कंपन (Vibration/Ethers) का प्रतिनिधित्व करता है।
4. **E - Energy (अग्नि):** यह शरीर की गर्मी, चयापचय (metabolism) और ऊर्जा का प्रतिनिधित्व करता है।
5. **S- Soil/Structure (पृथ्वी/मिट्टी):** यह शरीर की संरचना, हड्डियों और ठोस भौतिक रूप का प्रतिनिधित्व करता है।

COMMUNICATION SYSTEM

- Wireless communication has evolved rapidly from **early voice-centric systems to data-driven and intelligent networks**
- The progression from **1G to 5G** has enabled:
 - Mobile broadband
 - Massive connectivity
 - Support for IoT and smart applications
- Despite significant advancements, **current communication systems face key challenges**:
 - Spectrum scarcity
 - High energy consumption
 - Limited adaptability to dynamic environments
- Emerging applications such as **smart cities, autonomous systems, and immersive services** demand capabilities beyond existing technologies
- These limitations motivate the exploration of **next-generation pathways** in communication system design

➤ **Wireless Networks:**

- Wi-Fi:** Local wireless network technology for internet access.
- Cellular Networks:** Mobile communication through base stations.
- Bluetooth:** Short-range wireless technology for connecting devices.

➤ **Advantages:**

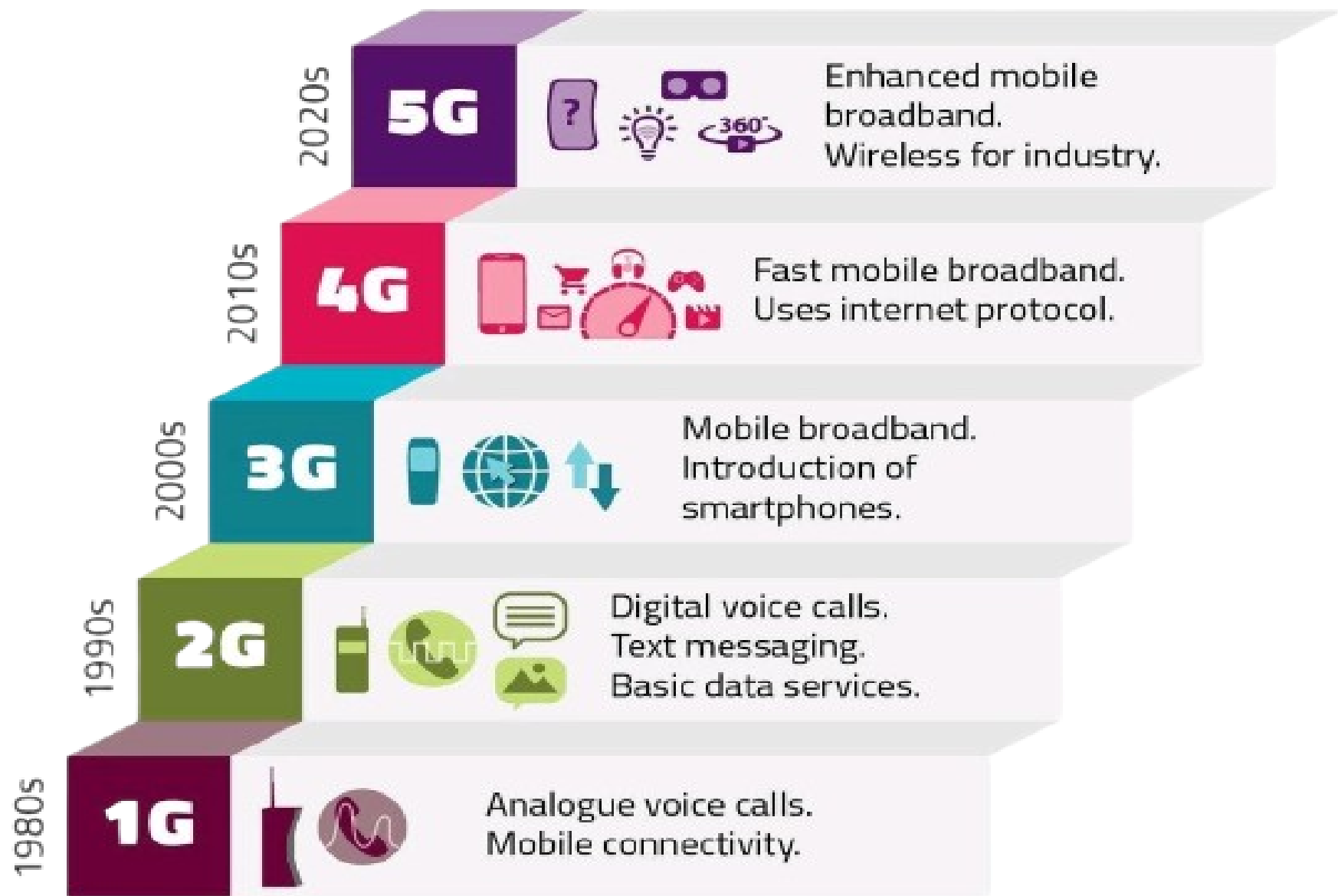
- Mobility:** Users can move freely while staying connected.
- Flexibility:** Easier to install and adapt compared to wired systems.
- Scalability:** Can accommodate a varying number of connected devices.

➤ **Challenges:**

- Interference:** Signal quality may degrade due to obstacles or other signals.
- Security:** Susceptible to eavesdropping and unauthorized access.
- Speed and Bandwidth:** May have limitations compared to wired connections.

WIRELESS COMMUNICATION

- ❖ Wireless communication provides a great facility for a humans in the terms of **mobility** and **portability**, suppressing the dependency on physical means of communication.
- ❖ Following the path of Evolution in wireless communication, we have reached to the era where **5G exists** and progress is **towards 6G** (Nex-Gen Technology).
- ❖ **5G** is a **paradigm shift** into the domain of handling **massive Machine Type Communication (MTC)** traffic for supporting the **Internet of Things (IoT)** network in addition to providing significantly higher **performance for traditional voice, data, and video applications**.



Device Technology Developments

The Scale (level) of Integration of chips has been classified as (based on No. of gates/chip):

- SSI – Small scale Integration (No. of Gates 10-100)
example- 7400 (NAND logic gates).
- MSI- Medium scale Integration (No. of Gates 100-1000)
example- 74161 (counter).
- LSI- Large scale Integration (No. of Gates 1000-10,000)
example- 8 bit Microprocessor
- VLSI- Very Large scale Integration (No. of Gates 10,000-1,00,000)
example- 16-32 bit Microprocessor/Microcontroller/Memories
- ULSI- Ultra Large scale Integration (No. of Gates 1,00,000-10,00,000) example- Special processors.

VLSI SYSTEM DESIGN

- System Design
- Application
- Need
- Device Type
 - Conventional MOSFET
 - Organic FET
 - Carbon NanoTube (CNTFET)
 - Single Electron Transistor
- Performance Parameters
 - Size
 - No of Module
 - Performance Computational Time (Speed)
 - Frequency
 - Power Consumption

Motivation

- Integration improves the design
 - Lower parasitics = higher speed
 - Lower power consumption
 - Physically smaller
- Integration reduces manufacturing cost
 - (almost) no manual assembly

Emerging Trend Concept

- Fuzzy Logic
- AI and Neural Network
- IoT
- Machine Learning
- Deep Learning
- Data Science & Analytics
- Security (Block Chain)

FUTURE TRENDS AND INNOVATIONS

AI-Driven Network Optimization

- ▶ Artificial intelligence is transforming network management through predictive analytics and automated resource allocation.
- ▶ AI-driven systems enhance performance, reduce downtime, and adapt to traffic patterns, creating smarter, more efficient communication networks.
- ▶ This evolution supports growing complexity and user demand.

Integration Of Satellite And Terrestrial Networks

- **UAV**
- **Drone Technology**
- Combining satellite and terrestrial networks extends coverage and reliability.
- This integration supports remote and underserved regions, providing seamless connectivity.
- Challenges include coordination, latency reduction, and harmonizing different technologies to achieve consistent user experiences.

TRENDS

- Communication systems are evolving beyond traditional data transmission toward **intelligent, adaptive, and integrated networks**
- **Next-generation pathways** are driven by:
 - Artificial intelligence and machine learning
 - Intelligent spectrum management
 - Advanced architectures and new spectrum bands
- The transition from **5G to beyond-5G and 6G** represents a **paradigm shift**, enabling:
 - Ultra-low latency
 - Massive connectivity
 - High reliability and efficiency

INNOVATIONS

- Key challenges such as **spectrum scarcity, security, energy efficiency, and implementation complexity** must be addressed through interdisciplinary research.
- Emerging technologies, including **AI-native networks, symbiotic radio, and sustainable communication**, will play a critical role in shaping future systems.
- Academic research, standardization efforts, and industry collaboration are essential for the **successful realization of next-generation communication systems**

AI BASED VLSI DESIGN

- AI is **not replacing** traditional EDA tools but **enhancing every stage** of the flow
- **From Human-driven → AI-driven flows**
 - Predictive analytics, automated exploration, self-learning tools.

AI-DRIVEN VLSI DESIGN AUTOMATION

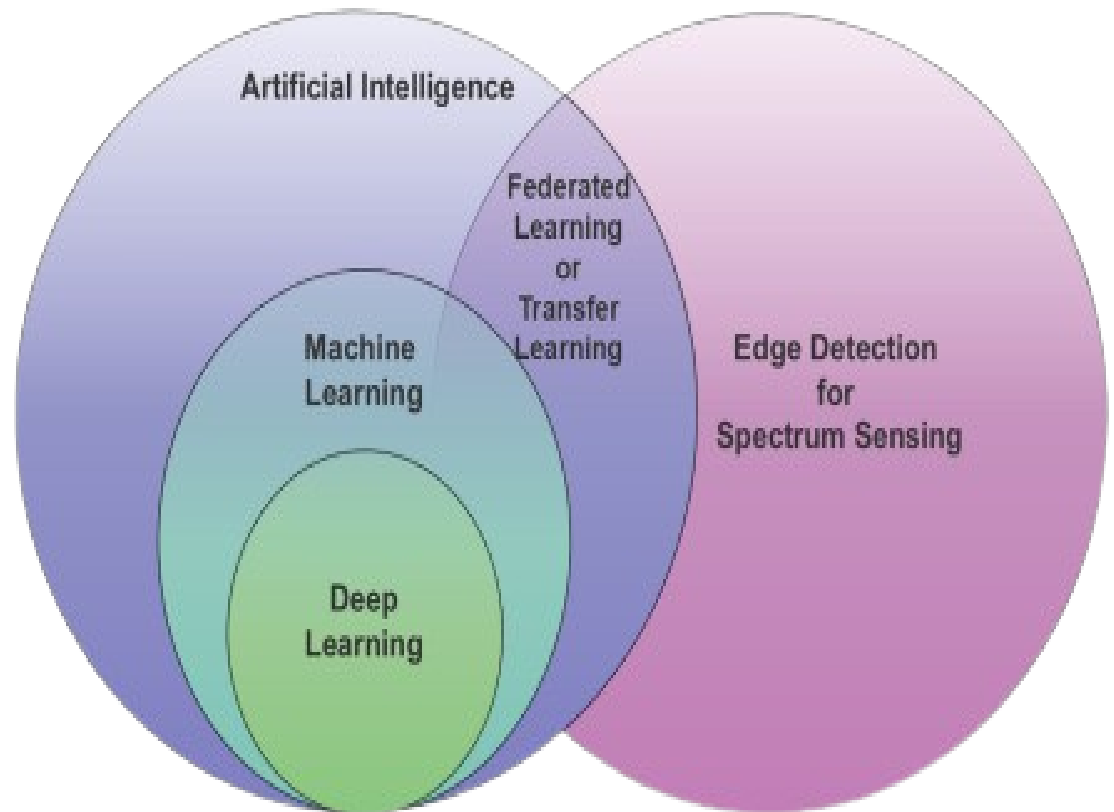
- AI-driven tools are revolutionizing VLSI design by automating complex tasks such as layout optimization, fault prediction, and circuit verification.
- These techniques reduce design cycles and improve accuracy, enabling the creation of **high-performance chips** with enhanced efficiency and reduced time-to-market.
- AI integration is now a critical enabler for next-generation semiconductor innovation.

Machine Learning Integration

- Integrating **machine learning** into communication networks enables dynamic optimization of resources and traffic management.
- It facilitates predictive maintenance, anomaly detection, and intelligent routing, significantly boosting network performance and resilience. Such integration is foundational for self-organizing networks and future autonomous communication infrastructures.

AI/ ML in Spectrum Management

- Managing spectrum poses a significant challenge due to the increasing demand for wireless services and limited resources.
- Through AI and ML, we can develop predictive models for spectrum usage, optimize network configurations, and automate interference detection and mitigation.
- These technologies can also facilitate cognitive radio systems and dynamic spectrum access, leading to more efficient spectrum utilization



Implementation Strategies for Next-Gen Communication Systems

- **Phased Evolution from 5G to Beyond-5G/6G**
 - Gradual integration of AI-driven features into existing 5G networks
 - Backward compatibility with legacy systems
- **AI-Enabled Network Design**
 - Deployment of AI/ML models for:
 - Spectrum management
 - Resource allocation
 - Interference mitigation
 - Edge intelligence for real-time decision making

Implementation Strategies for Next-Gen Communication Systems

- **Advanced Spectrum Utilization**
 - Dynamic and cognitive spectrum access
 - Efficient use of mmWave and terahertz bands
 - Spectrum sharing and coexistence strategies
- **Flexible and Virtualized Network Architecture**
 - Cloud-native and software-defined networking (SDN)
 - Network function virtualization (NFV)
 - User-centric and cell-free architectures
- **Energy-Efficient and Sustainable Design**
 - Low-power communication techniques
 - Energy harvesting and green networking
 - Optimization for massive IoT deployments

Implementation Strategies for Next-Gen Communication Systems

- **Security and Trust Management**
 - AI-assisted security mechanisms
 - Privacy-preserving communication
 - Robust protection against adversarial attacks
- **Standardization and Collaboration**
 - Alignment with global standard bodies (ITU, 3GPP)
 - Industry–academia–government collaboration
 - Development of testbeds and pilot deployments

Integration Circuits

- Circuits are made by fundamental components by connection.
- Based on the Style of connection it may be divided in two groups: (1) Discrete (2) Integrated
 - Discrete component are connected by wire on bread board/ PCB design are called Discrete circuits.
 - The complete circuit is fabricated on a single substrate called Monolithic Integrated circuits.

Level of Integration can measure by the following parameters:

- 1.No. of gates (Transistor) per chip.
- 2.Feature size.

Feature size Developments (CMOS Technology)

- When level of Integration increases and minimum feature size reduces. Feature size development is as under
 - 1980 - $2\mu\text{m}$
 - 1995 - $0.5\mu\text{m}$
 - 2001- 0.35
 - 2004- $0.18\mu\text{m}$

Reducing the feature size (Technology) will increase

- Packing density
- Increased no. of components

Advantages of Low Voltage Design

- Less Power consumption.
- Higher speed (less delay) because of significant reduction by interconnect length.
- Less area (less no of component)– compactness
- Significant cost saving.
- Less testing requirement at system level.
- Higher reliability due to improved interconnection on chip itself. ([High Integration](#))
 - ❖ System on Chip Design
 - ❖ Layout Minimum
 - ❖ Compact and Portable Devices
 - ❖ Integration Area of the circuits.

Introduction Contd...

- Addition is one of the fundamental arithmetic operations. It is used extensively in many VLSI systems such as DSP architectures, microprocessors etc.
- Used in Arithmetic operations, Addition, subtraction, division, multiplication and more.
- Low-power , high-performance adder cells is of great interest in Signal Processing & ALU hardware Design.
- Several researchers proposed many topologies which have their own advantages and disadvantages.

➤ Performance Evaluation Parameters

Circuit performance analysis to determine the output voltage swing with the input voltage variation from 1.8V to 0.8V

- (a) [Power consumption](#)
- (b) [Speed \(delay\)](#)
- (c) Power-delay product(PDP)
- (d) Energy Delay Product (EDP)
- (e) Load Analysis (2fF-500fF) driving capability
- (f) Noise analysis
- (g) Layout (Area)
- (h) [optimization the \(W/L\) ratio](#)

The Role of Semiconductors in Enabling 5G

- ❖ 5G is now the Standard for Electronics Device
 - ❖ Power Efficiency
 - ❖ Faster Data Processing
 - ❖ Miniaturization
 - ❖ Security
 - ❖ The Future of 5G and Semiconductors

5G and Semiconductor Manufacturing

- ❖ The Promise of 5G
- ❖ Enhanced Connectivity and Communication
- ❖ IoT Integration
- ❖ Edge Computing
- ❖ Quality Control and AI Integration
- ❖ Supply Chain Optimization
- ❖ Challenges and Security Concerns

The Impact of 5G on Semiconductor

- ❖ 5G is now the Standard for Electronics Device
- ❖ A wide range of Industries are leveraging 5G
- ❖ The Smart-phones as its main drivers
- ❖ Semiconductor companies working in 5G space

- Advance Micro Devices(AMD)
- Xilinx,
- Qualcomm,
- NXP,
- INTEL,
- Reliance,
- Jio,
- Bharti Airtel

Semiconductor chips

- ❖ 5G introduction to enable a surge in demand for semiconductor chips
- ❖ 5G and AIoT will need new Semiconductor materials
 - ❖ AIoT goal to design faster RF amplifier,
 - ❖ Specialized AI/ML clouds
 - ❖ Network edge consisting of sensor, actuators and microcontrollers
 - ❖ Gallium-nitride (GaN)
 - ❖ Gallium –arsenide (GaAs)
- ❖ 5G hardware foundations on different chips

Family of Communication Networks: From Access to Mobile Systems

- Modern communication systems consist of a **hierarchy of interconnected networks**, collectively forming the Internet.
- **Access (Edge) Networks** provide the last-mile connectivity to users and devices.
- **Wireless networks** enable mobility and flexibility, supporting technologies such as:
 - WiFi, Bluetooth, WSN, and Satellite Systems
- **Mobile networks** are a specialized subset of wireless networks, designed for:
 - Wide-area coverage
 - Seamless mobility
 - Cellular technologies such as 3G, 4G, LTE, and beyond
- This layered view highlights how **mobile and wireless systems coexist with wired and core networks**, forming an integrated communication ecosystem

CHALLENGES IN VLSI SYSTEMS DESIGN

India's Semiconductor Mission

- India's semiconductor market ~US\$50-60B by 2026
- First Made-in-India chip expected by mid-2026.
- Technology Node produced 28 to 90nm.
- Applications: automotive, telecom, and consumer electronics.
- Government approved 10 major semiconductor projects with ₹1.6 lakh crore (\$20B+) investment.
- Key fabs: Tata-PSMC in Gujarat, Micron ATMP plant, projects in Odisha, Punjab, etc.
- Support for design and innovation: tools for 300+ academic institutes and 80+ startups.
- Provides incentives, research support, and PLI (Production linked Incentive)schemes to foster a self-reliant chip ecosystem.

VLSI Design

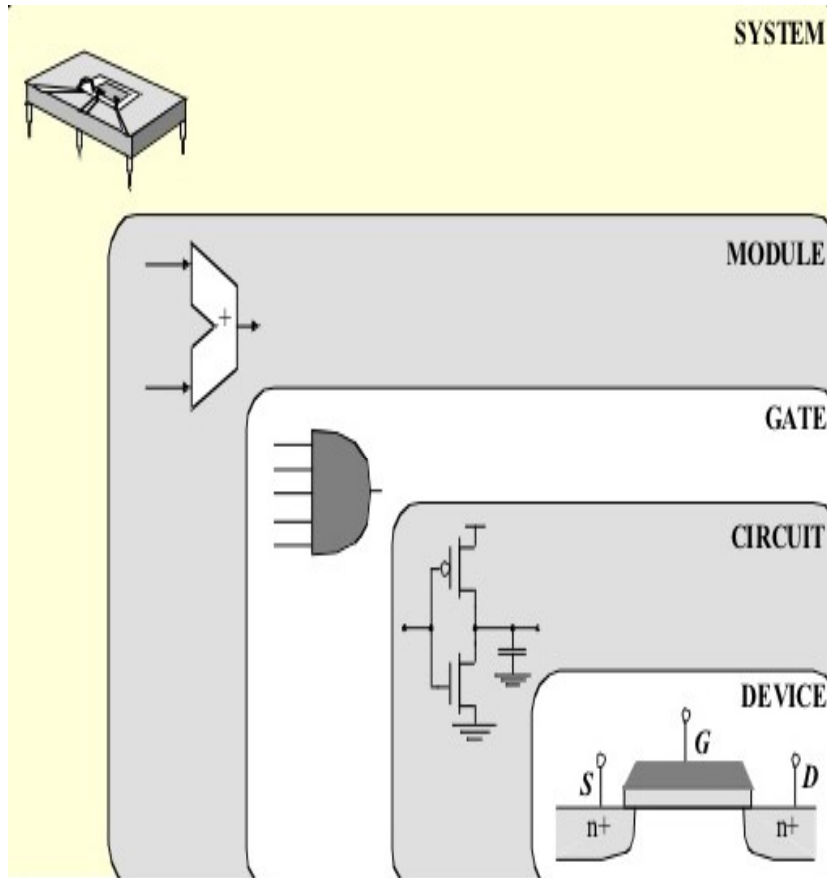
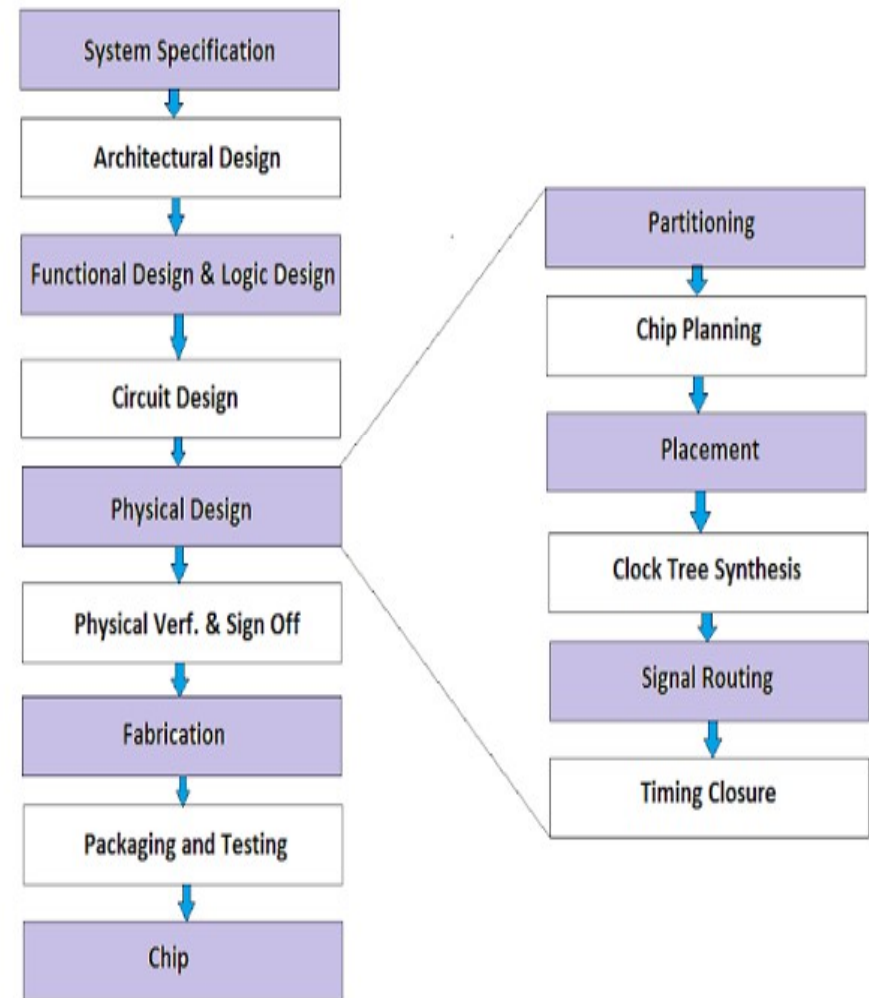


Fig. 1. Design Abstraction Levels

- **Highest Abstraction level: System (Processor)**
- **Lowest Abstraction level: Device(MOSFET, GAAFET)**
- **Goal: Optimize Power, Performance, Area (PPA).**
- **Moore's Law: Number of Trs. On a chip double every 18 months**

VLSI DESIGN FLOW CHART

- Specification → RTL → Physical Design → Verification → Tape-out.
- Most Exhaustive – Physical design
- Important- Verification after each step

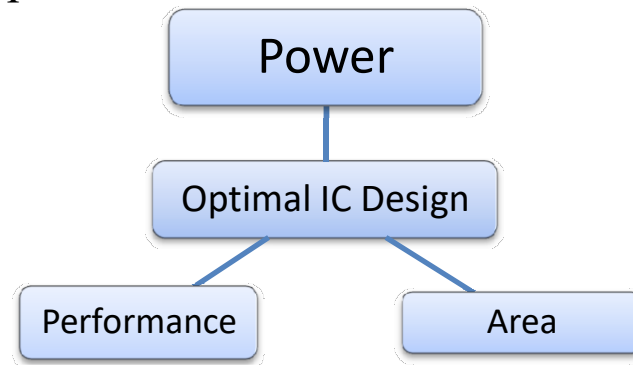


WHY IS DESIGNING GETTING HARDER?



CHALLENGES IN TRADITIONAL VLSI DESIGN

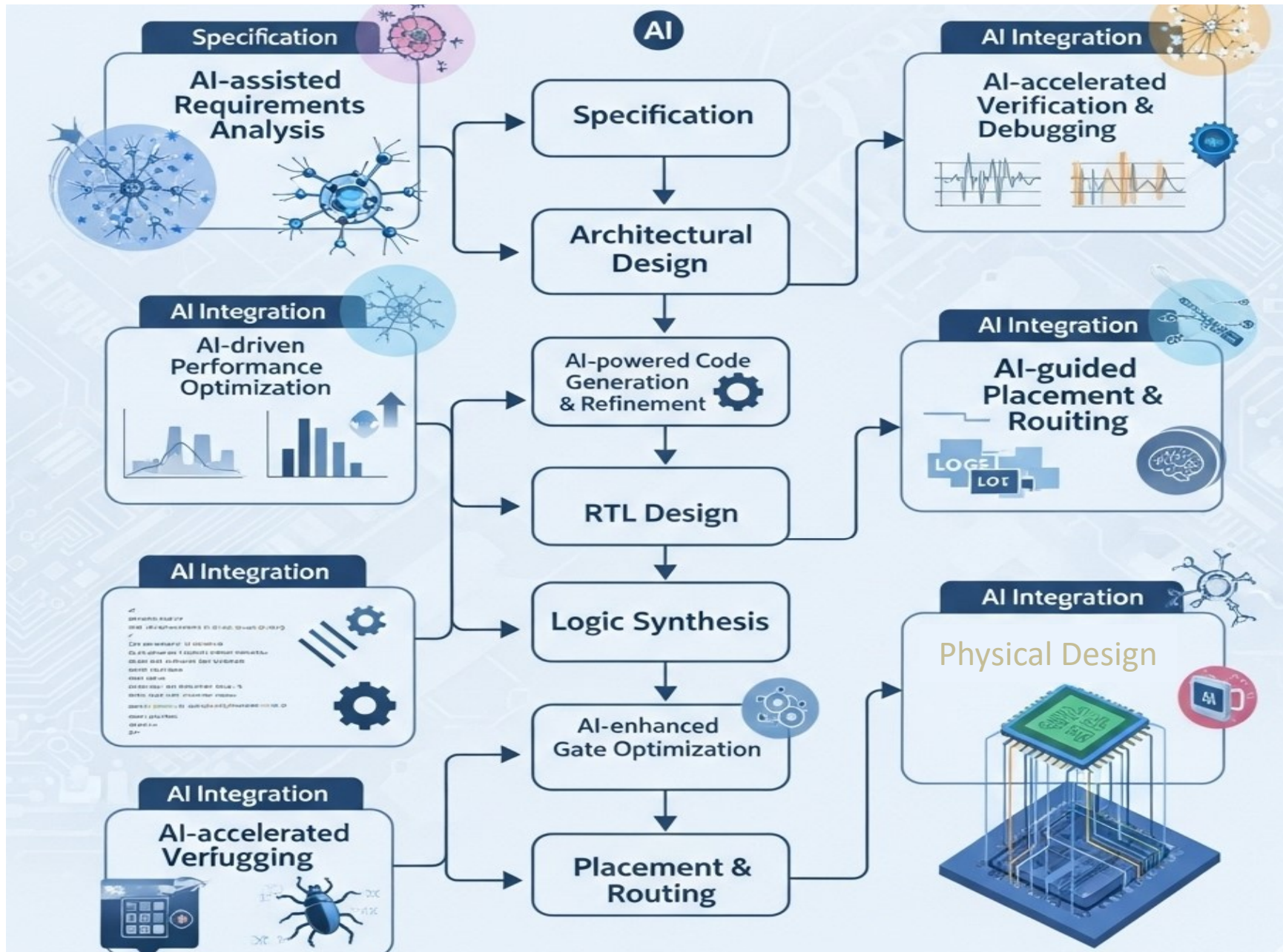
- VLSI Design Goals: Optimize PPA



- Design scale: Modern processors >50B transistors → high complexity
- *Cost: advanced-node development > \$500M;*
- Time pressure: verification ~70% of effort – physical verification - weeks
- Longer iterations → missed market windows.
- Manual heuristics → suboptimal layouts.
- New approaches needed → **AI Driven VLSI design**

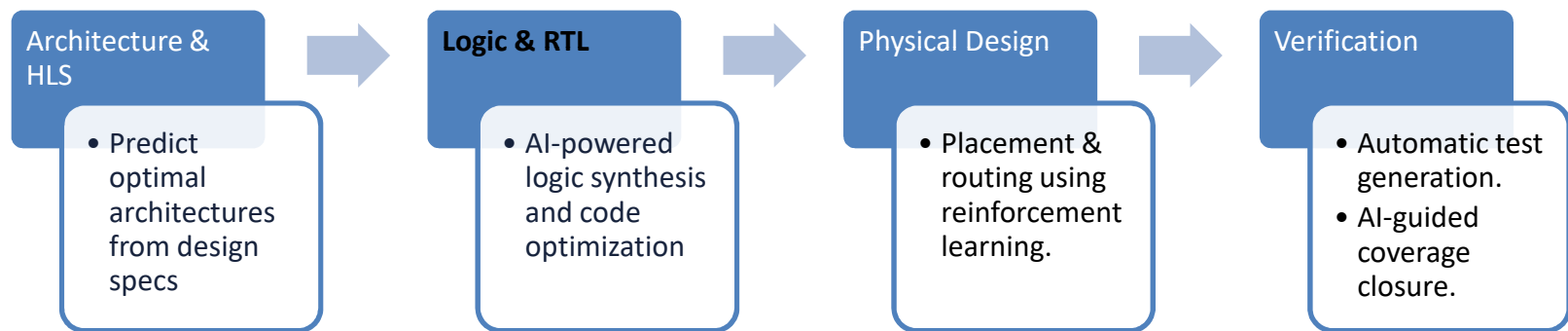
LOW POWER DESIGN STRATEGIES

- Low power designs are vital to meet energy efficiency demands in portable and large-scale systems.
- Techniques include dynamic voltage scaling, multi-threshold CMOS, and power gating, which collectively reduce leakage and switching power, ensuring **optimized performance** under strict power budgets.



SIMPLIFIED AI DRIVEN VLSI WORKFLOW

AI integrates into every critical stage of chip design, turning a sequential, iterative process into a predictive and optimized flow.



ARCHITECTURE & HIGH-LEVEL SYNTHESIS (HLS)

- **Traditional vs AI:**
 - Engineers manually explore design spaces.
 - reduced exploration by **70%** while improving accuracy of architectural predictions.
- **AI-driven HLS:**
 - **RL** to predict predicts best architectures → accelerates HLS
 - **Supervised ML** for PPA mapping
 - Large Language Models (**LLMs**) are being used to generate system-level designs in Python from natural language specifications
 - **Automated HLS:** AI-driven HLS tools convert high-level behavioral descriptions (e.g., C/C++) directly into optimized RTL
 - **Workflow:** Input specs → ML model → RTL generation.

ARCHITECTURE & HIGH-LEVEL SYNTHESIS (HLS)

- **Industry Examples:**

- **Google's Use of RL:** Google successfully used a deep reinforcement learning model to automatically generate a chip floorplan for its Tensor Processing Unit (TPU), achieving better results than human-generated designs in a fraction of the time.
- **Generative AI for RTL:** Researchers are using LLMs fine-tuned on hardware description languages (HDLs) like Verilog to automatically generate functional RTL code from high-level prompts, accelerating the initial design phase.

- **Benefits:**

- Reduces **design space exploration time** drastically.
- Avoids millions of trial-and-**error** simulations.

RTL AND LOGIC SYNTHESIS

AI streamlines : high-level design → gate-level netlist, optimizing the core logic of the chip.

- **AI's Role:**

- **Automated Testbench Generation & Debugging:** Generates RTL code and testbenches from specs. It can also analyze design failures and suggest fixes, accelerating the debugging cycle.
- **Logic Optimization:** ML models predict the impact of different synthesis options on PPA, guiding the tool to make intelligent decisions for timing closure and area reduction.
- **Formal Verification:** AI-based formal verification tools can analyze a design's correctness with less human intervention by learning from past bugs and predicting potential failure points.

RTL AND LOGIC SYNTHESIS

- Industry Examples:
 - **EDA Tool Integration:** Major EDA vendors like
 - Synopsys (DSO.ai),
 - Cadence (Cerebrus), and
 - Siemens (Solido ML) are integrating AI to automate and optimize synthesis tasks, learning from historical data to improve performance.

PHYSICAL DESIGN

Involves the physical layout of the chip, is a prime target for AI due to its **complexity and iterative** nature.

Floor planning, placement, routing → biggest PPA gains

- **AI's Role:**

- **Intelligent Floorplanning & Placement:** AI **algorithms** optimize the placement of components on the chip, **minimizing wirelength** and routing **congestion**. **RL agents** can iteratively adjust placements to improve timing and power.
- **Routing Optimization:** AI-powered routing tools predict and resolve bottlenecks, ensuring signals are connected efficiently while adhering to all **design rules**.
- **PPA Optimization:** ML models predict and mitigate issues.

PHYSICAL DESIGN OPTIMIZATION (PPA)

- **Industry examples:**
 - **Google's Alpha Place:** This deep RL model was used to place macros in a chip design, outperforming human experts in terms of timing and area, with the process taking only a few hours.
 - Reward = shorter wires, fewer congestion points, lower delay.
 - *Google TPU case:* RL agent completed floorplanning in 6 hours (vs weeks by humans). Achieved **–5% wire length, –10% power.**
 - *Synopsys DSO.ai:* Used for Samsung's 5nm chips → better PPA + reduced design time
 - **Supervised Learning:** Learns from millions of design iterations (EDA recipes).

SUMMARY OF AI TECHNIQUES USED IN VLSI DESIGN

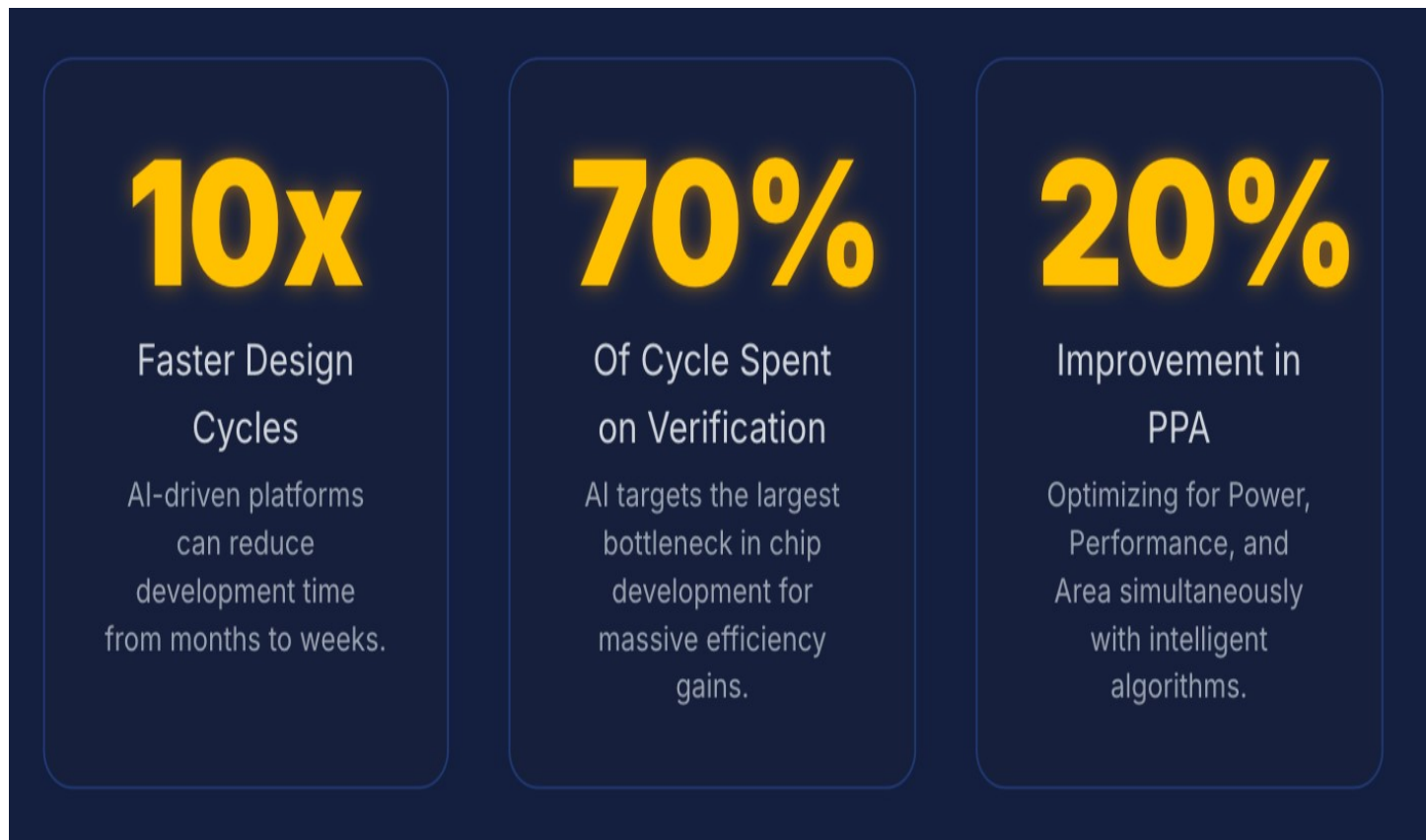
AI Technique	VLSI Design use
Supervised ML	PPA optimization, defect prediction
Deep Learning	Mask design, defect detection
Reinforcement Learning	Floorplan, placement, routing
GANs Generative Adversarial Networks	Synthetic test data generation
LLMs Large Language Model	Code and test generation

TRADITIONAL VS AI BASED VLSI DESIGN

AI-Assisted vs. Traditional Design	AI-Assisted Performance	Traditional Performance
Logic Synthesis Area Reduction	Up to 69.3% reduction	Classic algorithms
PPA Improvement	12% better overall PPA	300% fewer design permutations evaluated
Performance Boost	14% performance gain, 3% power reduction	A team of 10 engineers over several months
Circuit Size Reduction	25% smaller circuits	Human-designed circuits

IMPACT OF AI IN VLSI DESIGN

From manual heuristics to intelligent automation, Artificial Intelligence is fundamentally reshaping how we design the next generation of semiconductors.



INDUSTRY ADOPTION

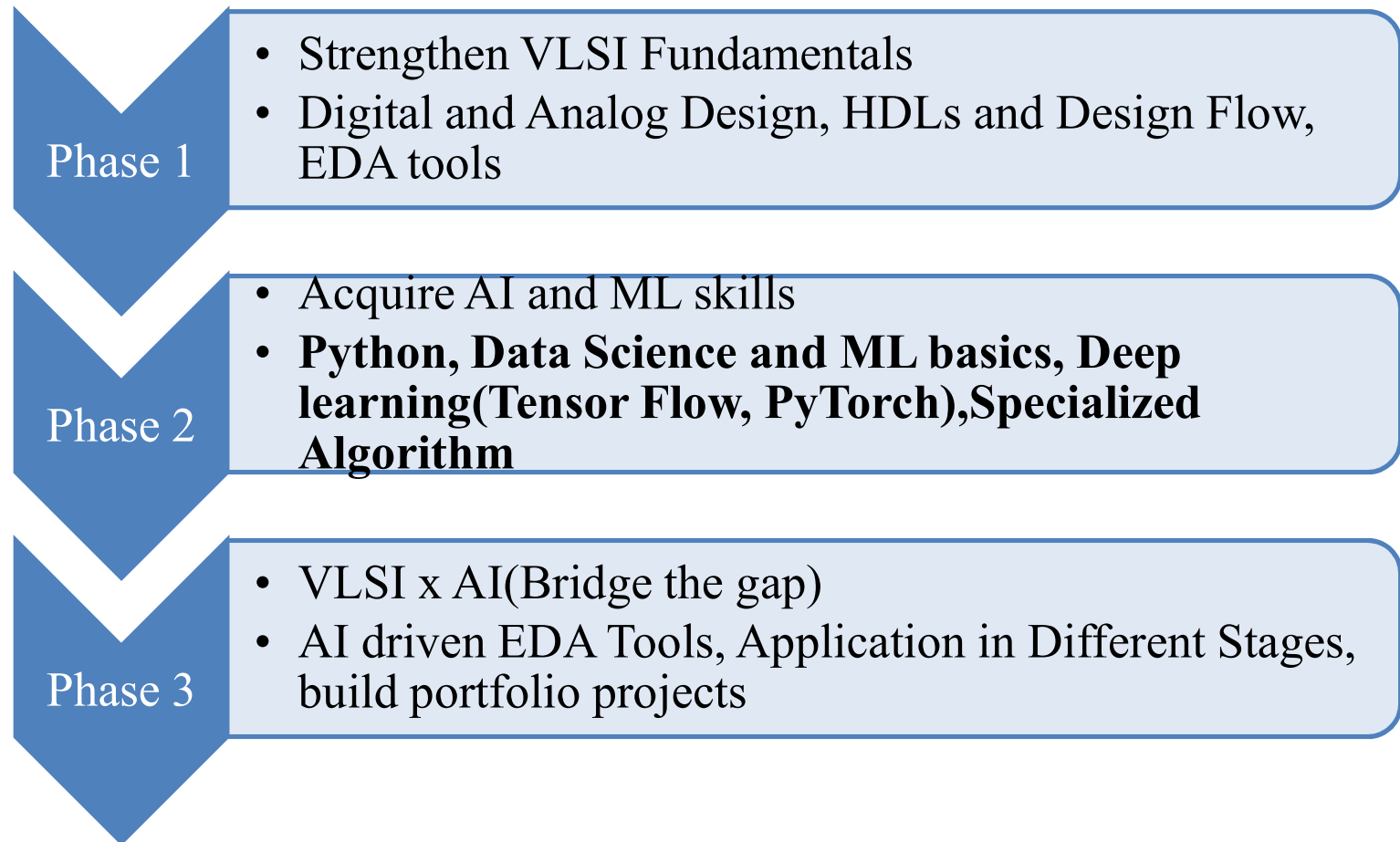
All major EDA companies are **embedding AI natively** into toolchains.

- **Synopsys.ai:** DSO.ai, VSO.ai → 20% PPA gain
 - *DSO.ai*: Optimizes physical design automatically.
 - *VSO.ai*: Automates verification → 33% more coverage, 7x regression speedup.
- **Cadence Cerebrus:**
 - Chip that **functions perfectly** on its first attempt → fewer re-spins.
 - **5–10x** faster cycles
- **NVIDIA AutoDMP:**
 - **GPU-accelerated** reinforcement learning for placement.
 - Achieved **30x** faster placement.

CADENCE REPORTS Q2 2025 FINANCIAL RESULTS

- **Accelerated Design Cycles:** Companies are seeing a **5x to 10x reduction** in their design cycles- faster
- **Enhanced PPA Metrics:** **20% improvement** in critical PPA metrics - more efficient chips.
- **Widespread Adoption:** This is driving business growth, as seen in Cadence's **16% year-over-year growth** in its core EDA segment- **>1,000 customers** already using their AI solutions.
- **Improved Accuracy:** **> 97% accuracy** in complex tasks like dynamic power analysis by collaborations Cadence and NVIDIA.

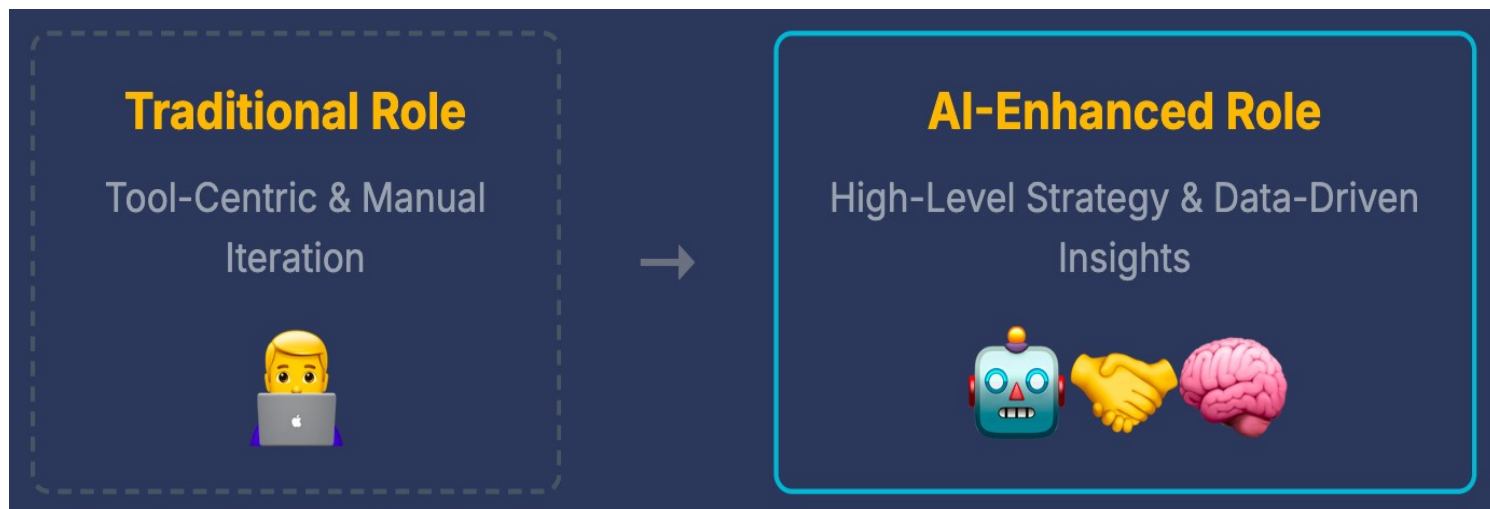
ROADMAP FOR AI RESEARCHERS/ VLSI ENGINEERS



CHALLENGES IN ADOPTING AI

- **Data dependency:** AI needs large labeled datasets → often Intellectual Property
- **The Hallucination Problem:** GenAI models
- **The Security Threat:** AI-generated code may introduce security issues
- **The Human Role:** critical for validation and ensuring correctness.
- **Trust barrier:** A single undetected error costs millions.
- **Black-box issue:** Lack of explainability makes adoption risky.
 - Difficulty debugging or modifying AI-generated designs.
 - Risk of "subtle bugs" and "edge cases" leading to catastrophic post-tape-out failures.
 - Solution- Explainable AI (XAI) to ensure trust, transparency, and regulatory compliance.

- NextGen VLSI pathways combine advanced materials, innovative architectures, and AI-driven design to push technological boundaries.
- Emphasizing reliability and testability ensures these advancements translate into **robust, high-performance chips**.
- Continued multidisciplinary efforts will be key to meeting the demands of future electronic systems and sustaining innovation momentum in semiconductor industry.
- AI will not replace engineers; it will augment them.



Spectrum Management And Efficiency

- Efficient use of the radio frequency spectrum is essential to support growing demand.
- Dynamic spectrum allocation and sharing techniques optimize utilization.
- Challenges include interference mitigation and regulatory compliance to maximize bandwidth availability without compromising service quality or causing disruption.

Challenges of AI And ML In Spectrum Management

Spectrum Scarcity and Efficiency:

- **Limited Spectrum Resources:** The electromagnetic spectrum is a finite resource, and its demand for various applications, including communication, is increasing rapidly. Optimizing the use of available spectrum and finding ways to efficiently utilize it is a significant challenge.
- **Dynamic Spectrum Access:** Traditional spectrum allocation methods may not be efficient in dynamically changing environments. AI and ML can help in developing dynamic spectrum access techniques, but the complexity lies in ensuring fair and efficient allocation in real-time.

Challenges of AI And ML In Spectrum Management

- **Interference Management:**
 - **Coexistence of Multiple Technologies:** With the coexistence of various wireless technologies and devices, managing interference becomes crucial. AI and ML can assist in interference detection, prediction, and mitigation, but handling the complexity of diverse technologies and their interactions poses a challenge.
- **Security and Privacy:**
 - **Security Concerns:** AI and ML systems can be vulnerable to adversarial attacks, and securing communication systems against such attacks is crucial. Ensuring the integrity and confidentiality of the data transmitted over the spectrum is a challenge.
 - **Privacy Issues:** As AI and ML systems rely on data for training and decision-making, ensuring the privacy of user data becomes a significant concern. Striking a balance between data-driven insights and user privacy is challenging.

Challenges of AI And ML In Spectrum Management

- **Spectrum Sensing and Awareness:**
 - **Uncertainty and Noise:** Spectrum sensing, which is crucial for cognitive radio systems, faces challenges due to uncertainties and noise in the spectrum. ML algorithms need to be robust against these uncertainties to provide accurate and reliable spectrum awareness.
- **Regulatory and Policy Challenges:**
 - **Adaptation to Regulatory Changes:** Regulations and policies related to spectrum allocation can change, and AI and ML systems must be adaptable to these changes. This requires continuous monitoring and adaptation to comply with evolving regulatory frameworks.

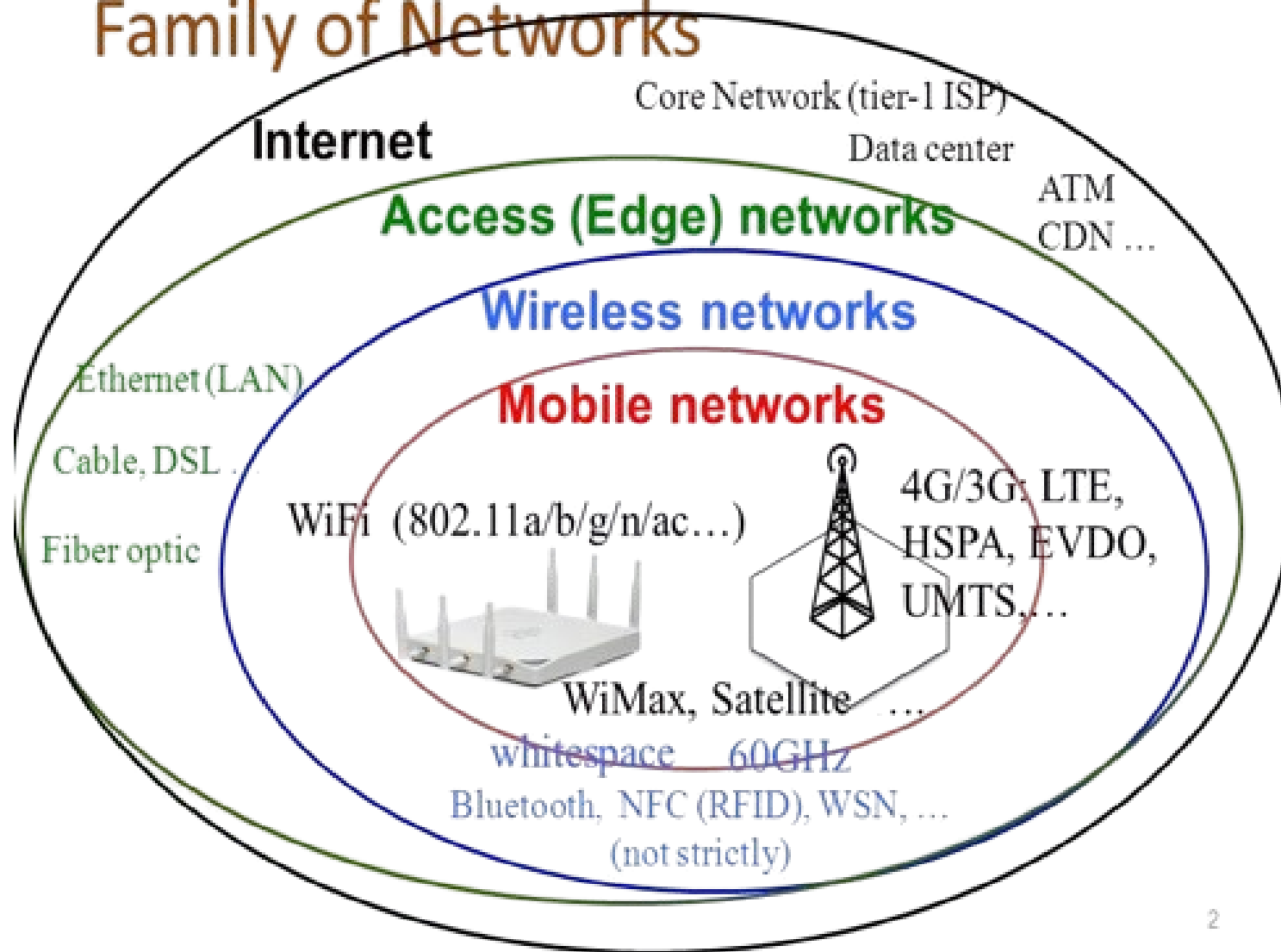
Resource Constraints And Lack Of Standardization

- **Resource Constraints:**
 - **Computational Complexity:** Implementing AI and ML algorithms in resource-constrained devices, such as IoT devices or edge computing platforms, can be challenging due to limitations in processing power, memory, and energy efficiency.
- **Lack of Standardization:**
 - **Heterogeneity in Standards:** The lack of standardized AI and ML frameworks for spectrum management can hinder interoperability and collaboration among different systems and devices.

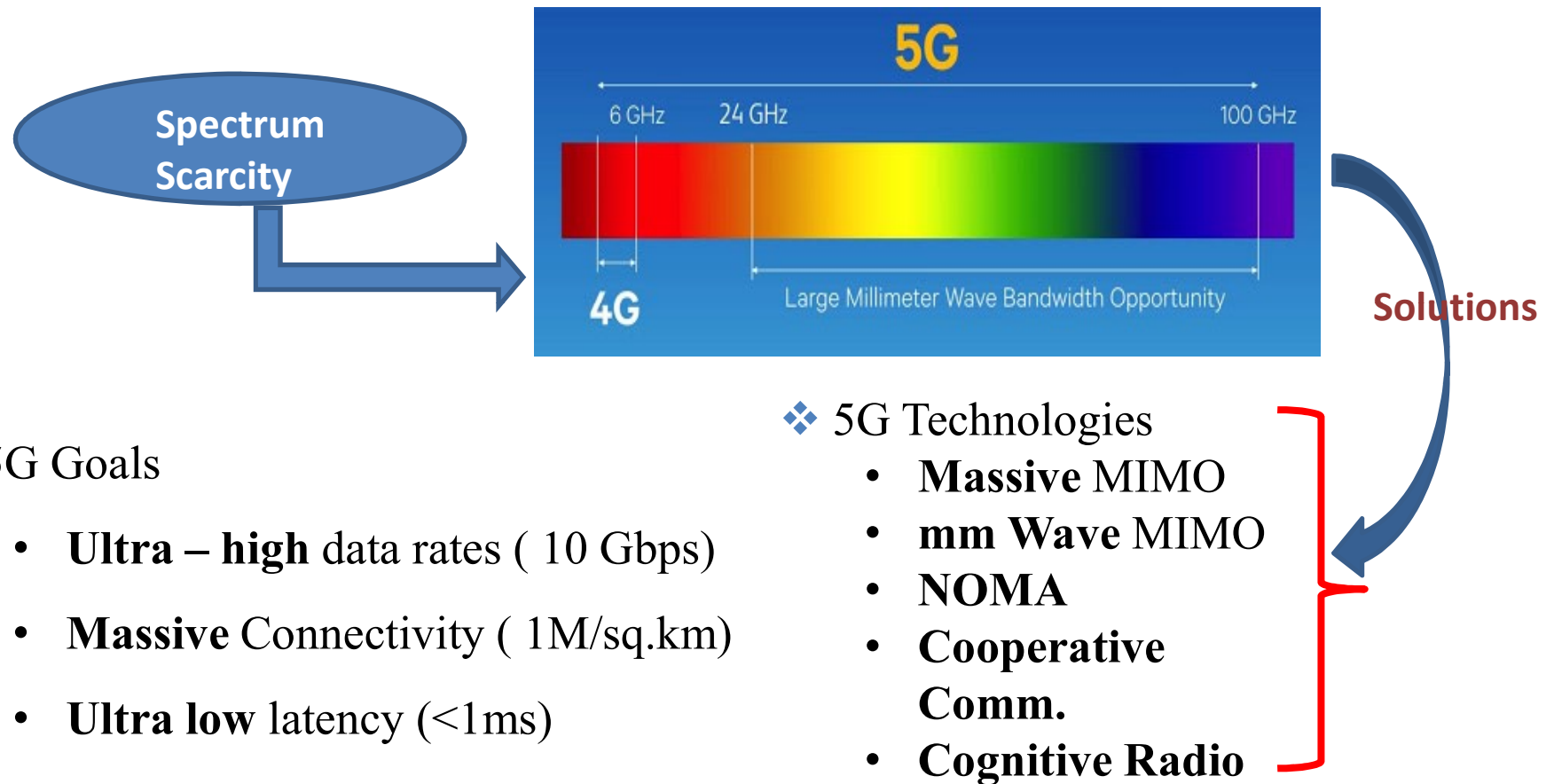
Security and Privacy Concerns

- Protecting data in next-gen communication systems is critical due to rising cyber threats.
- Ensuring **robust encryption**, user privacy, and secure protocols is paramount.
- The complexity of interconnected devices increases vulnerabilities, demanding continuous advancements in cybersecurity strategies to safeguard networks and users

Family of Networks



Enabling Technologies Leading to Next-Gen Systems

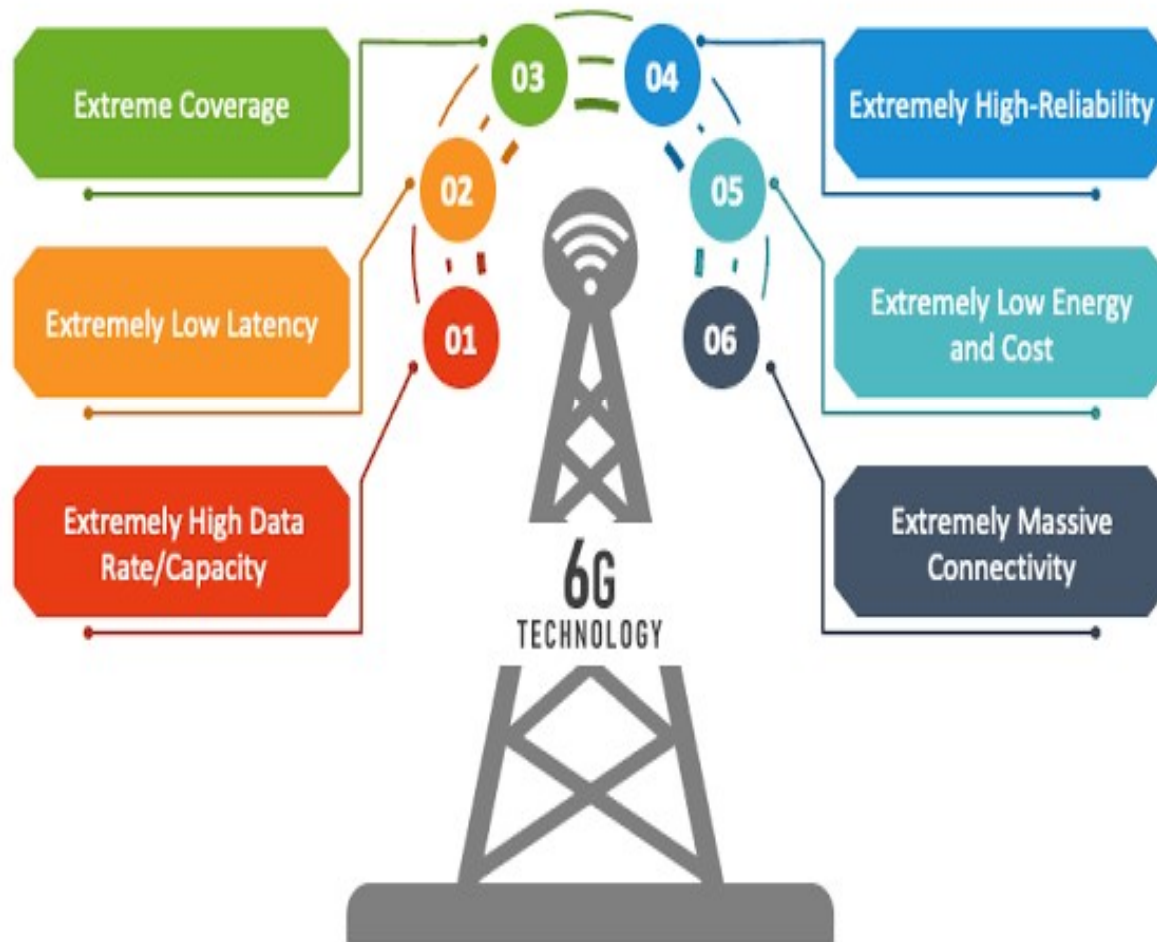


Communications in the 6G Era

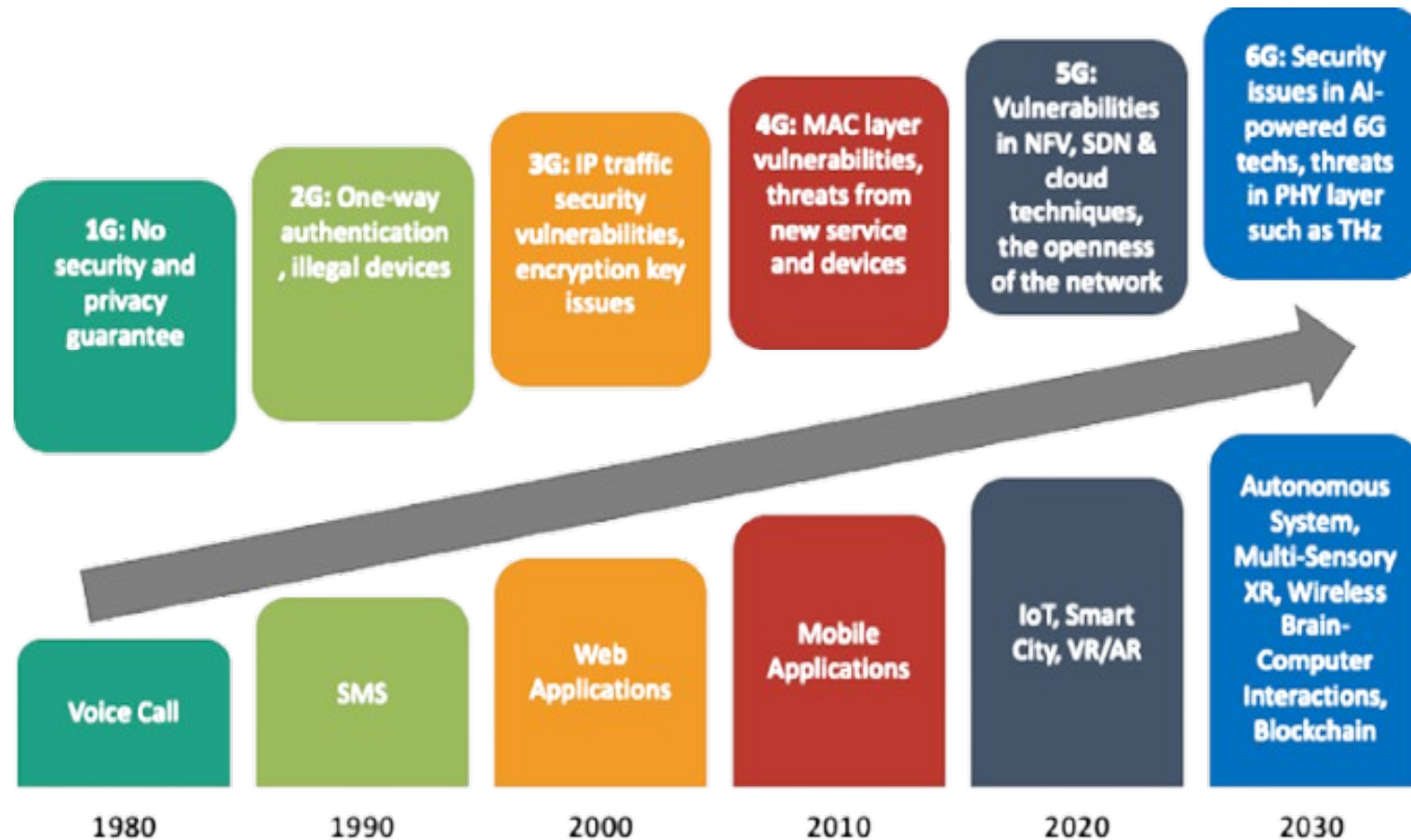
- ❖ The focus of wireless research is increasingly shifting toward **6G** as **5G** deployments get underway.
- ❖ At this stage, it is essential to establish a **vision of future** communications to guide the research.
- ❖ The future of connectivity is in the creation of digital twin worlds that are a true representation of the physical and biological worlds at every spatial and time instant, unifying our experience across these **physical, biological** and **digital worlds**.

6G TECHNOLOGY

Requirements for 6G Wireless Technology



6G Technology Timeline



Vision of Next-Gen Communication Systems

- Future networks are expected to be:
 - AI-native and self-adaptive
 - Context-aware and user-centric
- Integration of multiple functionalities:
 - Communication
 - Sensing
 - Computing
 - Control
- New spectrum domains such as millimeter-wave and terahertz bands will enable ultra-high data rates and low latency

Emerging Pathways and Research Significance

Next-gen communication systems will enable **transformative applications**, including:

- Smart cities and intelligent transportation
- Extended Reality (XR) and immersive communication
- Industrial automation and digital twins

These applications demand:

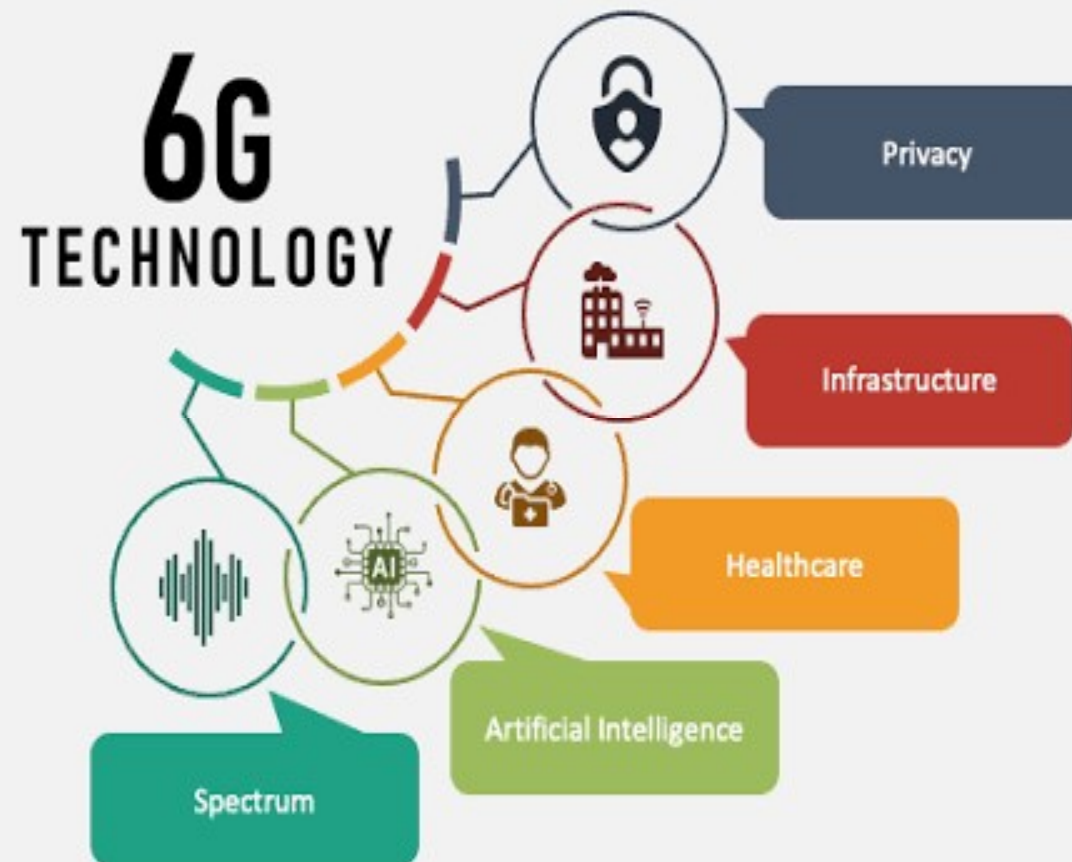
- Ultra-low latency
- High reliability
- Massive and heterogeneous connectivity

Emerging Pathways and Research Significance

- Key next-generation pathways include:
 - AI-assisted spectrum management
 - Energy-efficient and sustainable communication
 - Intelligent and symbiotic radio technologies
- The development of these systems requires **interdisciplinary research** across:
 - Wireless communication
 - Signal processing
 - Artificial intelligence
 - Security and hardware design

6G TECHNOLOGY

What will 6G Technology Bring to us?



APPLICATIONS OF NEXT-GEN COMMUNICATION

Internet of Things (IoT) Connectivity

- Next-gen communication supports massive **IoT deployments** by enabling seamless device interconnectivity with minimal latency.
- Enhanced protocols and edge computing capabilities ensure real-time data exchange,
- Empowering smart homes, Industrial automation, and Healthcare monitoring on a large scale.

5G and Beyond Networks

- 5G and its successors promise unparalleled data rates, ultra-low latency, and massive device density.
- These networks support diversified applications from mobile broadband to mission-critical services, driving innovation in sectors such as transportation, entertainment, and public safety with reliable, high-performance connectivity.

Smart Cities and Automation

- Next-generation communication systems enable **smart city** infrastructure by facilitating real-time data exchange between devices.
- Automation in traffic control, energy management, and public safety improves urban living conditions.
- These systems support scalability and adaptability essential for evolving urban ecosystems, driving efficiency and sustainability in city operations.

RF & Microwave Design—A Strategic Enabler in Modern Industry

- **Examples of modern implementations of RF & Microwave design:**
 - **5G/6G networks** – high-speed connectivity
 - **Satellite systems** – global comms & remote sensing
 - **Autonomous vehicles** – radar & safety sensors
 - **Defence & security** – radar, electronic warfare, secure communications
 - **IoT & wearables** – billions of connected devices

Why RF and Microwave Design Matters?

- **5G, 6G, Wi-Fi, and satellite IoT** demand ultra-high-frequency circuits with precise performance.
- RF design enables **low-latency, high-throughput communication** across billions of devices.
- Devices are shrinking, but functionality is expanding—RF front-ends must be compact, multi-band, and power-efficient.
- Techniques like 3D heterogeneous integration and System-in-Package (SiP) are solving this challenge.

Device-Level Innovation Driving RF & MW Circuits

- **These are examples of advanced materials and device technologies that form the foundation for designing the latest high-performance RF & Microwave circuits.**
- 1. GaN HEMTs:** enable high-power, efficient amplifiers (5G, radar)
 - 2. GaAs pHEMTs:** enable ultra-low-noise LNAs (satellite, deep-space)
 - 3. SiGe BiCMOS:** enables integrated RF + digital ICs (Wi-Fi 7, automotive radar)
 - 4. MEMS RF Switches:** enable tunable filters & adaptive antennas
 - 5. Graphene / 2D Materials:** emerging devices for THz communication

6G / sub-THz (90–300 GHz) Circuits

1. 6G targets 90–300 GHz sub-THz spectrum
2. Enables Tbps data rates, ultra-low latency
3. Demands new device materials (GaN, InP, Graphene) and novel circuit techniques
4. Applications: holographic comms, high-resolution radar, terahertz imaging

Material Vs Strength Table

Material	High Power	Low Noise	Low Cost	Reconfigurable	THz Potential
GaN	Strong	Moderate	Weak	Moderate	Strong
GaAs	Moderate	Strong	Moderate	Weak	Moderate
SiGe	Moderate	Strong	Strong	Weak	Moderate
MEMS	Weak	Moderate	Strong	Strong	Weak
Graphene/2D	Strong	Strong	Weak	Strong	Strong

Microfabrication Design

- ❖ Micro-electro-mechanical system (MEMS)
- ❖ Microsystems Technology (MST)
- ❖ Micro machines
- ❖ Realizing moving mechanical parts at the
 - ❖ Microscopic Scale
 - ❖ Microelectromechanical System
 - ❖ Microscopic sensors
 - ❖ Actuators
 - ❖ Transducers

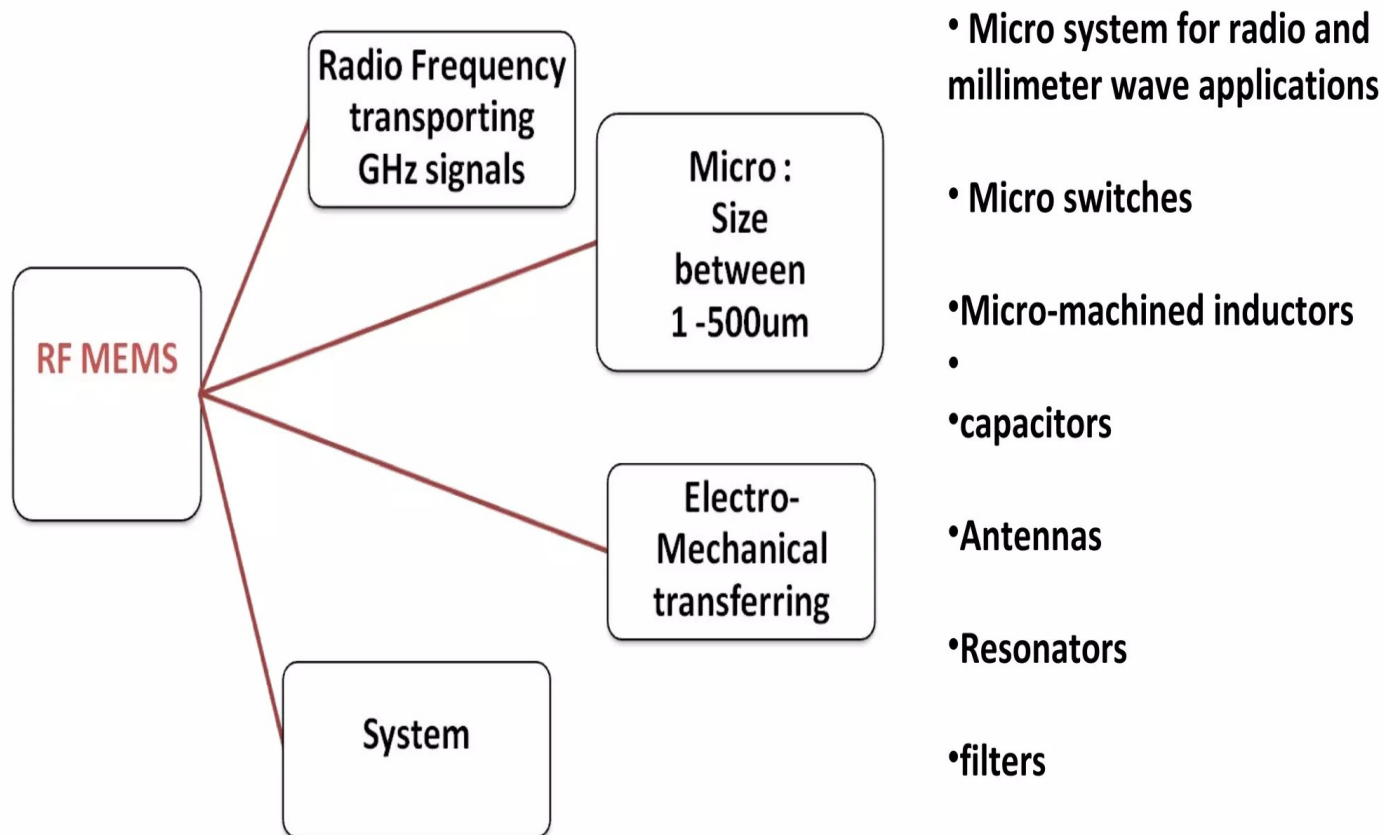
MEMS TECHNOLOGY

Applications of MEMS Technology



RF MEMS

Micro-electromechanical systems with electronic components comprising moving sub-millimeter-sized parts that provide radio frequency functionality.



RF and Microwave Circuit Design: Latest Trends and Techniques

- **Emerging RF/MW Applications:**
 1. High-throughput wireless/broadband communications
 2. Remote sensing and radar systems
 3. RFID and IoT connectivity
 4. AI/ML-assisted RF/MW devices
 5. Intelligent antennas with adaptive beam/polarization

AI/ML-Driven Design Automation

- AI/ML applied to circuit optimization, tuning, yield prediction
- Accelerates design space exploration
- Enables adaptive & self-healing RF systems
- Growing role in EDA tools (ADS, HFSS, CST)

RF and Microwave Circuit Design: Latest Trends and Techniques

- **Design Challenges for Future Applications:**
 1. Broadband for high data rates
 2. Robust spectrum utilization for multiband / cognitive communication
 3. Low-latency communication for V2V/V2X
 4. Compact integration of multi-functional components
 5. Thermal, parasitic, and system-level performance constraints

Infrastructure And Deployment Costs

- Deploying advanced communication infrastructure involves significant investment in hardware, software, and maintenance.
- Costs related to site acquisition, energy consumption, and skilled personnel present barriers, particularly in underserved or rural areas.
- Cost-effective, scalable solutions are needed for widespread adoption.