Resource Allocation and Spectrum Management in IOT

Agenda

- IOT
  - Wireless IOT
- Spectrum Management
- Resource Allocation
- Challenges and Opportunities
  - AI in Spectrum Management
  - AI in Resource Allocation
- Conclusion.

IOT

- The Internet of Things (IoT) can be defined as a world of interconnected things that are capable of sensing, actuating, and communicating among themselves and with the environment (i.e., smart things or smart objects).[1]
- In addition, IoT provides the ability to share information and autonomously respond to real/physical world events by triggering processes and creating services with or without direct human intervention. [1]

- An IoT system typically involves four main elements
  - Sensors/Devices
  - Connectivity
  - Data Processing
  - User Interface:

- Key Characteristics of IOT
  - Interconnectivity
  - Data Exchange
  - Automation
  - Unique Identifiers

Wireless IOT

- Wireless IoT is the concept of connecting physical devices, objects, and sensors to the internet using wireless communication technologies like Wi-Fi, Bluetooth, Zigbee, and cellular networks. These "things" collect and exchange data without physical cables, allowing for applications in smart homes, cities, healthcare, and agriculture. The specific wireless technology used depends on the application's needs for range, data rate, and power consumption [2]

- Common Wireless Technologies in IoT
  - WIFI, Bluetooth, Zigbee, cellular, etc..

Spectrum Management

- the process of efficiently allocating and using the limited radio frequencies for IoT devices to prevent interference, optimize performance, and ensure the success of the rapidly growing IoT sector
- Spectrum Management Challenges?
  - **Limited Spectrum:** The wireless spectrum is a finite and expensive resource.
  - **Static Allocation Inefficiency:** Traditional fixed-spectrum allocation leads to underutilized frequency bands.
  - **Congestion:** The sheer number of IoT devices creates significant network congestion and interference.
  - **Heterogeneous Traffic:** IoT networks must support a mix of low-power, low-data-rate devices and high-data-rate multimedia devices

Spectrum Management

- **Spectrum Access Technologies:**
  - **Orthogonal Frequency-Division Multiple Access (OFDMA):** Divides the spectrum into multiple sub-carriers for different users, managed by a base station.
  - **Random Access:** Devices compete for the same channel, as seen in protocols like LoRaWAN, which uses a random back-off mechanism to handle collisions.
  - **Time Division Multiple Access (TDMA):** Divides a channel into time slots, allocating a specific slot to each device.

Resource Allocation

- Process of strategically distributing resources like computational power, network bandwidth, and energy to IoT devices and applications to optimize performance, minimize costs, and ensure Quality of Service (QoS).
- Challenges – diverse devices, dynamic environments, etc.
- Goals - Load Balancing, Minimize Costs and Maximize Efficiency, Fairness
- What resources to be allocated?
  - Spectrum, Power, Time, Bandwidth, Computational Resources

Challenges and Opportunities

Resource Allocation Algorithms

- **Traditional Scheduling:** Centralized approaches where a base station or cluster head assigns resources to devices based on location or priority.
- **Game Theory:** Models resource allocation as a game where devices act as players and compete for resources.
- **Heuristic Algorithms:** Uses optimization techniques, like Improved Reptile Search Algorithm (IRSA) or Particle Swarm Optimization (PSO), to find near-optimal resource allocation solutions.
- **Machine Learning (ML):** Uses AI to learn optimal resource allocation policies from network data, balancing factors like energy and throughput.

Motivation of AI in Spectrum Management

- **Growing demand:** The proliferation of wireless devices and services in the 5G and 6G era has created an overwhelming demand for the limited radio frequency spectrum.
- **Limitations of static methods:** Traditional management techniques like fixed spectrum allocation often lead to underutilized frequency bands and cannot adapt to dynamic network conditions, resulting in spectral inefficiency.
- **Emergence of big data:** The increased availability of spectrum usage data, advanced algorithms, and powerful computing hardware have made AI a viable tool for complex network optimization.

AI in Spectrum Management

- **"AI in Spectrum Management" (tec@gov, 2024):** A study paper examining the use of AI in spectrum management, including planning, monitoring, and sharing. It highlights the potential of AI tools and techniques to address the spectrum crisis created by the proliferation of IoT devices and 5G.
- **"Machine Learning for Spectrum Sharing: A Survey" (arXiv, 2024):** This survey maps the state-of-the-art in machine learning for spectrum sharing, covering techniques for spectrum sensing, allocation, access, and handoff. It is relevant for understanding how various ML techniques are applied to address the complexity of spectrum management in current and next-generation networks.

AI in Spectrum Management

- **"A Systematic Literature Review of AI-enabled Spectrum Management (AISM)" (arXiv, 2024):** This paper provides a comprehensive overview of AI-enabled spectrum management methods. It reviews various learning models, data handling techniques, and performance metrics, addressing the research gap in consolidating advancements in this field as networks move towards 6G.
- **"Artificial Intelligence Empowering Dynamic Spectrum Access in Advanced Wireless Communications: A Comprehensive Overview" (MDPI, 2025):** This review examines the integration of AI in dynamic spectrum access for cognitive radio networks (CRNs). It discusses how deep learning is used for spectrum sensing and how multi-agent reinforcement learning (MARL) is used for distributed power allocation.
- **"AI-Enhanced Spectrum Sensing Cognitive Radio Networks: Revolutionizing 5G and Beyond" (Taylor & Francis Online, 2025):** This paper offers a comparative study of conventional versus AI-based spectrum sensing techniques, demonstrating the superior performance of AI-driven approaches in optimizing spectrum performance for 5G and future wireless communication systems.

AI in Resource Allocation

- transforms how resources are managed, moving away from static, predefined rules to dynamic, intelligent, and context-aware decisions. This shift is crucial for optimizing the performance of diverse and resource-constrained IoT devices in complex, dynamic network environments.[2]
- The primary motivations for using AI in IoT resource allocation
  - **Data Handling:** are to manage vast data volumes.
  - **Efficiency:** improve efficiency and responsiveness in dynamic environments
  - **Real-time optimization:** of limited resources like bandwidth, computing power, and energy.
  - AI enables IoT systems to learn, predict, and automate resource distribution to meet changing demands, reduce costs, and support scalable, resilient, and intelligent infrastructure

AI in Resource Allocation

- Spectrum allocation
  - ML addresses the scarcity of radio spectrum by enabling more efficient and dynamic sharing.
  - **Cognitive radio:** ML-powered Cognitive Radio Networks (CRNs) can sense the spectrum in real-time to identify and use unused frequency bands, or "white spaces," without interfering with licensed users.
  - **Prediction models:** Supervised learning algorithms, like Support Vector Machines (SVMs), can be trained on historical spectrum usage data to predict channel availability and traffic patterns.
  - **Reinforcement learning (RL):** RL agents can learn optimal spectrum allocation policies over time by interacting with the network environment, maximizing throughput and minimizing latency.

AI in Resource Allocation approaches

- **Supervised learning:** Uses labeled data to train models that predict resource needs based on network conditions and device behaviors. This is effective for forecasting demand or classifying channel availability. In predicting resource needs in IoT clusters.
- **Reinforcement learning (RL):** Uses a reward-based system where an "agent" learns the optimal policy for making decisions over time. This is well-suited for dynamic, real-time resource allocation problems like spectrum assignment.
- **Federated learning (FedML):** A distributed ML approach where model training occurs collaboratively across many devices while keeping data localized. This addresses privacy concerns and reduces communication costs associated with sending massive amounts of data to a central server.
- **Deep learning (DL):** Utilizes multi-layered neural networks to learn complex patterns in network data, leading to more accurate predictions and optimization in real time, especially in dense IoT deployments.

AI in Resource Allocation

- **Resource Allocation for Task-Oriented Generative Artificial Intelligence in Internet of Things[**J. Feng,2025] this proposes leveraging a heterogeneous computing environment and a specialized Hierarchical Soft Actor-Critic with an Intrinsic Curiosity module (HSAC-IC) algorithm to optimize resource allocation, task scheduling, and computing frequencies under strict latency constraints. Simulation results indicate the HSAC-IC scheme outperforms other methods, effectively meeting GAI service requirements and minimizing service generation costs.
- **"Deep Reinforcement Learning-Based Resource Allocation in Distributed IoT Systems" (arXiv, 2025):** This paper introduces a framework for training DRL models in distributed IoT environments. IoT devices use a DRL-based method to select communication channels, with the model trained using real-world data and feedback (ACK) from actual transmissions. It focuses on the practical implementation and performance evaluation in terms of frame success rate.

AI in Resource Allocation

- **"AI-Driven Resource Allocation for RIS-Assisted NOMA in IoT Networks" (IEEE, 2025):** This study proposes a DRL-based resource allocation framework for uplink IoT networks. It addresses complex optimization challenges in non-orthogonal multiple access (NOMA) networks by allowing an agent to autonomously adapt transmit power and modulation based on dynamic network conditions to maximize throughput.
- **“AI-Based Resource Allocation Techniques in Wireless Sensor Internet of Things Networks in Energy Efficiency with Data Optimization” (MDPI 2022):**an AI-based framework combining deep learning and metaheuristic algorithms to optimize energy and spectral efficiency in wireless sensor IoT networks. The research resulted in an energy-efficient protocol balancing these objectives through optimal power allocation and relay selection

Research Focus.

- **Computational Resource Demands:** Requires significant processing power, especially for complex DL models.
- **Need for Real-world Data:** Overcoming the scarcity of high-quality, practical datasets.
- **Energy Efficiency and Sustainability**
- **Adversarial Attacks:** New security threats targeting AI models and datasets.
- **Ethical Concerns:** Issues of transparency, bias, and privacy in AI-driven decisions.
- **Lightweight AI Models:** Developing energy-efficient models suitable for low-power devices.
- **Explainable AI :** Increasing the transparency of AI decision-making

Additional References

1. **Introduction to the Internet of Things (**https://ieeexplore.ieee.org/document/8390728**)**
2. An Overview of Machine Learning-Driven Resource Allocation in IoT Networks (https://arxiv.org/pdf/2412.19478)

Thanks