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ARTICLE

# Making Antennas for 6G

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**Abstract**
The impending advent of 6G technology heralds a new era in wireless communication, promising unprecedented data transmission speeds and wider network coverage. As the global demand for faster and more reliable internet connectivity grows, the development of advanced antennas suitable for 6G is becoming increasingly critical. This abstract delves into the innovative methodologies and materials involved in making antennas capable of meeting the requirements of 6G networks. Current research focuses on utilizing novel materials and designs to enhance the performance of 6G antennas. Metamaterials, possessing unique electromagnetic properties not found in naturally occurring materials, are pivotal in this development. They enable the construction of ultra-thin, highly efficient antennas that operate effectively at the higher frequency bands proposed for 6G, which are crucial for achieving the technology's potential. Moreover, the integration of smart antenna technologies, such as Massive MIMO (Multiple Input Multiple Output) and beamforming, is essential. These technologies adaptively direct and focus energy to improve signal reception and reduce interference, which is vital in the densely populated network environments expected with 6G deployment. This paper presents a comprehensive review of recent advancements in antenna technology, including the exploration of new materials, innovative design techniques, and the incorporation of smart systems, all aimed at supporting the robust infrastructure required for 6G wireless networks.

**Keywords:** 6G Antenna Technology; Beamforming; High-Frequency Bands; Massive MIMO; Metamaterials; Smart Antennas; Wireless Communication

**Abbreviations:** AiP: Antenna-in-Package, AR: Augmented reality, EMCT: European Microelectronics and Communication Technologies, HAPS: High Altitude Platform Stations, IoT: Internet of Things, MIMO: Multiple-Input Multiple-Output, RAN: Radio Access Network RF: Radio-Frequency, UAV: Unmanned Aerial Vehicles, VR: Virtual reality

## 1. The Cyber-Physical Continuum Vision

Antennas serve as crucial components for enabling wireless communications in networks like 5G and the forthcoming 6G systems. As we approach the era of 6G, substantial research and development efforts are underway to design antennas, Radio-Frequency (RF) front-ends, and characterize wave propagation intended for frequencies ranging from 100 GHz to 1 THz [1, 2, 3]. Making antennas for 6G requires exploring innovations such as massive antenna arrays, lens antennas, filter design, ultra-massive Multiple-Input Multiple-Output (MIMO), metasurface-based antennas, and reconfigurable intelligent surface technologies. Techniques like Antenna-in-Package (AiP) and on-chip antenna integration will be essential, necessitating high-performance interconnections, feed networks, and manufacturing tolerances. Additionally, sustainable green electronics introduce new rules for antenna and RF front-end development, driving the need for innovative multidisciplinary investigations, theoretical models, and experimental validation [4, 5, 6, 7].

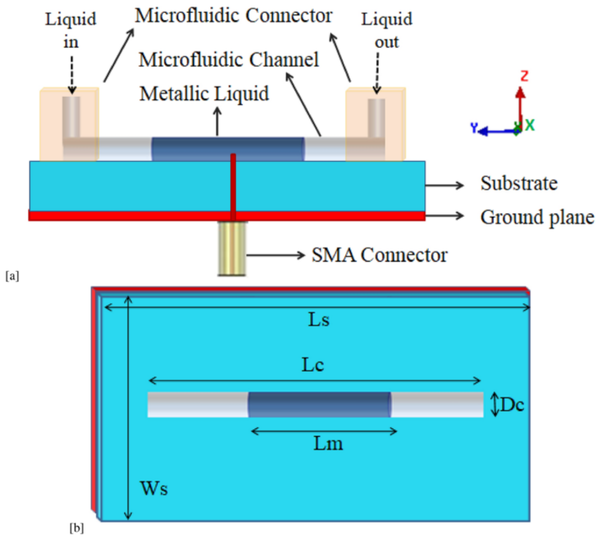


**Figure 1.** metallic liquid in sub-6 GHz antenna.

From the Fig. 1, the vision of 6G technology revolves around enabling a seamless "cyber-physical continuum" where the digital and physical worlds are tightly integrated, allowing for real-time data exchange and interaction between connected devices, machines, vehicles, and infrastructure. This concept aims to create a unified reality where people and things can move freely between the connected physical world and its programmable digital representation [8].

Key aspects of this cyber-physical continuum vision include:

1. **Limitless Connectivity:** 6G will provide ubiquitous, high-speed, and low-latency connectivity, enabling seamless communication between various entities in the cyber-physical realm.
2. **Cognitive Networks:** 6G networks will be intelligent and adaptive, capable of learning and optimizing themselves based on real-time data and user requirements.
3. **Network Compute Fabric:** 6G will integrate compute services, offering functionality beyond just communication, such as spatial and timing data processing.
4. **Trustworthy Systems:** Ensuring the security, privacy, and resilience of the cyber-physical continuum will be a crucial aspect of 6G, enabling trustworthy and dependable systems.

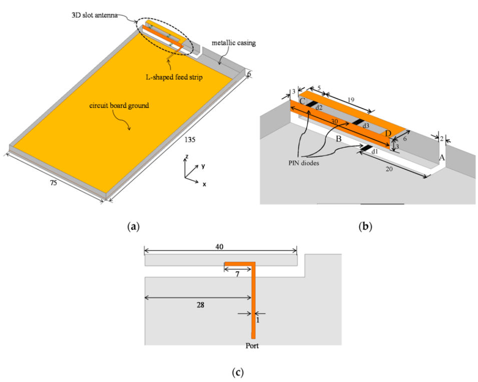


**Figure 2.** Reconfigurable 3-D Slot Antenna.

The realization of this cyber-physical continuum will unlock a wide range of use cases, including as given in Fig. 2:

- Internet of Senses: Enabling immersive experiences by seamlessly integrating digital and physical sensory inputs.
- Connected Intelligent Machines: Facilitating real-time coordination and control of autonomous systems, such as self-driving vehicles and industrial robots.
- Connected Sustainable World: Optimizing resource utilization and enabling sustainable practices through real-time monitoring and management of physical systems.

To achieve this vision, 6G technology will need to push beyond the technical limits of 5G, incorporating capabilities such as higher data rates, lower latency, expanded spectrum usage, extreme energy efficiency, and high-precision positioning and sensing. Antennas and antenna systems will play a crucial role in enabling this cyber-physical continuum, facilitating the seamless integration of digital and physical worlds [9, 10].

## 2. Ubiquitous Distributed Massive MIMO

One of the key technologies being explored for 6G is ubiquitous distributed Massive MIMO (Multiple-Input Multiple-Output). This concept involves distributing antennas across a wider area, rather than concentrating them in a single location [11, 12, 13, 14, 15, 16, 17]. By doing so, several benefits can be achieved:

1. Improved Coverage and Mobility: With antennas distributed over a larger area, the system can provide more consistent and reliable coverage, even in areas with obstructions or interference. This is particularly important for enabling seamless mobility in the cyber-physical continuum, where devices and systems need to maintain uninterrupted connectivity as they move.
2. Higher Bandwidth and Capacity: Distributed Massive MIMO allows for more efficient utilization of the available spectrum, enabling higher data rates and increased capacity to support the bandwidth-intensive applications envisioned for 6G.
3. Enhanced Beamforming and Spatial Multiplexing: By coordinating the transmission and reception of signals from multiple distributed antennas, advanced beamforming techniques can be employed to focus the signal energy more precisely, reducing interference and enabling spatial multiplexing for multiple users or devices.

Ericsson, a leading telecommunications company, is at the forefront of research and development efforts in this area as mentioned in Fig. 3. According to [18], Ericsson is working on distributed MIMO systems with synchronized distributed antennas to improve coverage and mobility for 6G. Additionally, the company is advancing the concept of distributed Massive MIMO, where antennas are distributed across a wider area to enable higher bandwidth and capacity [19].

Antennasplay a crucial role in realizing the potential of ubiquitous distributed Massive MIMO. Advancements inantenna systems, such as compact and efficient antenna designs, precise beamforming capabilities, and seamless integration with other components, will be essential for the successful deployment of this technology in 6G networks [20, 21].

## 3. High-Precision Localization and Integrated Sensing

Ericsson is at the forefront of research efforts to integrate localization, sensing, and imaging capabilities into the 6G radio system and antennas. This innovative approach aims to enable real-time mapping of the environment, which is crucial for realizing the cyber-physical continuum vision of 6G [22].

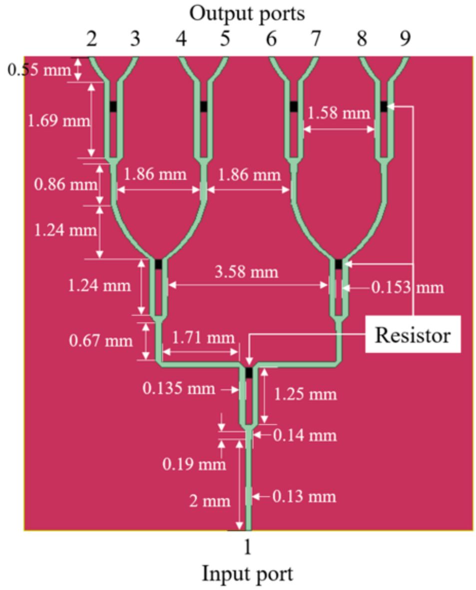


**Figure 3.** Triple-Band (DSRC, 5G, 6G) Antenna.

The key aspects of this integrated localization, sensing, and imaging technology include:

1. **Precise Positioning:** By leveraging the radio signals and advanced antenna systems, 6G networks can achieve highly accurate positioning and localization capabilities. This enables a wide range of applications, such as:
   - Seamless navigation and tracking of autonomous vehicles and drones
   - Precise asset tracking and inventory management in industrial and logistics settings
   - Enhanced location-based services for consumer applications
2. **Environmental Sensing:** The 6G antenna systems can be designed to sense and map the surrounding environment in real-time. This capability can be utilized for:
   - Obstacle detection and avoidance for autonomous systems
   - Building information modeling and construction site monitoring
   - Environmental monitoring and disaster response
3. **Integrated Imaging:** By combining the localization and sensing data, 6G networks can create detailed 3D maps and images of the environment. This integrated imaging capability has numerous applications, including:
   - Augmented reality (AR) and virtual reality (VR) experiences
   - Remote monitoring and inspection of infrastructure and facilities
   - Enhanced situational awareness for emergency services and first responders

Ericsson's research efforts in this area focus on developing advanced antenna systems and signal processing techniques to enable these integrated localization, sensing, and imaging capabilities within the 6G network infrastructure as shown in Fig. 4. By seamlessly integrating these functionalities, 6G aims to provide a comprehensive and real-time understanding of the physical world, enabling a truly seamless cyber-physical continuum [23, 24, 25].

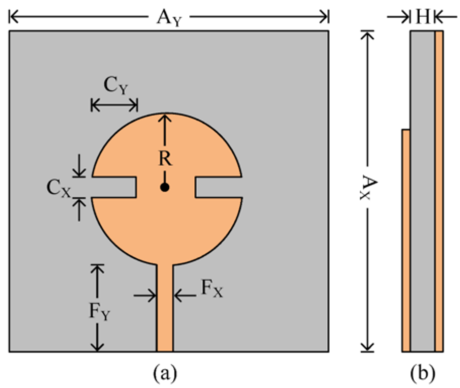


**Figure 4.** Compact Broadband Antenna.

## 4. Universal Cellular Coverage: Ground, Air, and Satellite

Ericsson is at the forefront of developing innovative antenna concepts that enable seamless connectivity across ground, air, and satellite networks, paving the way for ubiquitous cellular coverage in 6G systems. This comprehensive approach aims to merge terrestrial, aerial, and space-based communication infrastructures, ensuring uninterrupted connectivity for a wide range of applications and devices [26].

One key area of focus is the integration of unmanned aerial vehicles (UAVs) into the cellular network. Ericsson is exploring antenna designs that can facilitate reliable and efficient communication with UAVs, such as drones [27, 28]. By incorporating aerial vehicles into the 6G ecosystem, a multitude of use cases can be enabled, including:

1. **Aerial Surveillance and Monitoring:** UAVs equipped with advanced sensors and cameras can provide real-time monitoring and surveillance capabilities for various applications, including:
   - Environmental monitoring and disaster response
   - Infrastructure inspection and maintenance
   - Agricultural monitoring and precision farming
2. **Delivery and Logistics:** Autonomous drones can be utilized for efficient and rapid delivery of goods, particularly in areas with challenging terrain or limited accessibility.
3. **Emergency Response:** UAVs can play a crucial role in emergency situations, assisting in search and rescue operations, providing situational awareness, and delivering essential supplies to affected areas.

In addition to supporting aerial connectivity, Ericsson's antenna concepts aim to seamlessly integrate satellite communications into the 6G network architecture as per Fig. 5. This approach ensures universal cellular coverage, even in remote or underserved areas where terrestrial infrastructure may be limited or non-existent [29, 30]. By leveraging satellite connectivity, 6G networks can provide reliable and high-speed communication services to:

- Remote communities and rural areas
- Maritime and aviation sectors
- Disaster-affected regions

The integration of satellite connectivity not only expands the reach of 6G networks but also intro-

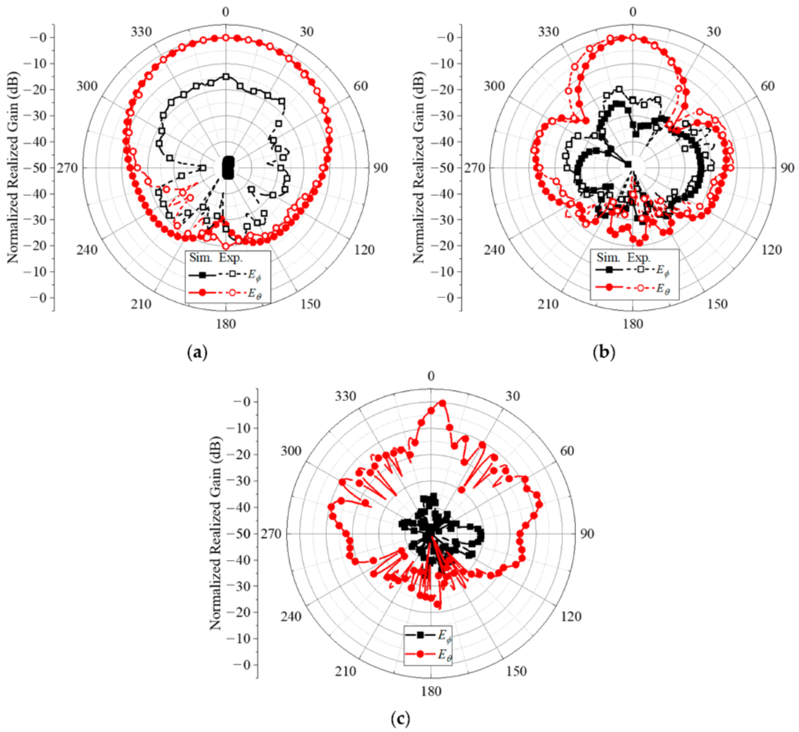


**Figure 5.** DSRC, 5G, 6G Antenna for Autonomous Vehicle Telematics.

duces new opportunities for applications such as:

- Global asset tracking and monitoring
- Telemedicine and remote healthcare services
- Real-time environmental monitoring on a global scale

Ericsson's research and development efforts in this domain involve exploring advanced antenna designs, beamforming techniques, and signal processing algorithms to enable seamless handover and roaming between terrestrial, aerial, and satellite networks. By combining these diverse communication channels, 6G aims to provide truly ubiquitous and uninterrupted connectivity, laying the foundation for a fully integrated cyber-physical continuum [31, 32].

## 5. Antenna Design Challenges and Advancements

The development of antennas for 6G systems presents several challenges and opportunities for innovation. Researchers are actively exploring groundbreaking technologies to address the unique requirements of 6G networks [33].

1. **Universal Metasurface Antennas:** A team led by Professor Chan Chi-hou at City University of Hong Kong (CityU) has developed the world's first 'universal metasurface antenna' capable of independently and simultaneously manipulating all five fundamental properties of electromagnetic waves: amplitude, phase, frequency, polarization, and direction [34, 35]. This breakthrough technology has immense potential for 6G wireless communication systems, enabling advanced waveform manipulation capabilities, enhanced security features for integrating sens-

ing and communications, and applications in large-capacity, high-security information systems, real-time imaging, and wireless power transfer [36].

2. **Collaborative Research Efforts:** Significant advancements in antenna technology often require collaborative efforts between academic institutions and industry partners. For instance, the universal metasurface antenna was developed through a collaboration between CityU and Southeast University in Nanjing, China, involving researchers from both institutions [37]. Similarly, Ericsson Antenna System is leading research efforts in areas like distributed Massive MIMO, integrated localization and sensing, and universal cellular coverage, collaborating with industry and academic partners on projects like MECT, MassIMO, KOMSENS-6G, and 6G Sky [38].
3. **Frequency Band Expansion and Reconfigurable Antennas:** 6G networks will require deployment on new frequency bands, particularly cmWaves (7-15 GHz), and potentially sub-terahertz frequencies in the future [6]. To address this, Ericsson is developing early technology for 6G Massive MIMO radios, which can increase network throughput with the least energy consumption and are a key technology for 6G mobile networks [13]. Additionally, antennas for 6G need to be able to reconfigure on-demand to adapt to network and traffic changes in real-time, through novel designs and intelligent metamaterials [39] as described in Table 1.

**Table 1.** Key challenges and innovations of THz antennas

| Key Challenges | Innovations |
|---|---|
| Developing fabrication and measurement techniques for THz antennas | Universal meta surface antennas capable of manipulating wave properties |
| Achieving high efficiency and beam-steering capabilities at THz frequencies | Collaborative research efforts between academia and industry |
| Integrating antennas with THz electronic components | Reconfigurable antennas using intelligent metamaterials |
| Compact size, wide bandwidth, and high gain for 6G antennas | Exploration of new frequency bands like cm Waves and sub-THz |

As the demand for wireless connectivity grows, with potentially trillions of IoT devices linked together at millimeter wave frequencies in 6G [40], antennas for 6G systems must be electrically sound, mechanically robust, and miniature in size to fit tight spaces while meeting demanding specifications [41]. Leading OEMs and companies like Benchmark, with expertise in next-gen communications, advanced computing, and aerospace/defense, are well-positioned to support the development of innovative antenna solutions for 6G.

## 6. Collaborative Research Efforts

Ericsson has a strong focus on collaborative research efforts to drive advancements in 6G antenna technology. With over 500 engineers and researchers dedicated to 6G antenna R&D across its global R&D centers [36], the company is leveraging its expertise from previous generations of networks to tackle the challenges of 6G.

1. **European Microelectronics and Communication Technologies for 6G (EMCT) Project:** Ericsson will receive 5-year funding from Germany's Ministry of Economic Affairs and Climate Action for its EMCT project [13]. This project is part of the European Union's Important Project of Common European Interest on Microelectronics and Communication Technologies (IPCEI-ME/CT) initiative, which will provide up to EUR 8.1 billion in public funding [13]. The EMCT

project aims to develop key technologies for 6G, including advanced antenna systems and radio frequency (RF) components.
2. **REINDEER Project:** Ericsson is a key participant in the EU-funded REINDEER project, which aims to develop a new smart connect-compute platform critical for future 6G systems [16]. The project will focus on developing 'RadioWeaves' technology, a new wireless access infrastructure consisting of a fabric of distributed radio, compute, and storage [16]. This innovative approach aligns with Ericsson's research efforts in areas like distributed Massive MIMO and integrated localization and sensing.
3. **Collaborations with Academic Institutions:** Ericsson has a long-standing track record of research collaboration with leading universities, such as Linköping University and Lund University. These collaborations have achieved technological milestones in areas like Radio Stripes and Massive MIMO [16], which are foundational technologies for 6G antenna systems as given in Table 2.

**Table 2.** Collaborative developments of major organizations

| Collaborative Project | Focus Area |
|---|---|
| EMCT | Advanced antenna systems and RF components |
| REINDEER | Distributed Radio Weaves infrastructure |
| Academic Collaborations | Radio Stripes, Massive MIMO, and other key technologies |

Through these collaborative research efforts, Ericsson aims to leverage the collective expertise of industry partners, academic institutions, and public funding initiatives to drive innovation and address the complex challenges associated with developing antenna systems for 6G networks.

## 7. Energy Efficiency and Site Footprint Optimization

Ensuring energy efficiency and optimizing site footprints are crucial considerations in the development of 6G networks and antenna systems. The Internet of Things (IoT) ecosystem, which will play a pivotal role in realizing the cyber-physical continuum vision of 6G, poses significant challenges in terms of energy optimization due to the limited energy resources of IoT devices and the substantial aggregate energy consumption of IoT networks [16].

A significant portion of an IoT device's energy is consumed by the radio sub-system. With the emergence of 6G, energy efficiency has become a major design criterion to improve IoT network performance [16]. Researchers have proposed optimization techniques to address this challenge, formulating the problem as a mixed-integer nonlinear programming problem, which is NP-hard. This problem is solved using fractional programming properties, Lagrangian decomposition, and an improved Kuhn-Munkres algorithm [16]. The proposed technique significantly improves the energy efficiency of IoT systems compared to the state-of-the-art work [17], addressing key challenges such as channel uncertainty, limited energy resources of IoT devices, and the need for energy-efficient 6G-IoT ecosystems [17] as shown in Fig. 6.

Another approach to enhancing energy efficiency involves the integration of High Altitude Platform Stations (HAPS) into the Radio Access Network (RAN) for 6G networks. Simulation results show that HAPS can significantly reduce energy consumption by up to almost 30% by exploiting the advantages of HAPS, such as self-sustainability, high altitude, and wide coverage [18]. The authors analyze the impact of different system parameters on performance, including:

- Elevation angle

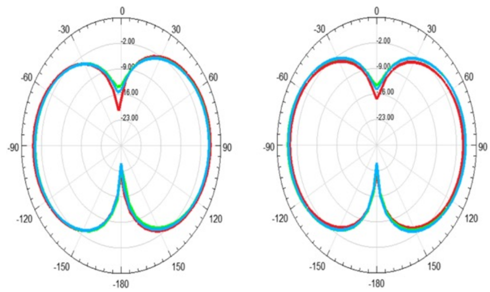

**Figure 6.** Terahertz Micro-Strip Patch Antenna.

- Percentage of traditional buildings
- Portion of indoor users

The results indicate that a larger elevation angle, higher proportion of traditional buildings, and fewer indoor users lead to higher energy savings, with the elevation angle having the most significant impact [18]. Even with only a small fraction of traffic (6.64% to 16.34%) offloaded to the HAPS, substantial energy savings can be achieved due to the non-load dependent energy consumption.

Artificial Intelligence (AI) and Machine Learning (ML) are poised to play a crucial role in addressing the energy efficiency challenges of 6G networks. 6G networks will need to deliver much more data at faster rates while still meeting stringent energy-efficiency goals, requiring the required energy for transmitting a bit to be significantly reduced. One key technology to achieve this is AI/ML, which can be built into the 6G air interface from the ground up, creating an 'AI-native air interface' that can dramatically improve the efficiency of the network. The potential benefits of this approach include:

- ML boosting 6G spectral efficiency by eliminating the need for reference symbols, improving efficiency by nearly 20% compared to 5G.
- Neural networks tolerating hardware flaws rather than avoiding them, allowing amplifier modules to operate more efficiently and leading to considerable power savings.
- AI/ML learning better medium access protocols to improve spectral efficiency and create more energy-efficient links.
- The AI-native 6G air interface achieving up to a 50% reduction in transmit power over 5G for the same bandwidth and data rate.
- AI/ML creating flexibility to align network power consumption with the CO2 targets of the country it is deployed in, making 6G networks more sustainable.
  The AI-native air interface will be a crucial component in building sustainable 6G technologies, maximizing efficiency while adhering to global ecological goals.

## 8. Ericsson Antenna System's R&D Capabilities

Ericsson has a dedicated team of over 500 engineers and researchers focused on 6G antenna R&D across its global R&D centers. Their efforts are centered on continuous improvements to Ericsson's passive and active antenna portfolio [6], ensuring that the company stays at the forefront of antenna technology advancements for 6G networks.

The research and development initiatives are spearheaded by Dr. Magnus Frodigh, the Vice President and Head of Ericsson Research. With over 30 years of experience in mobile technology research and development, spanning from 2G to 6G, Dr. Frodigh brings a wealth of expertise to the table. His contributions to the field are further evidenced by his impressive portfolio of 29 patents as mentioned in Fig. 7 [9].

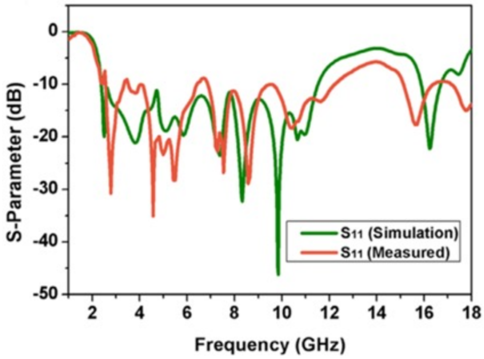


**Figure 7.** MIMO Antennas for 5G and 6G Wireless Systems.

Under Dr. Frodigh's leadership, Ericsson's 6G antenna R&D efforts encompass several key areas:

1. **Distributed Massive MIMO:** Developing advanced antenna systems for distributed Massive MIMO architectures, enabling improved coverage, mobility, and capacity through the strategic placement of antennas across a wider area.
2. **Integrated Localization and Sensing:** Exploring innovative techniques to integrate localization, sensing, and imaging capabilities directly into 6G antenna systems, enabling real-time mapping and understanding of the environment.
3. **Universal Cellular Coverage:** Designing antenna concepts that facilitate seamless connectivity across ground, air, and satellite networks, ensuring ubiquitous cellular coverage for a wide range of applications and devices.
4. **Energy Efficiency and Site Footprint Optimization:** Prioritizing energy efficiency and site footprint optimization through advanced antenna designs, leveraging techniques such as AI/ML and the integration of High Altitude Platform Stations (HAPS) into the Radio Access Network (RAN).
5. **Collaborative Research Efforts:** Engaging in collaborative research projects with industry partners, academic institutions, and public funding initiatives to drive innovation and address the complex challenges associated with developing antenna systems for 6G networks.

Ericsson's extensive R&D capabilities, coupled with its commitment to collaborative research efforts, position the company as a leading force in shaping the future of 6G antenna technology. By continuously pushing the boundaries of what is possible, Ericsson aims to enable the seamless integration of digital and physical worlds envisioned in the cyber-physical continuum of 6G networks.

## 9. Conclusion

The cyber-physical continuum vision of 6G networks presents an exciting and transformative prospect, seamlessly integrating the digital and physical worlds. Antennas and antenna systems play a pivotal role in realizing this vision, enabling ubiquitous connectivity, high-precision localization, and integrated sensing capabilities. Through advancements in technologies like distributed Massive MIMO, metasurface antennas, and reconfigurable antenna designs, the industry is paving the way for a future where limitless connectivity and real-time data exchange between devices, machines, and infrastructure become a reality. Collaborative research efforts, involving industry leaders like Ericsson, academic institutions, and public funding initiatives, are driving innovation in 6G antenna technology. By addressing challenges such as energy efficiency, site footprint optimization, and the exploration of new frequency bands, these collaborative endeavors are laying the groundwork for a sustainable and high-performance 6G ecosystem. As the world inches closer to the realization of the cyber-physical continuum, the development of cutting-edge antenna solutions will play a crucial role in unlocking the full potential of 6G networks.

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