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Introduction

Wireless technology has been evolving and advancing at an astonishing rate over the past four decades. The amount of development and accomplishments that the wireless industry has achieved is beyond imagination, and no one 40 years ago would have predicted the level of advancement we are experiencing nowadays. What is more, new frontiers and developments are underway to even go beyond some of the fundamental laws that have predicted the technology trends thus far. Wireless technology has relied heavily on advancements in electronics, algorithms, and RF front-ends and antenna systems. Moore's law has been driving the electronics and chip industry for several decades but recently has been overcome by the rapid development of computing power. The need for multi-band, and multi-functional RF front-ends and antenna systems has become a reality nowadays with smaller footprints and higher efficiencies. Our cell phones today have more computing, connectivity, and functionality than complete computers of the past decade.

This rapid technological advancement has been noticeable in every aspect of our daily lives. We are living in smart homes, driving smart cars, using smart phones, and living in smart cities, and these are keeping us aware and connected to our loved ones, assets, and work at any time. Internet coverage is covering more ground with satellite services that are now providing services to remote areas. This has increased the safety aspects of our lives and improved our decision-making and selection capabilities. We can always track our kids, follow up with coworkers, and perform our duties in a much more efficient way that can save a lot of time and effort. The need for more data and connectivity has been increasing exponentially every year (see Figure 1.1), thus pushing the need for rapid improvements on the device and network levels.

While a wireless system depends on RF connectivity, fast and efficient hardware and software components, displays, and control devices, the RF front-ends and antenna systems also play a major role in providing a reliable connection with the network. The very first component of the RF front-end is the antenna system.

MIMO Antenna Systems for 5G and Beyond, First Edition.
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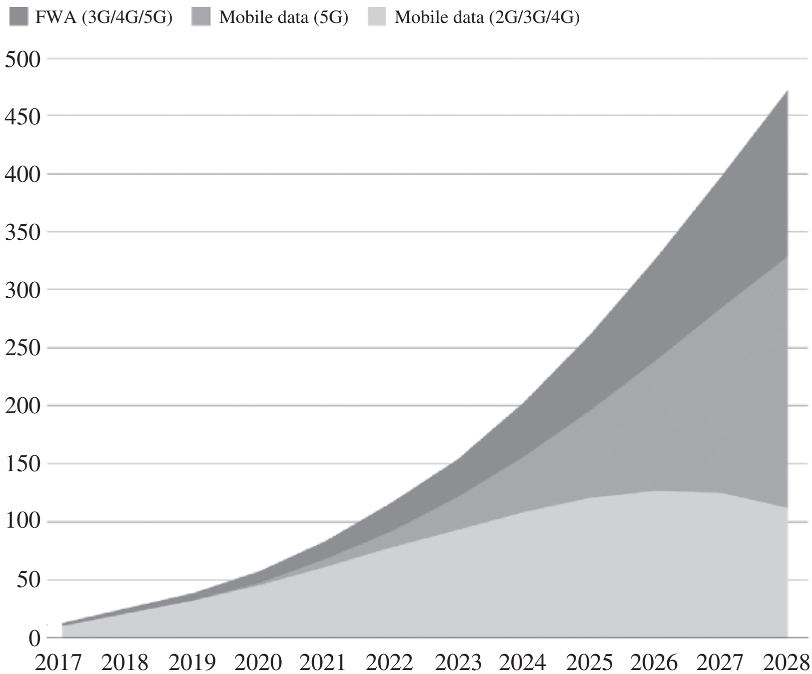

Figure 1.1 Global mobile network traffic in Exabytes (EB) per month. Source: Adapted from Ref. [1].

Antennas are the signal converters that convert the electrical signal from the electronics of your device (i.e., your data, whether you are browsing a web page or making a phone call) into an electromagnetic waveform that can travel in the air from your device to the receiving serving station (i.e., a cell phone tower, a wireless local area network access point, or your car radio via Bluetooth). The antenna can transmit your data to the base station, or receive data from the base station (i.e., it is a reciprocal element). Proper design of such antenna systems is essential to having a proper connection in any wireless system.

Antenna systems' design and development is a combination of science and engineering art. Their characteristics are affected by various parameters such as size, material, shape, surroundings, and types, among many others, and have to be carefully designed and characterized. Careful integration with other system components is critical after the initial design and verification phase is completed to fulfil the expected performance and metrics. While single antenna wireless systems were adopted in the first three wireless generations (i.e., first, second, and third), the fourth generation introduced a new paradigm of wireless communications. It is based on sending multiple data streams to improve the system capacity (data rates) and combat the degradation from multipath signals that exist in all modern environments. This new paradigm is called MIMO communications, which require the existence of multiple antenna systems at the receiver and the transmitter sides. The introduction of multiple antennas in small form factor devices poses serious challenges to make such systems a complete success and achieve the desired high capacity.

This book focuses on the design and engineering of antenna systems for current and future wireless technologies and standards. While the antenna concepts and examples in this book focus on the current 5G requirements and use cases, they are equally applicable to any other wireless standards, as the fundamental aspects of antennas are to be satisfied regardless of the targeted technology. MIMO antenna systems in particular will be given special attention in addition to millimeter-wave (mm-wave) solutions for 5G and beyond.

1.1 Wireless Technology Evolution

While wireless technology evolution is usually associated with different cellular telephony generations, several other factors have driven wireless technology evolution and fast advancement, especially in the past two decades. Among others, additive manufacturing, ultra-scale integration, automation and cost reduction, and fast computing power via the dense integration of processor cores and fabricating nanoscale transistors have contributed heavily toward the level of the technology we have today.

First-generation (1G) cellular technology appeared in the 1980s and relied on the advanced mobile phone system (AMPS) that provided voice-only services to mobile terminals. This was a purely analog technology. The antennas used were whip structures such as helical- or monopole-based ones that protruded from the device. A decade later, technology started to advance more in the digital domain and the global system mobile (GSM) was introduced, resulting in new mobile terminals introduced to the consumer market. It is based on digital techniques that allow the transmission of voice and data (mainly text) with data rates up to 270 kbps. This was considered the second generation of cellular technology (2G). GSM systems were based on time division multiple access (TDMA). Integrated printed antennas started to appear in some models in 2G mobile terminals, at the same time with smaller form factor devices. This is due to the large-scale integration of functionality in the components used.

The addition of multimedia features and incorporation of diversity techniques appeared in the third generation of wireless cellular technology (3G) in the early 2000. Wideband code division multiple access (WCDMA) technology was incorporated and provided wider bandwidths that allowed data transfers in the tens of Mbps. Internet browsing and online gaming became a reality for the first time. International roaming and more secure protocols were utilized. Antenna systems that are or printed fashion were used and multiple functionalities were supported by dedicated antennas, i.e., global positioning system (GPS), wireless local area networks (WLAN), etc.

The introduction of MIMO technology was the driver for 4G. While MIMO was the main focus of 4G, several advancements in modulation and coding and access techniques provided a noticeable capability improvement over 3G that allowed for ultra-fast data transfers in excess of 80 Mbps, making it 20 times faster than its predecessor. MIMO takes advantage of the multipath phenomena that were not very favorable in 3G systems. It creates multiple signal paths that can significantly improve the amount of data transferred within the same frequency band and transmission power levels. Long-term evolution (LTE) networks were built around MIMO technology where multiple antennas on the mobile terminal and multiple antennas in the base station are used to support a communication link. Placing multiple antennas on the mobile terminal is very challenging and needs careful attention to changes in antenna parameters such as isolation and field correlation. These aspects will be discussed in detail in the coming chapters.

The fifth-generation (5G) standard came to provide another leap in connection speeds reaching Gbps levels, with a new paradigm that provides a much broader connectivity framework with three vertices – one focusing on enhanced mobile broadband (eMBB), second providing ultra-reliable low-latency communications (URLLC) that consider fast decision-making features (in autonomous cars for example), and third is the massive machine-type communications (mMTC). For the eMBB which is used for cellular networks, two bands were selected to support 5G requirements; the sub-6 GHz band, also known as frequency range 1 (FR-1), and millimeter-wave band (mm-wave) also called frequency range 2 (FR-2). As there are multiple frequency bands with a large frequency ratio, two sets of antenna systems are expected to support each, in addition to several copies of each to support MIMO. With this, we can imagine how the antenna systems will be packed within a mobile terminal with limited space, and thus this becomes a very challenging problem. This book provides several solutions to 5G-enabled designs. Also, mm-wave bands need antenna arrays with higher gains to overcome the free space path loss (FSPL). Thus, careful integration and array

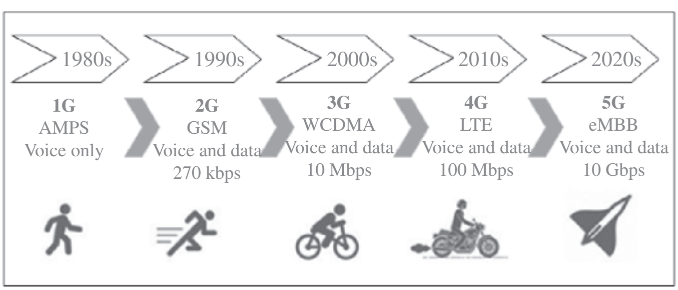

Figure 1.2 Wireless standard evolution from 1G to 5G and their main features.

designs with beam steering/switching are required. A summarizing figure that compares the differences in the services and speeds of various wireless cellular generations is shown in Figure 1.2

Currently, we are thinking beyond 5G or the sixth-generation (6G) wireless standard and its underlying technologies. Key features that are being considered are the use of sub-THz bands for extremely high data transfers of 100 Gbps at short distances, virtual reality (VR) and augmented reality (AR), the use of visible light communications (VLC), utilization of smart programmable radio environments such as reconfigurable intelligent surfaces (RIS), the use of non-terrestrial networks (NTNs), and pervasive artificial intelligence (AI) techniques to make networks smarter and faster. This framework includes so many new technologies that need seamless integration and interconnection to be able to communicate with each other, and that is why this is a hot area of current research and development. Figure 1.3 shows some of the use cases beyond 5G or 6G use cases and high-level architecture.

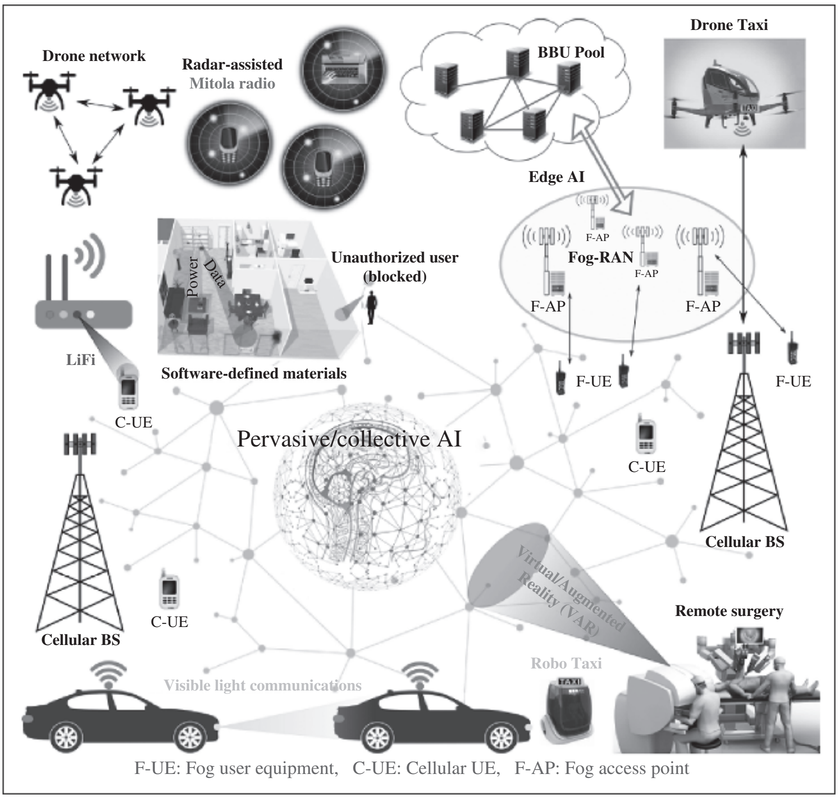

Figure 1.3 Beyond 5G (aka 6G) use cases and high-level architecture. Source: Reproduced with permission from Ref. [2]/IEEE.

1.2 Benefits of MIMO Technology

The fundamental relationship that relates the available bandwidth, signal power, channel conditions, and number of transmitters and receivers, and the achievable channel capacity (i.e., data rate) is given by:

$$C = \mathrm{BW} \log_2 \left[\det \left(I_\mathrm{R} + \frac{\rho}{N_\mathrm{T}} H H^\mathrm{T} \right)\right] \tag{1.1}$$

where C is the channel capacity in bits, BW is the bandwidth in Hz, I_R is the number of receiving channels (i.e., receive antennas), ρ is the signal-to-noise ratio (SNR), N_T is the number of transmitting elements (i.e. antennas) and H is the channel matrix. The major advantage of MIMO is the ability to increase C by increasing the independent channels used (i.e., the rank of H and value of I_R) without any increase in the BW or power. This can multiply the data rates by the increase in the number of independent channels [3].

To create multiple data streams from wireless terminals, multiple antennas are needed. Each antenna will be supporting an independent stream or channel, and based on the channel characteristics and conditions, the multiple streams can significantly improve the data rates achieved. The design of multiple antennas within small form factor wireless terminals is a challenging task that has been and continues to be addressed in past and future designs and applications. The introduction of new frequency bands, and standard coexistence requirements (i.e., LTE, WLAN, etc.) impose more challenges to make sure close-by transmissions do not disturb the others. Field interference and coupling are other challenges that need to be addressed as well.

Due to the clear advantages of MIMO, it has been considered a major technology in 4G wireless standards. All 4G wireless devices and terminals have at least two antennas operating simultaneously within the same frequency band. MIMO continues to be a major cornerstone in 5G wireless standard in both FR-1 and FR-2 bands. Several 5G-enabled devices are using four antennas to support MIMO and massive-MIMO (m-MIMO) applications. The use of m-MIMO will be considered at the base station side and not the mobile terminal side due to the need for tens to hundreds of antennas at the base station side. The use of a large number of antennas and channels at the base station side can improve the channel capacity due to the use of narrower beams toward the users, thus improving the SNR and capacity. It will also provide higher energy efficiency via the use of linear codes and directive beams in addition to the use of smaller lower power RF frontends as compared to high-power front-ends in conventional architectures. Finally, directed beams will overcome jamming and interference. M-MIMO has been deployed at FR-1 bands but also is considered for FR-2 [4]. Figure 1.4 shows a comparison between legacy and m-MIMO systems.

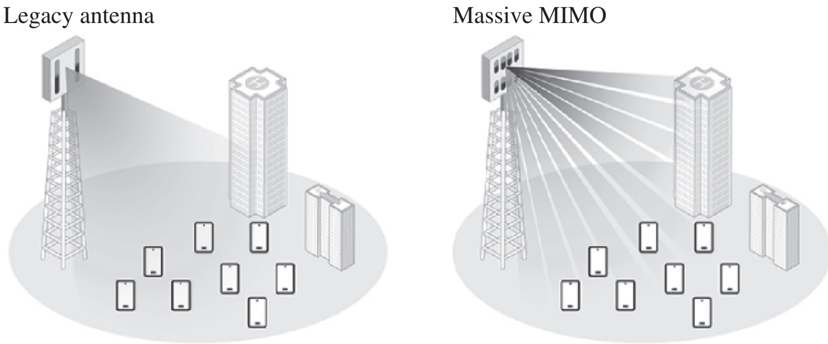

Figure 1.4 Beam coverage of legacy base stations and m-MIMO base stations.

1.3 Future Technology Trends

As we have seen, nowadays, 5G networks are still being deployed all over the world, mainly focusing on the FR-1 bands with few supporting FR-2. We should expect a stable increase in the infrastructure supporting 5G bands, and the deployment of the various applications and supporting networks to allow for seamless connectivity between the three vertices of the 5G triangle (i.e., eMBB, URLLC, mMTC) during the rest of the 2020s. While that is taking place, the research and development of what comes next is underway, i.e., 6G. Figure 1.5 shows a nice summary of the key performance indicators (KPIs) of the 4G, 5G, and 6G, focusing on the main features. As can be seen, 6G will introduce new wideband frequencies in the hundreds of GHz to allow for speeds of 100 Gbps to Tbps, opening a new domain of applications and use cases.

Holographic and multi-sensing communication systems are the new frontiers in wireless communications. The post-COVID area has shown the importance of video conferencing and instant multi-location world collaboration but lacked the feel of interaction and presence. Holograms will allow people to give talks, attend meetings, and give the feel that they are nearby while they are thousands of kilometers away. This will also open the doors of multi-sensing communications where interactions via AR and VR give the feel that someone is immersed into the environment that exists in the metaverse or at another location worldwide. To make these holograms a real-time reality, Tbps transmissions are required.

While 5G came with a framework of seamless connectivity between the three vertices mentioned earlier, the next-generation standard and networks will expand the scale of connectivity to include NTNs consisting of satellites in various orbits, high-altitude platforms (HAPs), and many others. At the same time, terrestrial networks can be integrated with new AI techniques that will

KPI	4G	5G	6G
Operating bandwidth	Up to 400 MHz (band dependent)	Up to 400 MHz for sub-6 GHz bands (band dependent) Up to 3.25 GHz for mmWave bands	Up to 400 MHz for sub-6 GHz bands Up to 3.25 GHz for mmWave bands Indicative value: 10–100 GHz for THz bands
Carrier bandwidth	20 MHz	400 MHz	To be defined
Peak data rate	300 Mbps with 4×4 arrays 150 Mbps with 2×2 antenna arrays	20 Gbps	≥1 Tbps (holographic, VR/AR, and tactile applications)
User experience rate	10 Mbps (shared over UEs)	100 Mbps	1 Gbps
Average spectral efficiency	25 Mbps with 2×2 antenna arrays 40–45 Mbps with 4×4 antenna arrays	7.8 bps/Hz (DL) and 5.4 bps 5.4 bps/Hz (UL)	1× that of 5G
Connection density	N/A	10^6 devices/km^2	10^7 devices/km^2
User plane latency	50 ms	4 ms (eMBB) and 1 ms (uRLLC)	25 µs to 1 ms (holographic, VR/AR and tactile applications)
Control plane latency	50 ms	20 ms	20 ms
Mobility	350 km/h	500 km/h	1000 km/h Handling multiple moving platforms
Mobility interruption time	N/A	0 ms (uRLLC)	0 ms (Holographic, VR/AR and tactile applications)

Figure 1.5 Key performance indicators (KPIs) between current wireless standards and upcoming 6G. Source: Reference [5]. (© 2021 IEEE. Reprinted with permission).

support the massive amount of information being handled in large data and information centers. The computing power should be increased multi-fold, and when considering the RF front-end, much faster and more reliable architectures will be required. Optical and RF-based communications will be integrated seamlessly with a massive amount of hotspot deployment to provide Tbps links with user terminals. The emergence of non-IP-based Internet protocols with AI engines will be the key to achieving this ultra-scale evolution of the network infrastructure.

New antenna designs will always be key to satisfying such wireless links using radio waves. As seen in Figure 1.5, antenna systems will cover extremely wide frequency ratios, from several hundreds of MHz to several hundreds of GHz. Switched beam antennas and phased arrays will be key for mm-wave and sub-THz applications, while reconfigurable and low-profile ones will be needed for sub-6 GHz bands. The aim of this book is to shine some light and give detailed examples and explanations on the design of such antenna systems for beyond 5G applications and frequency bands.

1.4 Book Organization

This book focuses on potential antenna technologies and solutions for 5G and beyond. Wireless terminals will become more environment-aware and will be supporting various standards and functions. Thus, it is inevitable to have multiple antenna systems within a single terminal. The need to support sub-6 GHz bands as well as millimeter-wave ones is essential and currently, the norm in 5G-enabled wireless terminals. This book revisits the fundamentals of some of the enabling technologies and provides various examples and implementation techniques to realize these concepts. More importantly, contents of this book also provide some practical solutions to the reader, be it in the research and development sector or the industrial sector.

Chapter 2 of the book starts by presenting some fundamental antenna metrics followed by a detailed description of MIMO technology. The definition of the performance metrics for MIMO such as the correlation coefficient, the total active reflection coefficient, port and field isolation, and capacity are explained in detail. Various diversity-combining techniques are discussed along with their advantages and disadvantages. The chapter ends with a discussion on MIMO antenna characterization using reverberation and anechoic chambers and the differences and capabilities of each.

The fundamental topic of feed-network design for passive and active antenna systems is presented in Chapter 3. The chapter starts with a revision on impedance-matching techniques using stubs and lumped elements. Various antenna-feeding mechanisms are presented such as microstrip feeding, aperture coupling, coaxial, and coplanar waveguide feeding. Open-loop tuning and closed-loop tuning techniques are discussed, followed by active switching methods using diodes for antenna selection control and frequency tuning. Active beamforming networks for arrays and MIMO antennas are then presented with several practical examples. A comparison between the advantages and limitations of digital and analog beamforming is discussed. Finally, the chapter ends by presenting wideband and reconfigurable feeding techniques.

MIMO technology has been implemented in the 4G wireless standards and will continue in all upcoming generations. Chapter 4 presents a comprehensive discussion of passive MIMO antenna solutions for 5G and beyond. The chapter starts with single-band implementations of sub-6 GHz (Frequency range 1–FR1) antennas with various types and characteristics (dipoles, monopoles, loops, inverted-F). Then, it presents antenna solutions and analysis for single band antenna solutions covering FR2 at mm-waves bands, which include dielectric resonator-based antennas (DRAs) and microstrip-based ones. Multi-band antenna design techniques are presented next with several practical examples covering both FR-1 and FR-2 bands. The chapter ends with ultra-wide-band (UWB) MIMO antenna solutions covering FR-1 and FR-2 bands using microstrip and dielectric resonator-based solutions. Several practical design solutions are presented and discussed to put the reader on track to develop such antenna systems.

Active MIMO antenna system design is discussed in Chapter 5. Reconfigurable antenna systems in frequency, pattern, and polarization are discussed in detail with several practical examples in guiding the design process for active diode-biasing networks and such control mechanisms. Various antenna types (microstrip, DRA, slots) and covered frequency bands are presented. The application of reconfigurable antennas to MIMO configuration is discussed for frequency, pattern, and polarization techniques. The challenges of designing such antenna systems are highlighted and discussed with practical considerations. The chapter ends with a detailed computer-aided design (CAD) example of modeling a reconfigurable MIMO antenna system and methods for biasing circuits with the diodes. The design file provided was made using ANSYS HFSS and is provided in the accompanying CD.

Massive MIMO (M-MIMO) architecture and antenna solutions are presented in Chapter 6. M-MIMO advantages such as improvements in capacity, latency, efficiency, and complexity are presented first. The design of the single antenna element is discussed with several implementation candidates covering various use cases and features (i.e., loading, use of metamaterials). Several examples of different unit element implementations followed by m-MIMO arrays for various frequency bands are presented next. A detailed practical example (i.e., AIR 6488) of an M-MIMO antenna system is discussed, followed by the challenges faced when considering such large and complex antenna systems.

Chapter 7 discussed the most recent developments and topics in MIMO antenna systems in various applications. The chapter considers MIMO developments in on-package and on-chip radios and systems operating primarily at mm-waves. Then some recent advancements in sub-THz applications and antenna solutions with MIMO capability are presented for beyond 5G use cases. Several recent technologies are highlighted and presented. The need for MIMO in metasurface implementations to increase the throughput is discussed with several examples. Reflective intelligent surfaces (RIS) and the need for MIMO/M-MIMO are presented and discussed with several examples from recent works. MIMO in orbital angular momentum (OAM) is gaining importance due to its potential ability to increase the channel capacity with the use of the simultaneous transmission of orthogonal beams. Finally, MIMO solutions for space applications are presented and discussed.

Due to the close proximity of antenna elements in small form factor devices (i.e. mobile handsets), the need for port decoupling becomes essential to achieve the benefits of MIMO technology and implementations. This is the focus of Chapter 8; decoupling techniques for MIMO antenna systems. The impact of mutual coupling is first discussed in detail, prior to the assessments of these effects on the main MIMO parameters such as correlation and antenna characteristics. Decoupling techniques then follow, with several examples of each method highlighting its pros and cons. Polarization-specific decoupling methods are presented as well.

Finally, Chapter 9 focuses on characterization and measurement methods for MIMO antenna systems which is an essential part of the design process. Over-the-air (OTA) tests using reverberation chambers and their capabilities are discussed in detail with some examples. The definition of the total radiated power, and total isotropic sensitivity as well as throughput testing are demonstrated. The details of multi-probe anechoic chambers and their operating algorithms are presented. Characterization and testing of user equipment (UE), i.e., mobile terminal, as well as base station arrays are shown. Other methods of testing and characterization from the industry are presented and discussed with the advantages and limitations of each.

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