1 Introduction

The antenna first used in radio communication was a small antenna, which was a fan-type monopole (Figure 1.1), developed by G. Marconi, used for trans-Atlantic Ocean communication in 1901 [1]. The antenna appeared to be very large, as it was hung by two masts 48 meters high and 60 meters apart so that it could never be considered small [1]; however, since the dimensions were a small fraction of wavelength (about 1/6 of the operating wavelength, 366 meters), it was "electrically" small.

An Electrically Small Antenna – ESA – (the definition is described in 2.1) is an antenna of dimensions much smaller than the wavelength. In the classical sense, there are two types of ESA; one is an electric element, which couples to the electric field and is referred to as a capacitive antenna, and another is a magnetic element (electric loop), which couples to the magnetic field and is referred to as an inductive antenna. These are ESA categories; however, many practical antennas are some combination of these two types. It should be noted that small electric and magnetic elements in the forms of dipoles and loops have been used since 1887 when Hertz successfully generated and detected electromagnetic waves and verified Maxwell's prediction [2]. His invention of such small antennas certainly proved his success in demonstrating existence of electromagnetic waves. Although more than 120 years have passed since Hertz's experiment, his small dipoles and loops shown in Figure 1.2 (a) and (b) were so basic that essentially the same antennas are still being used.

Typical antennas in practical use for the early days of radio communications were ESAs. Examples of them are shown in Figure 1.3: (a) top-loaded monopole, (b) fan-type monopole, (c) multi-wire, (d) rectangular cage type, and (e) cage type, and so forth. Most of them were installed on ships and operated in frequency bands of LF and HF. Since then, small antennas have been used in various communication systems, particularly mobile systems, where small antennas were required. Antenna types used are not only linear but also planar and others such as composite and integrated types. Antenna technology has made steady progress along with the progress in communication systems and electronic devices, especially during World Wars I and II that provided the need for advanced antenna design and the surge of technology. Operating frequencies have gradually been raised to higher regions; from MF and HF bands to VHF, UHF, and SHF in recent years. Use of higher frequencies and smaller-sized electronic devices gave impetus to develop smaller antennas. One of the major trends in recent antenna technology is miniaturization of antenna systems, yet with improved functioning and further sophistication. The latest applications of small antennas are mainly to mobile communications and newly deployed

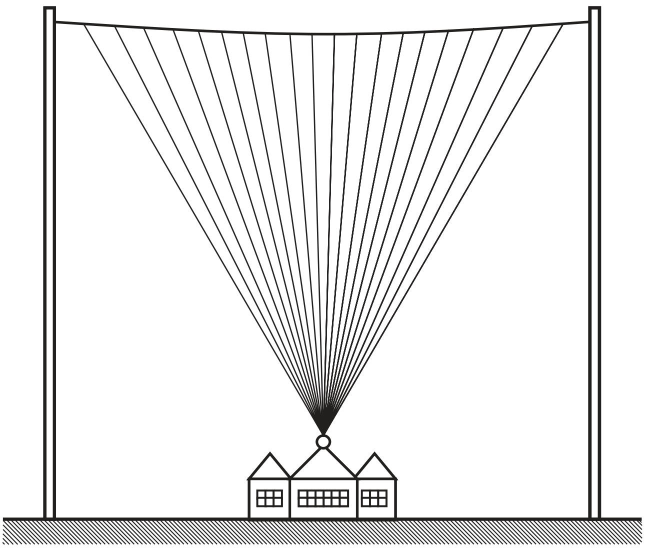

Figure 1.1 The first radio communication antenna used for trans-oceanic communications developed by Marconi in 1901 [1].

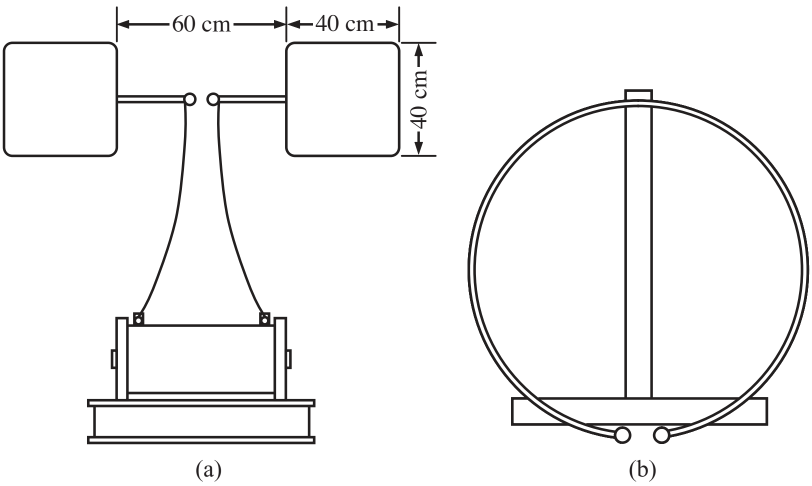

Figure 1.2 Hertz antenna used for his experiment of the first radio wave transmission experiment [2, 3, 4].

various wireless systems. The typical mobile systems are mobile phone systems, which have evolved from the first generation systems in the early 1950s to the present fourth generation through the third-generation systems and further progressed wireless systems such as smart phones and handy tablets, where small antennas are indispensable. Recently emerged wireless systems also demand small antennas. These recent wireless systems are applied not only to communications, but also to control, sensing, identification, medical use, body communications, and data and video transmission. Typical systems

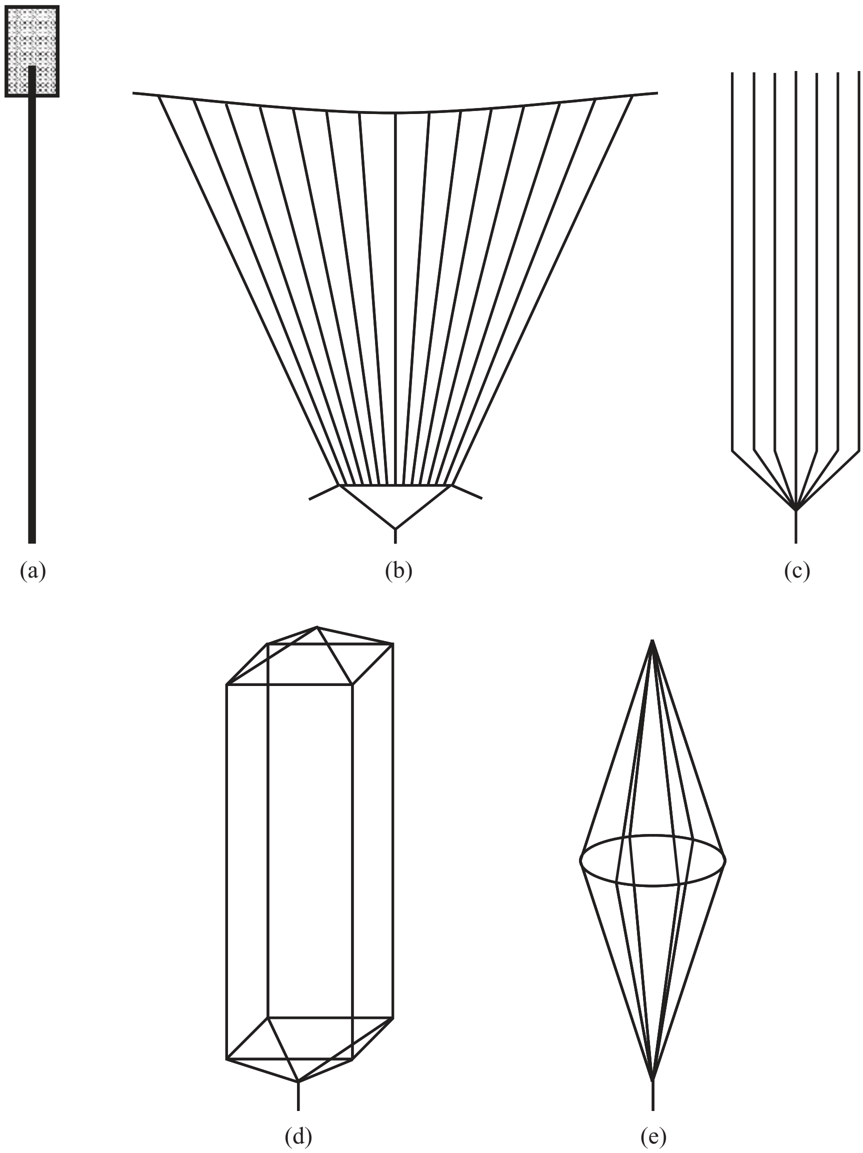

Figure 1.3 Typical antennas used in early radio communications; (a) top-loaded monopole, (b) fan-type monopole, (c) multi-wire, (d) rectangular cage type, and (e) cage type [2, 3, 4].

for which small antennas are required, are NFC (Near Field Communication) systems, including RFID (Radio Frequency Identification), UWB (Ultra Wideband) systems, and wireless broadband systems such as WLAN (Wireless Local Area Network) systems and WiMAX (Worldwide Interoperability for Microwave Access) systems.

Requirements from various mobile systems have intensely stimulated research and study of small antennas and as a consequence have brought promotion of novel antenna systems development. They have also contributed to improved antenna performances

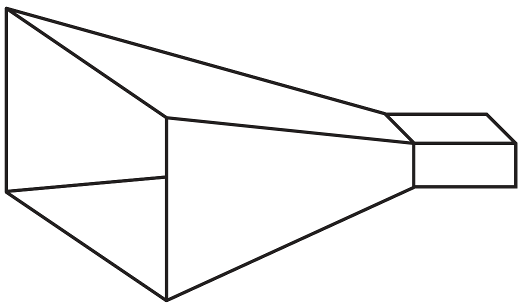

Figure 1.4 A millimeter-wave horn antenna, which is physically small, but electrically large.

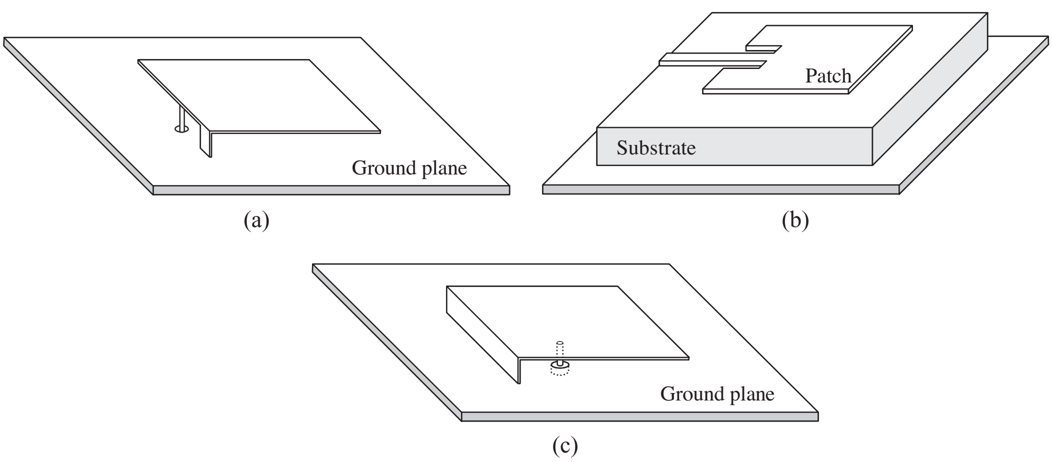

Figure 1.5 Typical planar antennas; (a) PIFA (Planar Inverted-F Antenna), (b) patch antenna, and (c) MSA (Microstrip Antenna).

year by year and the antenna functions have gradually been enhanced to meet the requirements raised from the advanced systems. Meanwhile, discussions on the fundamentals of small antennas have continued ceaselessly ever since Wheeler's work, because of continued significance. Problems that concern limitations are still regarded as very interesting and controversial topics. Knowledge of the limitations informs antenna engineers how to approach the limitations with an antenna of given size.

There is some ambiguity in the expression "small antenna," because one can say, "This is a small antenna," when it looks physically small. For example, a millimeter-wave (MMW) horn antenna (Figure 1.4) of only the size of a human palm looks simply small and it might be called a "small" antenna. However, since a MMW antenna often has the aperture of a few or more wavelengths, the antenna dimension shouldn't be said to be "small," but in fact "electrically large" in terms of the operating wavelength. On the contrary, for an antenna having dimensions of a small fraction of the operating wavelength like the Marconi antenna mentioned earlier, the antenna is referred to as an "electrically small" antenna. Here, small antennas will be treated in a wider sense, in

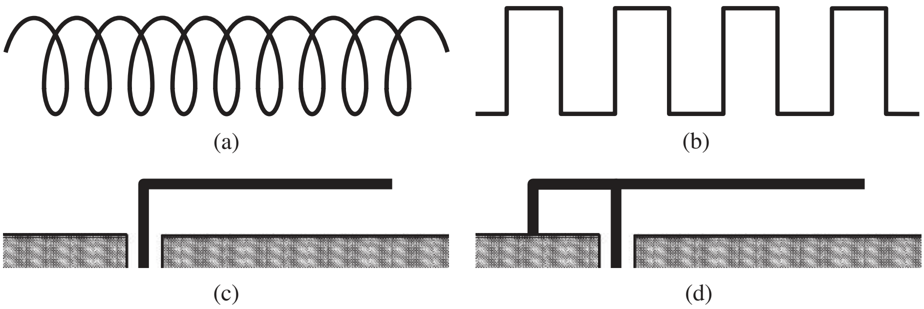

Figure 1.6 Typical linear small antennas; (a) NMHA (Normal Mode Helical Antenna), (b) Meander Line Antenna, (c) ILA (Inverted-L Antenna), and (d) IFA (Inverted-F Antenna).

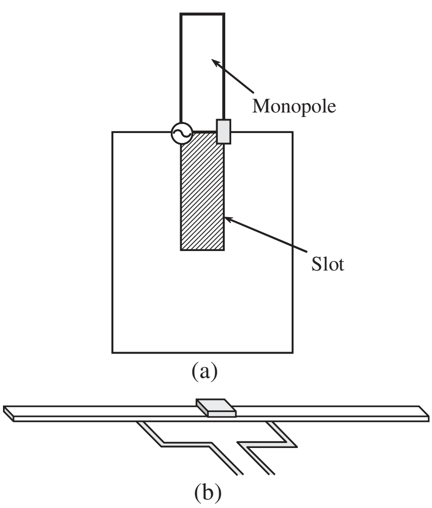

Figure 1.7 Examples of composite antenna; (a) self complementary antenna and (b) active integrated antenna.

which antennas are defined four ways; first, in terms of simply physical size; second, in comparison with the operating frequency; third, in relation with function; and fourth, in the size-constrained structure. Small antennas defined in terms of the function may be unfamiliar in general; however, antennas so defined should be appreciated as a significant concept that comprehensively embraces the term "small."

Various types of small antennas have so far been evolved from simple dipoles or loops. Planar and low-profile antennas are typical ones. Practical examples are illustrated in Figure 1.5, which shows (a) Planar Inverted-F Antenna (PIFA), (b) patch antenna and (c) Microstrip Antenna (MSA). Meanwhile, examples of linear antennas are shown in Figure 1.6, which depicts (a) Normal Mode Helical Antenna (NMHA), (b) Meander

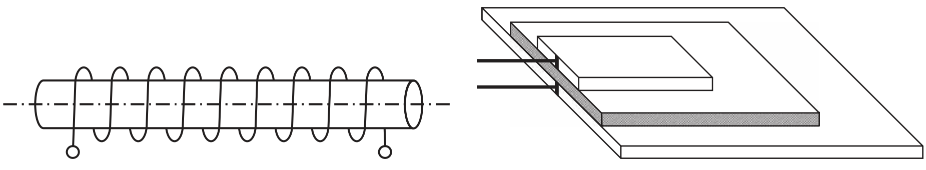

Figure 1.8 Examples of loaded antenna: (a) a ferrite loaded coil, and (b) dielectric loaded patch antenna.

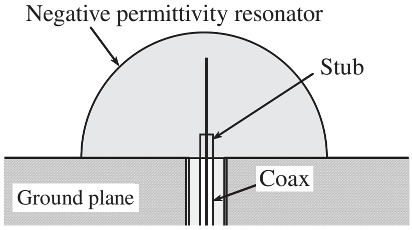

Figure 1.9 Example of metamaterial (negative permittivity) loaded small antenna [5–7].

Line Antenna (MLA), (c) Inverted-L Antenna (ILA), (d) Inverted-F Antenna (IFA) and composite antenna. Examples of composite antennas are shown in Figure 1.7, which depicts (a) an example of complementary antennas and (b) an example of active integrated antennas. Integration technique, by which some device or circuitry is combined with an antenna structure so that the antenna works with enhanced performance or function, can be utilized for small-sizing. Application of materials such as ferrite and/or dielectrics is also a useful means to reduce antenna size. Examples are an antenna loaded with a ferrite and an MSA loaded with dielectric material as shown in Figure 1.8(a) and (b), respectively. Presently, introduction of metamaterials such as mu-negative or epsilon-negative materials (MNM or ENM) and double negative materials (DNG) into the antenna structure has been discussed extensively worldwide as one of the promising candidates for antenna miniaturization [5–13]. An example of application of negative-epsilon material to small antenna structure is depicted in Figure 1.9 [6]. Development of negative-mu materials will also contribute to new small antennas [14]. These antennas will be discussed in later sections.

References

[1] J. Ramsay, Highlight of Antenna History, *IEEE Antennas and Propagation Society Newsletter*, December 1981, 8.

[2] S. Tokumaru, *Invitation to Radiowave Technology*, Kohdansha, Japan, 1978, pp. 48–50 (in Japanese).

[3] O. Lodge, *Signaling Across Space Without Wires*, Van Nostrand, 1900.

[4] G. Pierce, *Principles of Wireless Telegraphy*, McGraw-Hill, 1910.

[5] H. R. Stuart and A. Pilwerbetsky, Electrically Small Antenna Elements Using Negative Permittivity Resonator, *IEEE Transactions on Antennas and Propagation*, vol. 54, 2006, no. 6, pp. 1644–1653.

[6] F. Bilotti, A. Ali, and L. Vegni, Design of Miniaturized Metamaterial Patch Antennas with μ-Negative Loading, *IEEE Transactions on Antennas and Propagation*, vol. 56, 2008, no. 6, pp. 1640–1647.

[7] P. Y. Chen and A. Alu, Sub-Wavelength Elliptical Patch Antenna Loaded with μ-Negative Permittivity Resonator, *IEEE Transactions on Antennas and Propagation*, vol. 58, 2010, no. 1, pp. 13–25.

[8] N. Engheta and R. W. Ziolkowsky, eds., *Metamaterials-Physics and Engineering Explorations*, IEEE Press, 2006, John Wiley and Sons.

[9] A. Lai, C. Caloz, and T. Itoh, Composite Right/left-Handed Transmission Line Metamaterials, *IEEE Microwave Magazine*, September 2004, pp. 34–50.

[10] C. Caloz, T. Itoh, and A. Rennings, CRLH Metamaterial Leaky-Wave and Resonant Antennas, *IEEE Antennas and Propagation Magazine*, vol. 50, 2008, no. 5, pp. 25–39.

[11] G. V. Eleftheriades and K. G. Balmain (eds.), *Negative Refraction Metamaterials: Fundamental Principles and Applications*, Wiley-IEEE Press, 2005.

[12] J. L. Volakis, C.-C. Chen, and K. Fujimoto, *Small Antennas, Miniaturization Techniques and Applications*, McGraw-Hill, 2010, chapter 6.

[13] F. Capolino (ed.), *Applications of Metamaterials*, CRC Press, 2009, Part IV.

[14] T. Tsutaoka, *et al.*, Negative Permeability Spectra of Magnetic Materials, *IEEE iWAT* 2008, Chiba, Japan, P202, pp. 279–281.

2 Small antennas

2.1 Definition of small antennas

Here in this book, small antennas are treated with a concept that embraces not only electrically small antennas, but also other types of small antennas. Categories used to classify small antennas include functions as well as dimensions, because small antennas being used practically are not only what we call "Electrically Small Antennas," but also simply physically small antennas – antennas of partly electrically small dimensions and antennas equivalently small in terms of functions. Conventionally, ESA has been the main subject when small antennas are discussed; however, other types of small antenna have comparable significance with the ESA, depending on the situation of the practical applications. The categories used here are Electrically Small Antenna (ESA), Physically Constrained Small Antenna (PCSA), Functionally Small Antenna (FSA), and Physically Small Antenna (PSA) [1].

An ESA is an antenna conventionally defined as an electrically small-sized antenna; i.e., one having dimensions much smaller than the wavelength. However, this definition is unclear, since the dimensions are not described precisely. Wheeler defined the ESA as an antenna having the maximum size that can be circumscribed by a radian sphere, with a radius of one radian in length ($= \lambda/2\pi$) [2]. However, an antenna having the maximum dimension of a radian length may not necessarily be categorized as an ESA, because taking a dipole antenna as an example – which has the length of a radian length, $2 \times \lambda/2\pi$ ($= 0.32\lambda$) – it can no longer be called electrically small, as the size becomes no longer a small fraction of the wavelength. Hence classifying the radian-length dipole antenna as an ESA is not reasonable.

There was another definition of ESA – that was an antenna having dimension not greater than one eighth of a wavelength [3]. One more definition was given by King, who did not use the term ESA, but "very short antenna," that referred to an antenna having the length in terms of $ka \leq 0.5$ (a: a half length of a thin linear dipole and $k = 2\pi/\lambda$, (λ: wavelength)) [4]. Recently, Best followed King's definition that ESA is an antenna having $ka \leq 0.5$, the same dimensions as King's. This is more reasonable to define as ESA, so hereafter we will reserve the term ESA for small antennas having dimension ka smaller than 0.5, where a is the radius of sphere circumscribing the antenna.

A PCSA is an antenna, not having dimensions of ESA, but a part of which has dimensions corresponding to the ESA. A low-profile antenna, for example, with the height over the ground plane or the thickness of say λ/50 or so, like an Inverted-L antenna, planar antennas such as a patch antenna, a microstrip antenna (MSA), and so forth, can be classified into "Physically Constrained Small Antenna" (PCSA).

Another classification of small antennas relates to antenna functions. When an antenna can attain either additional functions or enhanced performances with the dimensions being kept unchanged, it can be said to have an equivalent reduction in the antenna size, because with normal antennas such enhanced function or improved performance could result only from enlargement of dimensions. An example is an antenna designed to have wideband, multiband performance, radiation pattern shaping, and array thinning without any change in the dimensions. This class of antenna is referred to as "Functionally Small Antenna" (FSA).

Among the FSA, there may be antennas that can be categorized also as ESA and/or PCSA at the same time, because their antenna dimensions are small enough to be comparable with a fraction of a wavelength, which is the criterion for ESA and/or PCSA.

A "Physically Small Antenna" (PSA) is an antenna, which differs from any of the above, but has physically small dimensions as measured. When the volume of an antenna is bounded by 30 cm or less, we may call the antenna a PSA. There is not any strict physical meaning in the definition, but only a sensual measure based on the common understanding of "smallness" in physical size. An example is a millimeter-wave horn antenna with an aperture size of, say 5 cm approximately. Many of the MSAs may be classified into either PCSA or PSA.

These definitions cannot be analytically formulated in practice, because an antenna may be differently classified depending on the practical situation. For instance, when a short monopole categorized in the ESA is put on a rectangular conducting plate of 1/4 wavelength, the antenna can no longer be classified into ESA, because the antenna dimensions are effectively enlarged with inclusion of the plate. The plate of finite size acts as a part of the radiator so that the monopole plus the plate constitutes an antenna system. In this case, the radiation performance of the monopole is enhanced by contribution of the radiation current on the plate induced by the monopole. A very small ceramic-chip antenna practically used in small mobile terminals is another example.

In any case the size of the antenna system must be defined with the maximum size, which includes the platform together with the antenna element.

Although an antenna may be classified into one of the four categories mentioned above, the categories are not necessarily distinct so that one class of antenna can be categorized also in another class. For instance, when a very thin patch antenna has the edge (radiating aperture) of 1/5 wavelength in its periphery, the antenna is referred to as both an ESA and a PCSA.

2.2 Significance of small antennas

The significance of the small antenna is recognized from its important role in various wireless systems, where small antennas are indispensable. In the early days of communications, when electronic devices such as thermionic vacuum tubes were not yet available, antenna technology was essential to extend the communication range. Development of tuning and matching concepts gave impetus to promote further increase in communication capability. In those days, most of the antennas used were ESA, because operating frequencies were mostly MF and HF bands. In the 1930s, antennas such as slot antennas and ferrite antennas were put to practical use. It was around this era when needs for small antennas furthered researchers' interest in studying the fundamentals of small antennas, and investigation of limitations of small antennas was inspired. In parallel with research, practical development of small antennas was advanced. Examples are normal mode helical antennas, MSAs, and patch antennas. Their practical applications extended to various mobile systems, particularly to land vehicles. Remarkable progress of antenna technology can be attributed to World Wars I and II. After the wars, and toward the end of the twentieth century, various composite antennas and integrated antennas appeared. Meanwhile, mobile communications drove development of small antennas, as mobile terminals needed small equipment, for which small-sized, compact, and lightweight antennas were required.

So far, creation and invention of small antennas have accelerated rapidly in response to worldwide demands raised urgently by the growth of mobile phone systems. Recent trends are increasing demands arising particularly for newly deployed wireless mobile systems – NFC (Near Field Communication) systems, including RFID (Radio Frequency Identification), UWB (Ultra-Wide Band), and wireless broadband systems such as WLAN (Wireless Local Area Networks) and WiMAX (Worldwide Interoperability for Microwave Access). Small antennas have already played an obscure but key role in such wireless mobile systems, as the systems do not work without these devices. Antennas in these systems have acted as a key component, since they almost determine the system performance, especially in small wireless equipment, because the systems are designed to exhibit almost the highest achievable electronic performance, and only the antenna can further improve the system performance. Since downsizing of electronic devices and their design technology as well has expedited progress in small wireless equipment, small antennas have become inevitable for these systems. As such, it can also be said that such newly deployed wireless systems owe much in their development to small antennas, and in turn small-antenna technology has advanced by being employed in these wireless systems. Recent urgent demand is application of small antennas to the MIMO (Multi-Input Multi-Output) systems. WiMAX already employs the MIMO system in order to transmit high data rate to the 4G (4th Generation) mobile systems, and other wireless broadband systems where high data rates will be needed will adopt the MIMO system. Small antennas are suitable for small MIMO equipment, where space to install antennas is limited to small areas, and close proximity of antenna elements is unavoidable.

Downsizing of an antenna without degrading the antenna performance imposes a severe design issue for antenna engineers – how to keep the antenna performance unchanged while the antenna size is reduced. The latest demands for small antennas are not only physically small, but also functional, typically wideband, multiband operation, or including signal processing capability.