AWE-Inspiring Electrically Small Antennas

Richard W. Ziolkowski

Abstract

Anytime-wireless-everywhere (AWE) aspirations for Internet-of-Things (IoT) applications to be enabled through current 5G and evolving 6G and beyond ecosystems necessitate the development of innovative electrically small antennas (ESAs). While a variety of ESA systems are reviewed, those realized from the near-field resonant parasitic (NFRP) antenna paradigm are emphasized. Efficiency, bandwidth and directivity issues are highlighted. Multifunctional, reconfigurable, passive and active systems that have been achieved are discussed and illustrated; their performance characteristics and advantages described. This overview finalizes by going back to the future and considers enterprising research areas of current and forward-looking interest.

Key terms

Bandwidth; directivity; efficiency; electrically small antennas; Huygens source antennas; metamaterial-inspired; metamaterials; near-field resonant parasitic (NFRP) antennas; sensors; wireless power transfer (WPT)

1. Introduction

The Fourth Industrial Revolution, Industry 4.0, is upon us. It represents the integration of humans and technological systems, i.e., cyber-physical systems. It promises many advances including, for instance, biometric sensors to help us maintain our health; sensor networks to enable smart infrastructure and buildings; smart agriculture to monitor crops and manage operations; autonomous vehicles to enhance our standards of living; wireless power transfer (WPT) to reduce device weight and size, eliminating short-life batteries and reducing environmental wastes; and marvelous mobile communication platforms and satellite constellations to enhance social interactions, collaborations, and cohesiveness. Electromagnetics, including antennas, propagation and measurement research, has played, is playing and will continue to play a pivotal role in realizing these anytime-wireless-everywhere (AWE) inspired dreams.

Antennas are the central technology that empowers all aspects of the Industry 4.0 wireless ecosystems, particularly those associated with the much anticipated Internet of Things (IoT) and its ubiquitous devices. Seemingly contradictory desires for radiating and receiving elements with superior multifunctional and reconfigurable performance characteristics in smaller, easier-to-fabricate and cheaper packages abound. Over 2400 journal, magazine and conference papers have been published on electrically small antennas alone in IEEE Xplore over the last decade. Needless to say, AWE-inspired electrically small antennas are an active research area for academic, commercial, and government investigators who are stakeholders in advancing wireless technologies.

This overview on electrically small antennas will begin with a brief discussion of the standard figures of merit associated with the performance characteristics of electrically small radiating and scattering systems. It will then focus on what some of the recent innovations in this area are. Systems that have overcome many of the traditional performance trade-offs associated with electrically small elements will be discussed. Novel applications benefiting from these developments and consequent future opportunities will be highlighted.

Given the ginormous number of contributions made in the ESA area by so many researchers, I will apologize up-front to all whose work is not mentioned. I will naturally emphasize the efforts associated with my group and collaborators from around the world. There are numerous books one can consult specifically for many more details on electrically small antennas, e.g., [1–3], as well as traditional antenna textbooks used worldwide, e.g., [4–6].

All of the simulations to be discussed were performed analytically (and implemented in Matlab), with in-house developed finite difference time domain software, and with commercial software environments. A majority of the antenna designs were modeled with different versions of the ANSOFT high frequency structure simulator (HFSS). More recent designs were...
obtained with the corresponding HFSS tools now in the ANSYS Electromagnetics Suite. All simulations were performed with realistic materials unless otherwise noted.

2. ESA Figures of Merit

H. A. Wheeler basically provided the generally used definition of an electrically small antenna (ESA) to our technical community in 1947 [7] and later carefully clarified it in 1959 [8]. The now well-known radiusphere is the smallest sphere of radius $a$ that completely surrounds the antenna. An electrically small transmitting or receiving antenna is one with $a < \frac{\lambda}{2\pi}$ or $ka < 1$. As Wheeler indicated, the radiusphere surface can be considered to be the boundary between the near and far fields of a small antenna. An associated interpretation leads to the Friis transmission equation [4, 8]. Let $P_{\text{trans}}$ be the input power to an antenna whose effective area is $A_{\text{trans}}$ and that is driven at the source wavelength $\lambda$. Let $P_{\text{rec}}$ be the power received by an antenna whose effective area is $A_{\text{rec}}$ and that is separated from the transmitting antenna by the distance $r$. The surface area of the sphere of radius $r$ centered at the transmitting antenna is $S_r = 4\pi r^2$. Denoting the cross-section of the radiusphere as $C_{\text{RS}}$, it is given by the expression $C_{\text{RS}} = \pi a^2 = \lambda^2/(4\pi)$. Then

$$P_{\text{rec}} = \frac{A_{\text{rec}} A_{\text{trans}}}{C_{\text{RS}} S_r} = \frac{A_{\text{rec}} A_{\text{trans}}}{\lambda^2 r^2}$$

(1)

The Wheeler cap measurement method [9, 10] in fact uses a derived quantity, the 3-dB fractional bandwidth (FBW), from the FBW in comparison to that of a magnetic ESA of similar $Q$ the lower bound of an electric ESA with $ka \approx 3 Q_{\text{p}}$. Thus, the FBW values are essentially maximized when the lower bound on $Q$ is achieved.

There has since been a never ending stream of reports that have attempted to define a more precise lower bound on $Q$. They have taken into account an antenna’s geometric and other design parameters; have offered yet better understanding on how to properly calculate its reactive power; and have even incorporated time variations in its material, structural and circuit element properties, e.g., [13–22].

There are several useful rules of thumb to keep in mind that have arisen from the chatter. As has been discussed, for instance, in [23, 24], the lower bound on $Q$ should take into account the radiation efficiency $\eta_{\text{rad}}$:

$$Q_{\text{lb}} = \eta_{\text{rad}} Q_{\text{Chu}} = \eta_{\text{rad}} \left[ \frac{1}{(ka)^3} + \frac{1}{ka} \right]$$

(4)

i.e., the lower bound is smaller that the Chu limit. If the antenna is circularly polarized (CP) rather than linearly polarized (LP), this relation becomes:

$$Q_{\text{lb,cp}} = \frac{1}{2} \eta_{\text{rad}} \left[ \frac{1}{(ka)^3} + \frac{2}{ka} \right]$$

(5)

These lower bound expressions point out why larger intrinsic losses and, hence, lower radiation efficiencies are acceptable in practice because larger bandwidths ensue.

Another useful improvement was derived in [13]. It was shown that the lower bound of an electric ESA with $ka \ll 1$ is more correctly $Q_{\text{lb},e} \sim 1.5 Q_{\text{lb}}$ and that of a magnetic ESA is $Q_{\text{lb},m} \sim 3 Q_{\text{lb}}$. Thus, an electric ESA will generally have twice the FBW in comparison to that of a magnetic ESA of similar electrical size.

Yet another important fact is that more bandwidth is accessible by a three-dimensional (3D) antenna that efficiently fills the radiusphere rather than a planar one. In fact, $Q_{\text{lb,planar}} \sim \frac{9\pi}{8} Q_{\text{lb}}$ [14, 17], i.e., the FBW of a planar antenna is about 3.5 times smaller than a 3D one that fills the radiusphere. There have been many studies that have suggested antenna designs that truly approach the fundamental lower bound, e.g., [23–27].

A stellar example is the self-resonant four-arm spherical folded helix antenna at $ka = 0.265$ with the measured $Q = 1.52 Q_{\text{lb}}$ [23–25]. A review of hundreds of ESA designs in relation to the $Q$-based lower bound is given in [28].

Finally, defining the electrical size $ka$ when a ground plane is present unfortunately becomes a bit nebulous. It has been shown that if the currents on the ground plane are localized near the radiator, the ground plane size has a minimal effect on
the impedance matching, e.g., [29]. Thus, the often used electrically small criterion for a radiator integrated with a ground plane, \( ka \leq 0.5 \), is quite reasonable. Nevertheless, it has also been shown that it fails to account for the directivity which changes dramatically depending on the size of the ground plane relative to that of the radiator [29, 30]. On the other hand, the radian sphere radius in the compilation [28] was chosen expeditiously to be the sphere which encloses the entire ground plane if its radius is smaller than \( \lambda/4 \), and to be the radius of the radian sphere totally enclosing the radiating elements otherwise.

### 2.2. Directivity and Efficiency

Directivity represents how much real power is radiated by an antenna into a particular direction when it is excited by a source relative to how much would be if the same source was driving a hypothetical isotropic electromagnetic radiator. The elemental radiators, i.e., infinitesimal electric Hertzian dipole (EHD) and loop (equivalent to a magnetic dipole) antennas are well-known to have a maximum directivity equal to \( D_{\text{max}} = 1.5 \) (1.76 dB) [4–6].

Electrical small radiating systems with enhanced directivity have been realized recently. These Huygens dipole antennas, i.e., balanced pairs of electric and magnetic dipole elements, have attained directivities in access of the infinitesimal system value, 3 (4.77 dB), as will be discussed more below, i.e., note that with \( N = 1 \) in (9), the maximum \( D_{\text{max}} = 3.0 \). The fact that those electrically small systems have their maximum directivity in access of this limiting value is simply due to the fact that they are finite in size and, consequently, have bits of other modes present which make small contributions to the overall radiated power.

More generally, recall that if the total radiated power is \( P_{\text{rad}} \) and the power supplied to the antenna system is \( P_{\text{input}} \), then the total overall efficiency of an antenna would be

\[
\text{Total Overall Efficiency} = 100\% \times \frac{P_{\text{rad}}}{P_{\text{input}}} \quad (6)
\]

The radiation efficiency is then

\[
\text{Radiation Efficiency} = 100\% \times \frac{P_{\text{rad}}}{P_{\text{accepted}}} \quad (7)
\]

where the total power accepted by the antenna is \( P_{\text{accepted}} = (1 - |S_{11}|^2) P_{\text{input}} \). The better matched an antenna is to its source, the more power it has to potentially radiate.

If the radiating system has an effective transverse area \( A_{\text{eff}} \) and if it is uniformly driven at the excitation wavelength \( \lambda \), then its maximum directivity and realized gain are [4]

\[
D_{\text{max}} = \frac{4\pi}{\lambda} A_{\text{eff}} \quad (8)
\]

\[
RG_{\text{max}} = \epsilon_{\text{total}} \times D_{\text{max}}
\]

where the total efficiency of the radiating system, i.e., taking into account the material losses, mismatch losses, ..., is \( \epsilon_{\text{total}} \). Consequently, a larger effective radiating aperture will provide a higher directivity. Moreover, these relations clearly indicate that an ESA, by nature, is directivity challenged. Note that \( \epsilon_{\text{total}} = (1 - |S_{11}|^2) \epsilon_{\text{em}} \), where the term \( \epsilon_{\text{em}} \) represents the overall efficiency associated with the radiator (all of the efficiencies tied to losses other than the mismatch loss) and, hence, the accepted power. Therefore, the maximum gain is

\[
G_{\text{max}} = \epsilon_{\text{em}} \times D_{\text{max}}. \quad \text{At a given frequency, the gain of a time-harmonic (continuous wave, CW) antenna on transmit and receive is identical.}
\]

Is there a means to achieve directivities well beyond the dipole values with a single radiator? By taking into account both the transverse electric and magnetic modes, Harrington demonstrated that the maximum directivity from a source region as a function of the maximum number of multipole modes, \( N \), that it can radiate is [31, 32]:

\[
D_{\text{max}} = N^2 + 2N \quad (9)
\]

Therefore, by exciting many higher order modes, one can in principle achieve very high maximum directivity from a single element. There has been much interest recently in the physics literature to use high permittivity dielectrics to enable the overlap of dipole and higher order modes in nano-systems to attain high directivity. A Huygens nanoparticle laser based on this concept was reported in [33].

Another approach, in principle, is a superdirective system. A useful operational definition of superdirectivity, e.g., as emphasized by Hansen [34], [35], is to achieve a directivity greater than that obtained with the same antenna configuration being uniformly excited (constant amplitude and phase). While this is basically an array definition, a precise one for a single element is a bit stickier because even a tiny ideal electric Hertzian dipole is “superdirective” by it, i.e., because its directivity is 1.5, its effective electromagnetic area from (8) is \( A_{\text{eff}} = 3\lambda^2/8\pi \) which is much larger than its physical area. The concept of superdirectivity has permeated the physics and applied physics literature repeatedly since Oseen discussed the concept of “needle radiation” nearly a century ago [36] and continues to be an active research field [37]. Nevertheless, it is extremely challenging in practice. There have been and continue to be many attempts to overcome the ill-posedness associated with superdirectivity, especially taking into account system constraints e.g., [38, 39]. A superdirective electrically small radiating system was recently reported in [40] based on a metamaterial-inspired multilayered nanoparticle.

### 3. Overcoming Conventional ESA Stigmas and Trade-offs

As noted above, experimentally verified examples of ESAs that have overcome the conventional wisdom of their drawbacks have been reported. Many were initially associated with the concept of electromagnetic metamaterials [41–43], artificial materials whose electromagnetic properties can be designed to have properties not attainable with naturally occurring media. Many more recent examples have arisen from the fundamental electromagnetic physics and engineering principles they imbue.

#### 3.1. Metamaterial-based ESAs

The adaptation of a variety of epsilon-negative (ENG), mu-negative (MNG), and double negative (DNG) metamaterials
(MTMs) to achieve miniaturized antennas followed immediately after the initial surge of publications investigating their exotic physics properties. There are several review papers available with extensive reference lists that cover many of the designs in the first MTM decade [44–49]. I simply call your attention to several small metamaterial-based antennas reported by some of the early research teams in this area: [50–68]. Small communications and cross-dipole antennas were reviewed, respectively, in [69] and [70]. A variety of compact CRLH-based antenna systems have been reviewed very recently [71, 72], as have antennas augmented with meta-structures, e.g., [73–77].

My team’s initial metamaterial-based ESA concept consisted of a center-fed electrically small dipole antenna centered in and surrounded by either a DNG [50] or an ENG [51] shell. For simplicity, I will denote it as a core-shell antenna. The driven dipole radiator is a highly capacitive element. The double positive (DPS) air region itself acts as a capacitive element. The ENG shell, for example, is also electrically small and is excited by the fields radiated by the dipole. Consequently, it too is a capacitive element. However, because it is filled with a negative permittivity medium, it acts like an inductor. The combination of the capacitive and inductive elements forms an electrically small LC resonator. Nearly complete impedance matching to the source without any matching network and radiation efficiencies approaching 100% by properly tuning them together was demonstrated [51]. It was later proved that the driven element does not have to be surrounded by the ENG shell. The consequent electrically small LC resonator formed by it and the ENG shell is strongly excited by the driven dipole as long as the dipole is in close proximity to it [78]. The basic principles of this core-shell antenna concept were verified experimentally with the dual structure, a coax-fed semi-loop antenna surrounded by a MNG hemisphere on a ground plane [79].

It must also be emphasized that there were many in the IEEE Antennas and Propagation (AP) and Microwave Theory and Techniques (MTT) professional societies who were adamant that many of these metamaterial-based concepts were not credible, even despite existing experimental results. Monographs were even published by well-known colleagues labeling some of the work as “voodoo science” or the materials with exotic and even simple properties (e.g., empathically denying the existence of media with negative parameters) as “unobtainium” [80,81]. Some negative feelings still persist because, like many persisting and emerging areas, e.g., magnetic fusion, graphene, quantum computers, ..., there is much hype about the potential outcomes to acquire recognition and funding. Others who have jumped on the bandwagon have misused the terminology and, unfortunately, have nurtured them.

We must all understand and continue to be reminded that it really does take years to properly vet innovative ideas and truly demonstrate their unique advantages over existing systems. For instance, it was suggested that the dipole-ENG shell system could be realized based on a Drude model of a plasma in a glass shell whose density was small enough that the operating frequency of the driven dipole was below its plasma frequency. Analytical and numerical models [82, 83] suggested this approach was realistic. More than a decade later, the concept has been verified with some outstanding experimental efforts [84].

As a historical side note discussed in [85], my team and collaborators had considered passive and active materials constructed with artificial molecules before the turn of the century. As they would be currently termed, these passive and active “meta-atoms” were developed as complex passive and active loads connected to very electrically small dipole and loop antennas [86–91]. The fields re-radiated, i.e., scattered, by these designed electric (magnetic) inclusions in a substrate superimposed to yield a variety of dispersion engineered permittivity (permeability) responses. Over a decade later, the electric (meanderline antenna loaded with an inductor and magnetic (loop antenna loaded with a capacitor) unit cells shown in Fig. 1 were successfully combined into one of the electrically smallest DNG unit cells still today and a block of the resulting low loss DNG metamaterial was tested. The results experimentally verified their simulated performance characteristics [92, 93], i.e., a refractive index $n = -3.1$ with less than 1.0 dB/cm loss at 400 MHz with unit cells whose overall size was $\sim \lambda/75$.

![Figure 1: DNG Metamaterial with $n_{real} = -3.1$ at 400 MHz [92, 93]. Top: isometric view of the composite DNG unit cell. Middle: Meanderline antenna-based ENG layer of the unit cell. Left: photo, Right: Simulation model. Bottom: Capacitively-loaded loop (CLL) antenna-based MNG layer of the unit cell. Left: photo, Right: Simulation model.](image-url)
considerations in [86]. One of the first investigations on how long in time it takes for a metamaterial to realize its properties employed a related CLL-based AMC [98]. Similar time-domain considerations facilitated the realization of a zero-index metamaterial superstrate [99] for a high-gain antenna in a 60 GHz high-data-rate system. Predicted multi-Giga-bit information transfer based on an on-off-key (OOK) modulation was confirmed experimentally [100].

An electrically small NFRP antenna system that used a structured ground plane to achieve a high directivity was designed in [101]. However, we found it a severe challenge in general to fit the required periodic structure within in a Wheeler sphere smaller than $ka = 1.5$. As a consequence, we turned to other approaches to attain higher directivity ESAs as will be illustrated below.

### 3.2. Metamaterial-inspired ESAs

Even though very small unit cells were realized, a metamaterial, i.e., a block of artificial material consisting of enough layers of these unit cells in the wave propagation direction to attain homogenized values of the permittivity and permeability (basically 3-5) is still quite thick if one desires an antenna system that has its $ka = 0.5$, i.e., $a \sim \lambda / 12.6$. Moreover, the unit cells were planar; contained lumped elements; and redesigning them for a curved geometry, e.g., the core-shell antenna system, was and remains very challenging. The three-dimensional lego-design used in [79] was bulky, and we found that precise registration (alignment) of the elements in the various layers was required for the best performance. Nevertheless, other teams successfully combined a single layer of metamaterial unit cells both as substrates and superstrates, which would now be denoted as metasurfaces, with radiating elements for enhanced performance characteristics [53, 59, 61].

Luckily, a paradigm shift associated with the metamaterial-based ESAs and ESAs in general arose from those efforts with the antennas reported in [102]. We found that exciting only a single metamaterial unit cell that was resonant near the operating frequency of interest with a small driven element was sufficient to achieve a highly efficient ESA without the need for any matching network. Because no metamaterial was involved, but its success followed from metamaterial designs, we coined the term “metamaterial-inspired” to denote those original ESAs. Many of the original metamaterial-inspired designs were reviewed in [44]. There have been numerous metamaterial-inspired ESAs recently reported, e.g., [103–110].

As they were investigated further, it became clear that the fundamental radiation physics and engineering of the original designs is best captured with the designation: near-field resonant parasitic (NFRP) antennas. The NFRP antennas consist of a simple driven element and one or more NFRP elements. The concept is illustrated in Figs. 2(a) and 2(b) with field and circuit concepts, respectively. By adjusting the sizes and shapes of the driven and NFRP elements, as well as the distance and material between them, one can engineer the imaginary part of the antenna’s input impedance, i.e., its reactance, to be zero and its real part, i.e., its resistance, to be matched to that of the source, as well as emitting fields that are well matched to the impedance of free space. Nearly complete impedance matching and a high radiation efficiency are thus attained [44].

A simple example is shown in Fig. 3(a). The driven element is a small curved top-hat dipole radiator; the NFRP element is an Egyptian axe dipole (EAD) [101]. The surface currents on the driven and NFRP elements illustrated in Fig. 3(b) illustrate one of the advantages of the design, i.e., the main radiating currents occur primarily on the NFRP element, not the driven one. This aspect allows for the presence of more NFRP elements to achieve multiple functions with only a single driven element.

![Figure 2: Fundamental operating principles of NFRP antennas [44]. (a) Electromagnetic concepts. (b) Equivalent circuit aspects.](image)

![Figure 3: Egyptian axe dipole (EAD) NFRP antenna [101]. (a) HFSS model. (b) Simulated surface currents.](image)

Two of the early NFRP antenna designs and their prototypes serve as a prelude to more recent examples. They were developed during a DARPA sponsored Multidisciplinary Research Initiative (MURI) program that was led by the Boeing Aerospace Company [85]. Boeing Phantom Works fabricated our designs and they were tested at the National Institute of Standards and Technology (NIST) in Boulder CO.

The Z-antenna shown in Fig. 4 is an electric NFRP design. A coax-fed printed monopole acts as the driven element. The inductor loaded $Z$ structure is the NFRP element. The design served several purposes at the time. It demonstrated the flexibility to realize versions as small as $ka = 0.046$ at VHF to UHF frequencies; the ability to tune the resonances of one de-
sign over a very large bandwidth, i.e., to demonstrate frequency agility; and to understand how the overall efficiency of this type of antenna varied, for example, when $ka$ was varied by almost an order of magnitude, i.e., from 0.016 ($\sim 30\%$) to 0.14 ($> 90\%$) [111]. Prototypes of the UHF designs were fabricated and tested [44, 112]. They were quite valuable since they taught us how to tailor the parameters to account for the lumped element being introduced into the NFRP element rather than into a circuit. The 570 MHz, $ka = 0.40$ design shown in Fig. 4 had an measured overall efficiency greater than 80%.

Figure 4: Electrically small Z-antenna. (a) HFSS model. (b) 300 MHz Prototype. [112]

The 3D magnetic EZ antenna shown in Fig. 5 was a magnetic NFRP antenna. The driven element was a coax-fed semi-loop. The NFRP element was an extruded, 3D CLL structure. Prototypes of the original design [102] were fabricated for operation at the UHF frequency of 300 MHz [44, 113] and at the VHF frequency of 100 MHz [44, 114]. The former, which had $ka \sim 0.43$ at 301 MHz, had a measured overall efficiency greater than 94%. The latter is shown in Fig. 5. It was a low profile antenna (height = $\lambda/25$) whose measured resonance frequency was 105 MHz giving $ka = 0.46$ and whose measured overall efficiency was $\sim 95\%$. The change in the radiation efficiency as $ka$ decreases was also studied [114]. It was found in analogy with the lower bound in $Q$ that the radiation efficiency of the magnetic NFRP designs decreased much more quickly as $ka$ did in comparison to the their electric counterparts. Variations of this 3D magnetic EZ design has proven to be quite resilient as an ESA for high power microwave (HPM) systems [115–117].

Figure 5: Electrically small 3D Magnetic EZ antenna. (a) HFSS model. (b) 100 MHz Prototype. [114]

The VHF and UHF systems were examined because achieving physically tiny, highly efficient antennas in those bands and even lower ones might have enabled a host of applications. A $\lambda/2$ dipole antenna at 30 MHz is approximately 5.0 m in length. Very interesting robust communications concepts have been reported recently at the lower end of the VLF band [118] among mobile agents such as robots in complex non-line-of-sight indoor and urban-type scenarios. The need for efficient miniature antennas has driven the realization of several unique designs [119–126].

3.3. Non-Foster Circuits

Recalling the lower bounds on $Q$ for passive ESA systems, their bandwidths are naturally narrow. Most of the described early electric- and magnetic-based NFRP ESA systems exhibited fractional bandwidths on the order of 3-4% and 1-2%, respectively, in sync with those bounds. Despite the general demand for greater bandwidth, there are many narrow band antenna applications for which ESAs are well-suited. They include, for instance, the low frequency ESAs for communications between mobile agents in complex environments noted above [118] and for wireless power transfer (WPT) involving dedicated transmitters, which will discussed below. Furthermore, in conjunction with the rapid growth of the Internet of Things (IoT) applications, low power wide area networks (LPWAN) and their associated technologies, such as LoRA and Sigfox, have become popular for low-rate (narrow bandwidth) long-range radio communications [127]. LoRA systems are important for rural settings and have promising potential for search and rescue applications [128]. Nevertheless, there is always the demand for greater bandwidths in compact wireless devices.

Figure 6: Methods to obtain an ESA with a large instantaneous bandwidth. (a) Active matching network. (b) Internal active element.

Because the noted physics-based bounds on $Q$ are directly...
connected to passive radiating systems, an approach to achieve a large instantaneous bandwidth with an ESA is accomplished by introducing active systems. There are two basic approaches as illustrated in Fig. 6. The first is to introduce an external active matching network that compensates for both the resistance and reactance of the input impedance of the ESA to match it to the source. The second introduces an active internal reactance element into the antenna itself. Both methods can be facilitated by using non-Foster elements, i.e., powered transistor-based circuits whose impedance characteristics can decrease with increasing frequency in violation of Foster’s Reactance Theorem [129, 130]. Foster’s theorem basically tells us that the stored electric and magnetic field energies of a passive electromagnetic system must remain positive as the frequency changes, i.e., the frequency derivative of its reactance must be positive. Non-Foster (NF) elements can exist because their power source introduces energy into the system, negating the passive bounds.

There have been a number of successful realizations of wide bandwidth ESAs employing both types of active approaches. External active matching networks have been considered over the last 50 years [131–144]. More recent variants recognize that the Chu bound arises from the fact that passive antennas are LTI (linear time-invariant) systems. A variety of non-LTI (active) systems have been considered to attain wider bandwidths from electrically small systems. As argued in [21], the use of nonlinear and time-varying components has a long history back to first wireless telegraphy experiment in 1902 by Marconi which was successfully enabled by a spark-gap ESA. Impedance modulation, usually through the use of time varying inductor and capacitors [145], is a form of parametric amplification (see, e.g., [146], Chap. 11). This time-variation concept is also a fundamental aspect of space-time, time-modulated, and magnetless non-reciprocal metasurfaces to control radiated wavefronts and directional beams [147–153]. Another approach is the use of temporal modulation of the matching network, e.g., through the introduction of switches for direct amplitude modulation (DAM) of an ESA [154–157]. On the other hand, the internal (embedded) active elements have been reported only in the last decade [139, 158–174].

The process that my team and collaborators has used to achieve a NF-augmented NFRP antenna emphasizes the initial choice of a highly efficient, frequency-agile, passive NFRP antenna that has either an inductor or capacitor incorporated into its NFRP element(s) and has as low a $Q$ value as possible. The presence of such a lumped element facilitates the frequency agility, i.e., it allows the antenna’s resonant frequency to be tuned. Since such a low-$Q$ passive radiator will have a wider bandwidth, it relaxes the demands on the active element’s required performance.

Sweeping the lumped element’s value allows one to obtain a reactance versus resonance frequency (X-f) curve and it will have a NF behavior, i.e., a negative slope with respect to the frequency. A negative impedance convertor (NIC) based on a pair of cross-coupled transistors is then designed to create an active inductor or capacitor that replaces the passive one and matches the X-f curve. The NFRP antenna design with this active element being present is further refined with a co-design process. It is critical that realistic lumped element models and all interconnecting traces in the NIC circuit implementation with the NFRP element be included in the co-design process to account for the parasitic capacitances, inductances, and resistances associated with them. The final optimal design should have the resistance of the non-Foster element as small as possible across the entire extended bandwidth to maintain the high radiation efficiency of the passive design.

Several frequency agile versions of the basic CLL-based protractor NFRP antenna [44] have been obtained and their prototypes tested [175–177]. This magnetic dipole type of NFRP antenna has been an attractive choice in practice because one can incorporate a varactor into its NFRP element, e.g., across its gap, and tune its resonance frequency simply by changing the voltage applied to the varactor. This choice was encouraged because of the successful use of varactors for tunable magnetic metamaterial unit cells in the physics literature, e.g., [178]. The analysis, simulation, and testing of the NIC-capacitor augmented version was described in the articles [159, 161, 163].

![Figure 7: The canopy antenna augmented with four non-Foster elements, which are the four NIC-based inductor posts that support the metal canopy [158].](image)

Nevertheless, the first NF-augmented ESA design we developed was actually an electric one, the canopy antenna [179]. Its structure is illustrated in Fig. 7. The NFRP element is the metallic spherical cap connected to a ground plane by four inductor posts. It is excited by the coax-fed monopole. The electric choice was associated with the noted fact that passive electric dipole based ESAs naturally have more bandwidth than the magnetic ones. Moreover, of the various electric-based NFRP ESAs considered in [179], the $Q$ value of the canopy design came closest to the $Q$ lower bound. The electrical size was purposely picked to be small, i.e., $k_{\omega} = 0.0467 (a \approx \lambda / 134)$, for a 297.4 MHz operating frequency. The passive design had $Q = 1.75$ $Q_{\text{Chu,lb}} = 1.17 Q_{\text{Thal,lb}}$ and a $FBW_{10dB} = 0.0133\%$. Replacing the passive inductors with NIC-versions, the FBW was greater than 10% [158]. This stellar result actually encouraged the subsequent NIC-inductor augmented EAD-based NFRP ESA prototypes [159, 160, 163], one of which is shown in Fig. 8(a). The measured results confirmed a bandwidth several times the...
fundamental passive upper bound. Similar outcomes have been reported with embedded NF elements in [166, 167]. Performance comparisons of the two-dimensional (2D) NF EAD version in Fig. 8(a) and a three-dimensional (3D) variation were considered in [168]. The results confirmed that initial passive antenna designs that have wider instantaneous bandwidths (i.e., smaller $Q$ values), regardless of their 2D or 3D nature, will perform better than narrower bandwidth ones when they are augmented with the NF elements. This outcome is due to their decreased sensitivities to component and fabrication tolerance errors encountered with the NF circuit realizations. The recently tested 3D CLL-based NIC-capacitor augmented magnetic NFRP ESA shown in Fig. 8(b) further confirmed these conclusions [173].

Despite the promising results from both the internal and external NF approaches, many challenges remain. Many of them are nicely reviewed in [180]. In particular, it is well known that the cross-coupled transistor realizations, for instance, of NIC elements depend on positive feedback for their operation and, hence, are very prone to instabilities. Stability analyses [136, 181–183] have led to further understanding of the appearance of NIC instabilities and their mitigation. Moreover, the NIC designs are very sensitive to the actual parameters of the physical components used to realize them, as well as to their assembly with manual soldering. A very promising method that avoids component tolerance and assembly issues is to realize the NIC element as a complementary metal–oxide semiconductor (CMOS) processed integrated circuit (IC) [184–186]. Another attractive approach recently reported is to not avoid the instabilities, but to use them to power the radiating elements as self-oscillating antennas [187]. The initial prototype crossed [187] and Huygens [188, 189] dipole self-oscillating antennas have significantly wide measured frequency-agile impedance bandwidths.

Yet another performance issue with active elements, particularly in a receiving antenna, is the signal-to-noise-ratio (SNR). There have only been a few investigations reported. Both [190] and [191] consider the active matching circuit approach. While the former indicates that there may be NF advantages overall, the latter concludes there are none. In contrast, the internal NF element approach SNR study [173] with the 3D NF CLL-based ESA shown in Fig. 8(b) demonstrated significant improvements. More studies will need to be performed to attain a conclusive answer in general if there is one. Again, because of the active nature of the systems, the SNR outcome may simply depend on the NF element design and how it is employed.

4. More Complex Electrically Small NFRP Antennas

One of the advantages of the NFRP ESA paradigm is that it facilitates incorporating several NFRP elements within an electrically small volume. Because the NFRP elements are not connected directly to the source in any way nor necessarily with each other, the function that each one performs can be developed (in many cases) completely independent from the others. Multifunctional ESAs are an immediate consequence. They are, of course, quite advantageous in many wireless applications desiring more capabilities in ever smaller footprints. Moreover, this separation of intended functions allows one to incorporate additional electronic components that are associated with either the driven or NFRP elements or both. This additional degree of design freedom allows one to achieve a variety of reconfigurable ESA systems.

4.1. Multifunctional Designs

A few of the earlier NFRP designs illustrate the multifunctional concept in an electrically small package. By introducing two orthogonal electric NFRP elements of different sizes and a bowtie-shaped driven element that excites both of them, linear polarized (LP) fields at two independent frequencies of operation, GPS-L1 and Global Star (GS), were obtained in [192]. Moreover, CP fields were also obtained at a specified operating frequency $f_0$ with the same configuration without any phase shifter simply by adjusting the NFRP element shapes and sizes to have one resonance slightly above $f_0$ and one below it so their reactances naturally provide the requisite 90$^\circ$ phase difference between the LP radiators. A three metal layer, dual-band CP version also made good use of the crossed-dipole resonator configuration [193]. All had high radiation efficiencies.

The two resonator design was extended to four resonators in [194] to obtain CP fields radiated at the GPS-L1 and GPS-L2 frequencies. The tested prototype is shown in Fig. 9(a). Four interleaved magnetic-based protractor NFPR elements were driven by two printed monopoles fed with a single coax. The electric resonator concept was further extended to eight elements in [195]. The optimized design parameters of this compact structure were determined to naturally obtain CP radiation and multi-band operation that covered all five of the GPS bands, L1–L5. The tested prototype is shown in Fig. 9(b).

Other multi-band NFRP ESAs have also been developed. These include monopole [196] and dipole driven [197] elements loaded with CLL NFRP elements as their resonators. Integrating an AMC surface with pairs of crossed-dipole resonators, a tri-band CP antenna was achieved [198].

Filtennas are another multifunctional antenna concept that leads to more compact front-ends in wireless communication systems. They represent the advantageous integration of the filter(s) with the antenna into a single module. They possess attractive features such as a controllable passband frequency.
Figure 9: Experimentally validated multifunctional NFRP ESAs. (a) Four resonators for dual-band CP operation. [194]. (b) Eight resonators to obtain CP operation at all five GPS frequencies, L1-L5 [195].

response in both their reflection coefficient and realized gain values. They have become popular for the next generation of wireless devices supporting high-speed data rates and portable applications [199]. Electrically small filtennas that have relied on CLL-based resonators [200], more complex driven elements to attain LP radiation [201], and more complicated NFRP elements to achieve more bandwidth for both LP and CP performance [202].

4.2. Reconfigurable Designs

Reconfigurable antennas are now a standard means to achieve multifunctional performance in wireless mobile terminals [203, 204]. Innovative technologies have advanced their capabilities [205]. Nevertheless, achieving reconfigurability in an electrically small package remains a challenge.

Several reconfigurable NFRP ESAs have been developed. Systems that change both pattern [206–211] and polarization [212] characteristics have been investigated. The NFRP paradigm has been particularly advantageous because the switches can be placed either in the driven elements or in the NFRP elements.

Two examples are illustrated in Fig. 10. The pattern reconfigurable ESA [208] shown in Fig. 10(a) radiates three unidirectional beams along the horizontal plane into separate 120° sectors with beamwidths completely covering each of them. The driven element is fixed. Diodes are embedded in the electric and magnetic NFRP elements and are switched on and off to direct the beam into the desired sector. Thus, this ESA provides coverage of the entire azimuthal plane.

The polarization reconfigurable ESA [212] shown in Fig. 10(b) has its NFRP elements fixed. The diodes are incorporated into its driven element. It radiates unidirectional fields in the broadside direction. Depending upon the ON and OFF states of the diodes, it radiates one of four polarization states: one of two LP states along two orthogonal planes and either LHCP (left-hand circular polarization) or RHCP (right-hand circular polarization) states.

Figure 10: Experimentally validated reconfigurable NFRP ESAs. (a) Pattern reconfigurable ESA whose unidirectional 120° sector beams point along the azimuthal plane [208]. (b) Polarization reconfigurable ESA that can radiate four different polarization states: two LP and two CP [212].

5. Directive Electrically Small NFRP Antennas

As noted above, electrically small electric and magnetic dipole antennas have a directivity near to 1.5 (1.76 dB). More importantly for the following discussion, they radiate a figure-eight pattern in one principal plane with its null directions being along the dipole’s axis and an omnidirectional pattern in the orthogonal one. An ESA that would radiate primarily into one hemisphere rather than both, i.e., that would have a high front-to-back ratio (FTBR), would have many advantages for applications in which maximizing the power radiated (received) towards a receiver (from a transmitter) is desirable. For instance, as a transmitter, it would not waste half of its radiated power in an unwanted direction. Moreover, if this could be achieved without the necessity of a ground plane, an antenna engineer would have more flexibility in integrating the antenna system with a mobile platform. For instance, while a monopole antenna with a finite ground plane has an omnidirectional pattern about it, its peak direction is significantly elevated from it. An NFRP ESA such as the one shown in Fig. 10(a) does not have a ground plane to finesse. Its peak is along the horizontal plane and it has a high FTBR with respect to the selected beam direction.

The two main approaches to achieving higher directivity with a NFRP ESA have been the use of a quasi-Yagi configuration in which a NFRP element acts as a director and/or another acts as a reflector. The other is by engineering a Huygens source, i.e., by arranging the driven element in manner that it effectively excites a balanced pair of in-phase electric and magnetic NFRP elements. Both approaches have achieved unidirectional endfire and broadside radiating sources.

5.1. Quasi-Yagi

The quasi-Yagi ESAs come in two main styles, 2D and 3D. For instance, the 2D version [213] is printed on a single copper-clad substrate. While it had a modest directivity, it was flexible. Its prototype was tested successfully in two bending modes and on
cylinders of different radii.

The 3D versions have quite different arrangements. A spiral-shaped driver and director mounted on a ground plane were very closely spaced in [214] and obtained an endfire realized gain of 8.81 dBi at 450 MHz. The LP ESA shown in Fig. 11 consisted of three EAD elements. Basically an EAD NFRP antenna (driven and NFRP elements) integrated with an EAD parasitic reflector. Two variations of this design were reported [215]. One prototype operated around 0.96 GHz with \( ka = 0.76 \) and its reflector separated from the tightly coupled pair by approximately \( \lambda/10 \) at the upper frequency of its 9.4\% FBW, 1.02 GHz. Its radiation efficiency (RE) was greater than 93\% and its peak broadside directivity (along the axis of the system) was 5.05 dB with a 11.4 dB FTBR. The second was \( ka = 0.5 \) version of the first with a slightly smaller profile operating around 1.1 GHz with a narrower 2.3\% FBW. The peak broadside directivity was 4.2 dB with a 5.8 dB FTBR. A related CP ESA [216] consisted of a driven crossed-dipole loaded with NFRP elements and a similarly shaped cross-dipole reflector. Its prototype had \( ka = 0.71 \) and a \( \lambda/15 \) profile with a 10.56\% 3-dB AR bandwidth centered around 1.47 GHz. It had a broadside gain was 2.31 dBi with a FTBR of 6.4 dB and a 80\% average RE value at 1.39 GHz.

A pattern reconfigurable version of the spiral-shaped system was reported in [217]. A polarization reconfigurable version of the EAD-based system shown in Fig. 11(a) is reported in [218]. With diodes integrated into its driven element, it achieves four polarization states, 2 LP and 2 CP with peak realized gains around 3 dBi and greater than 10 dB FTBR and 70\% RE values.

A 300 MHz NFRP EAD antenna was integrated with a slot-modified parasitic copper disk to obtain an electrically small system with a high directivity and a large FTBR in [219]. The EAD NFRP element acted as the director. The slot-modified disk acted as the reflector. They were separated by \( \lambda/10 \). The system radiated a broadside unidirectional cardioid pattern with significant directivity and an increase of the FTBR value relative to the EAD antenna alone. It had a high radiation efficiency, but very small FBW, < 1.0\%. In order to achieve more bandwidth, the parasitic disk was augmented with NIC-based capacitors. A wider directivity bandwidth was achieved [165]. Both the EAD element and the parasitic disk were later augmented, respectively, with a NIC-based inductor and NIC-based capacitors [164]. This 300 MHz NF-based ESA is illustrated in Fig. 11(b). It had \( ka = 0.5 \) and attained peak directivities greater than 6.3 dB with larger FTBR values > 20 dB and RE values > 84\% over a much larger realized gain bandwidth, > 10\%. It was the first example of an ESA that overcame all of the conventional tradeoffs, i.e., it was efficient and had a large bandwidth with high peak directivity and FTBR values over it.

### 5.2. Huygens Dipole Antennas

Much recent work to achieve ESAs with higher directivity has been focused on Huygens sources. A Huygens source is actually well-known originally from reflector antenna developments [4]. A crossed electric and magnetic dipole combination located at the focal point of a parabolic reflector will induce currents on its surface that are parallel everywhere leading to cross-polarization free far-field behavior.

The magneto-electric antennas that originated in the mid-2000’s [220] are nicely reviewed in [221]. While the electromagnetics is the same, they have been described in terms of complementary sources. A large number of other authors have reported modifications and improvements of the original design, e.g., [222, 223]. They are distinguished from the electrically small systems to be described next in that they are on the order of \( \lambda/2 \) in size. Recent works have discussed a miniaturized version by included a CLL-based metamaterial into the configuration [224] and a reconfigurable system [225].

The NFRP Huygens dipole antennas (HDAs) consist of a driven element and orthogonal electric and magnetic NFRP elements. As shown in Fig. 12, when the equivalent electric and magnetic currents arising from the driven antenna exciting the NFRP elements are properly balanced, they produce a unidirectional cardioid pattern [226, 227]. The direction of the peak directivity follows from the right-hand rule of the electric current direction crossed with the magnetic one.

The initial NFRP ESA was the endfire planar LP design shown in Fig. 13(a) [228]. Its electrical size was \( ka = 0.46 \), and...
it was resonant at 1.475 GHz. It was designed with two 0.7874 mm thick Rogers Duroid disks and the subsequent three copper layers. A transmission line oriented along the x-axis feeds a dipole antenna oriented along the z-axis on the middle layer. The dipole excites an electric EAD NFRP element printed on one outside surface that is oriented parallel to the z-axis and two magnetic CLL-based NFRP protractor elements printed on the other one whose dipole moments are oriented parallel to the y-axis. As shown, the radiated cardioid pattern had its peak directivity, 4.50 dB, along the +x-axis at $f_{\text{res}} = 1.54$ GHz and had a 17.1 dB FTBR value. The overall (RE) efficiency was 85.9% (86.6%). The unidirectional emitter shown in Fig. 10(a) is of a similar endfire HDA nature.

The first broadside radiating HDA is shown in Fig. 13(b). It also consisted of two of the same copper-clad substrates. A coax-fed dipole is printed on the bottom surface of the lower one; the EAD NFRP element is printed on the upper one. Two 3D copper CLL NFRP elements lie on the top surface of the bottom substrate. The gap at the center of the EAD is traversed with an inductor. The offset gaps of the CLLs are traversed with capacitors. The resonance frequency was 299.17 MHz and its $ka = 0.45$ with a 87.9% RE value. It was very low profile, the overall height being $\lambda_{\text{res}}/78$. The measured $\text{FBW}_{10\text{dB}}$ of the prototype was 0.62%, i.e., a 9.3 MHz, –10-dB impedance bandwidth. As a consequence, its design was modified to achieve a better passive performance and the lumped elements were replaced with NIC versions. The resulting NF-augmented HDA had a FBW that was 10 times larger [170]. Most recently the preliminary results of a frequency-agile self-oscillating NF Huygens radiator were presented that has a measured 1:2 bandwidth, from 30 to 60 MHz [189].

A different endfire HDA was reported in [230]. It also was a two Rogers Duroid disks substrate layer design. A printed spiral acted as the magnetic NFRP element. Meander-line inductor-loaded electric dipole driven and NFRP elements completed the design. It had $ka = 0.47$ at the ISM-band frequency, 0.916 MHz, and was very low profile with a height of $\lambda_{\text{res}}/103$. The directivity was 4.66 dB and an RE of 66.4%. Its $\text{FBW}_{10\text{dB}}$ was 1.65%. Another broadside radiating HDA was reported in [231] that evolved from [229]. Two complementary spiral resonators (CSRs) and a CLL structure were used as the electric and magnetic dipoles, respectively.

A CP HDA was developed in [232]. It is illustrated in Fig. 14. It consists of two orthogonal pairs of EAD-CLL NFRP elements driven by a coax-fed crossed dipole. The electrically small ($ka = 0.73$) prototype operated at 1584 MHz. It was a low profile design with its height being $\lambda_{\text{res}}/25$. The measured peak realized gain was 2.7 dBic with a 17.7 dB FTBR value and a 68% RE value. In a similar manner to the introduction of multiple EAD and CLL elements into an electrically small package, a variety of yet more complex, multifunctional HDA-based systems have been realized. A two LP, one band system was reported in [233]. A dual band LP system was reported in [234]. A two port, dual CP system was reported in [235].

**Figure 13:** Huygens dipole antenna configurations. (a) Endfire radiating [228]. (b) Broadside radiating [226].

Note that the $\text{FBW}_{10\text{dB}}$ of Fig. 13(a) was 1.57%. Similarly, the $\text{FBW}_{10\text{dB}}$ of Fig. 13(b) was 0.20%. Because of the delicate balance needed between the electric and magnetic resonators, the bandwidths of these HDA systems are narrow. The measured $\text{FBW}_{10\text{dB}}$ of the prototype was 0.62%, i.e., a 9.3 MHz, –10-dB impedance bandwidth. As a consequence, its design was modified to achieve a better passive performance and the lumped elements were replaced with NIC versions. The resulting NF-augmented HDA had a FBW that was 10 times larger [170]. Most recently the preliminary results of a frequency-agile self-oscillating NF Huygens radiator were presented that has a measured 1:2 bandwidth, from 30 to 60 MHz [189].

5.3. Additional Reported ESAs

As previously noted, ESAs have attracted significant interest in the antennas and propagation community and beyond. Whether you like or dislike “metamaterials (MTMs),” the fact is that they have caused a true disruption in the way that many researchers view artificial materials and think about and understand the
physics and engineering associated with electromagnetic-based radiating and scattering systems. Over time, those insights may be the most important contribution that the MTM frenzy has made. As with the already noted examples, they have impacted numerous ESA designs.

Nevertheless, there are many miniaturized antenna systems that have been conceived and explained with conventional approaches. The four-arm spherical helix antenna [25] is an excellent example from the first decade of this century. Another is the omnidirectional monopole-driven slot antenna [236]. This antenna was further showcased in the measurement analysis and campaign in [237]. A very important aspect of this work is that it nicely emphasizes the difficulties associated with measuring ESAs and provides reasons why they occur and the means to mitigate them. The list of potential problems, e.g., currents on measurement cables, misalignment of the surface normal, and polarization mismatch, is rather daunting. You will notice sleeve (bazooka) baluns in the prototype pictures herein which were necessary to help ensure accurate measured results.

As one moves to higher frequencies, these measurement difficulties increase. Discrepancies between simulated and measured results are most often predominantly blamed on fabrication and assembly errors, especially when the antenna under test (AUT) is simply put into a commercial test range and a button is pushed. While the ESA measurement demands of reviewers continue to be unrelenting, i.e., “no measurements, no publication”, this topic has received little attention in the literature despite its importance. It deserves more consideration.

An ESA constructed as a driven monopole coupled to a custom-designed parasitic was developed in [238] for hearing-instruments. A meander dipole-based ESA was tailored for a RFID-based pressure sensor in [239] for glaucoma monitoring. Many other more conventional ESAs have been developed for a variety of medical related applications [240]. They all have important societal benefits.

While there are a vast number of compact/small antenna articles published indicating MTMs as being part of the radiating/receiving structures and none are actually present, there are others that are intimately connected to metamaterial-inspired concepts if one were to examine them closely. For example, the patch antenna in [241] was made small using a shorting pin and a defected ground structure (DGS) (i.e., DGSs evolved originally from electromagnetic bandgap (EBG) structures, which have often been identified as MTMs [41]). The interesting NFRP ESA developed in [242] is close in design to a 2D magnetic EZ antenna [102]. The RFID antennas considered in [243] involve a driven dipole coupled to a NFRP CLL element. The LC resonators loading a planar inverted-F antenna considered in [244] are well-known MTM unit cells. Directly driving 2D split-ring resonators (SRRs) led to interesting performance characteristics in [245]. Directly driving 3D SRRs led to the excitation of both electric and magnetic responses and an attractive quasi-isotropic ESA in [246]. Does it really matter whose favorite terminology is used to explain an antenna’s operation if it is actually correct and helps a reader understand it? Absolutely not! What is really important is if the antenna does what is intended, has good performance characteristics, and has been described adequately for a reader to understand its operation and to be able to reproduce the reported results.

6. Forward Looking ESA Applications

Given the anticipated demand for efficient, multifunctional, compact wireless devices for AWE-inspired applications, there are many opportunities for the development of novel practical ESAs for current fifth generation (5G) and evolving 6G and beyond systems. However, to make significant progress, multidisciplinary approaches involving not only further electromagnetic discoveries, but also unfolding material, circuit and measurement advances must be cultivated and nourished. Several topics that my team and collaborators are currently investigating are discussed below. They are but a tiny subset of the multitude of possibilities open to the antennas and propagation communities.

6.1. WPT and Rectennas

It is expected that AWE wireless and electronic devices have the potential to revolutionize many aspects of human life. They are being employed not only in consumer areas like communications, personal entertainment, smart homes, intelligent transportation systems, and smart cities, but also for security and health-care applications. However, the lack of very compact, long-lasting portable power sources has hindered the deployment of many IoT concepts, e.g., current battery and supercapacitor systems are too large, too heavy, or too short-lived. Consequently, wireless power transfer (WPT) technologies (e.g., also termed microwave power transmission (MPT) when restricted to microwave frequencies) have become a major trend to overcome this issue.

WPT systems negate the need for heavy, bulky, short-lived batteries and for their replacement, particularly in devices embedded in the human body or in structural materials such as in building and tunnel walls or bridge road beds. Moreover, they are environmentally friendly in the context that they avoid the need to dispose of those short-lived batteries. Furthermore, many WPT-enabled devices can be powered simultaneously from the same source. The recent pursuits of the IoT paradigm have led to the intense development of a variety of WPT technologies [247, 248].

WPT comes in many forms: near-field, mid-range and far-field systems. I will emphasize only the far-field systems. There are two main approaches to wirelessly powering devices remotely and robustly over long distances. One exploits already available ambient electromagnetic resources through wireless energy harvesting (WEH), i.e., unintentional WPT or energy recycling, which is discussed nicely, e.g., in [249–251]. Because the magnitudes of the transferred unintentional wireless power are small, WEH takes advantage of many existing frequency bands and necessarily requires broadband or multi-band antennas to capture as much of the available spectrum as is possible.

The other WPT approach is intentional WPT in which sources radiate fields at specified frequencies to wirelessly power a device. Intentional WPT aims to transfer as much power as possible from the wireless source to the targeted devices. Far-field WPT has a long history dating back into the
1960’s. There are several very nice reviews of the past and recent developments [252–260]. A major component of any far-field WPT system is a rectenna, i.e., a receiving antenna integrated with a rectifying circuit to convert the incident electromagnetic (AC) power into DC power. Narrowband operation within specific frequency bands, particularly the industrial, scientific, and medical (ISM) bands, is quite common. However, the realization of high performance, ultra-compact (electrically small) rectennas, i.e., the antenna-rectifying circuit combination, is challenging. While a majority of IEEE publications on WEH and WPT have been associated with the microwave engineering community, a variety of electromagnetic analyses have also been reported. For instance, the theoretical bounds on the power transfer efficiency (PTE) and those associated with practical antennas has been studied, e.g., [261, 262]. Reviews of the key components of rectenna systems and their design requirements can be found, e.g., in [263, 264]. Reviews of antennas for microwave [265] and millimeter-wave [266] WEH and WPT, as well as the applications of metasurfaces to WEH and WPT [267, 268], have very recently appeared.

IoT devices such as sensors, communication devices, and RFID (radio frequency identification) tags require a single rectenna that is electrically small, but has a large energy capture capacity. Consequently, the HDA systems with their cardiod-shaped radiation patterns are notably advantageous. They acquire the maximum amount of power from their driving sources while not wasting power radiated in the opposite direction. A CP system has notable advantages over a LP one in certain scenarios in which the orientation of the rectenna is not guaranteed and the WPT source is either a LP or CP system.

Some of the initial metamaterial-inspired ESAs were transformed into rectennas by integrating rectifying circuits with them. Both electric [269] and magnetic [270] NFRP antenna prototypes demonstrated their predicted performance characteristics. Moreover, the NFRP HDA systems discussed above were recently adapted to realize electrically small \((ka < 0.77)\) and low-profile, 0.04 \(\lambda_0\), linearly (LP) and circularly (CP) polarized WPT rectennas at 915 MHz in the ISM band [271]. They too were facilitated by the seamless integration of highly efficient rectifiers, i.e., the RF signal to DC power conversion circuits, with the LP and CP HDAs. Their optimized prototypes have cardioid, very wide broadside radiation patterns, and effective capture areas larger than their physical size. Experimental results verified that they achieved a measured 89% and 82% peak AC-to-DC conversion efficiency, respectively, effectively confirming their simulated results.

One important lesson learned with those early electrically small rectenna systems was that the NFRP designs could be modified so that the antenna was matched directly to the rectifier without any intervening matching network, significantly improving their conversion efficiencies. While this aspect of the NFRP design approach was employed in the LP HDA system in [271] to attain its high conversion efficiencies, the original CP HDA rectenna design could not be tuned to be matched directly to the rectifier. The power lost to the necessary matching element was remedied in [272]. By changing the driven dipole to a more inductive form, the antenna was matched directly to the rectifier and the system reached a maximum conversion efficiency of 90.6%. The effectiveness of directly matching the receiving antenna to the rectifier in both WPT and WEH rectenna systems was also emphasized in [273].

The advantage of the NFRP paradigm to facilitate the presence of orthogonal LP HDAs simultaneously as illustrated in Fig. 14 was further explored for a simultaneous wireless information and power transfer (SWIPT) in [274]. SWIPT is currently being investigated in a wide range of different systems for both civil and industrial applications [260, 275]. It is one aspect of the green communications concept [276]. The CP HDA antenna and HDA rectenna designs guided the modifications needed to achieve a SWIPT HDA system. The prototype HDA-based SWIPT system had two integrated ports. One LP HDA pair was attached through one port to a rectifier for the WPT performance. The second, orthogonal LP HDA pair and its port were dedicated to communications. Similar performance characteristics to the LP versions of the LP HDA antenna and rectenna systems were obtained with over a 30 dB isolation between the two functions.

### 6.2. Wirelessly Powered Sensors

The next generation of sensors and control systems will be embedded in the AWE-inspired IoT electronic devices and will be consequential if they are powered with WEH and WPT technologies [277–281]. Wirelessly powered sensors and sensor networks for monitoring the health of humans (Wireless Healthcare), crops (Smart Agriculture), buildings (Smart Buildings) and even all systems and activities associated with urban environments (Smart Cities) are but a few of the imagined applications. They all will require large scale, battery-free cooperative wireless sensor networks. The HDA rectennas coupled with sensors are exceptional candidates as nodes for these systems.

Two electrically small rectenna-based wirelessly powered light and temperature sensors were developed in [282] that operate at 915 MHz in the 902–928 MHz ISM bands. One was a NFRP EAD antenna that was seamlessly integrated without any matching network with a highly efficient sensor-augmented rectifier. Its prototype was electrically small with \(ka = 0.47\) at its resonance frequency, 906 MHz; was very thin (a single piece of copper-clad substrate); and its peak realized gain was 1.27 dBi. Because the system acts as an electric dipole, its omnidirectional property is ideal for capturing incident AC wireless power from any azimuthal direction and converting it into DC power. Both a photocell as the light sensor and a thermistor as the temperature sensor were demonstrated. The resistive properties of the photocell and thermistor changed the rectifier’s output voltage level; an acoustic alarm was activated once a threshold value was attained. A peak 90% AC-to-DC conversion efficiency was obtained and its omnidirectional pattern was confirmed.

A LP version of the three layer electrically small, low-profile NFRP HDA shown in Fig. 14 was designed and similarly integrated with the same light- and temperature-sensor-augmented rectifiers. Its prototype had \(ka = 0.73\) at its resonance frequency, 908 MHz, and was low profile with its height being \(\lambda_{res} / 25\). Its broadside realized gain cardioid pattern had a 3.8 dBi peak value, more than 3 dB higher than the EAD value. The measured
peak AC-to-DC conversion efficiency was 88%.

Measurements of the prototypes of both the light-sensor and temperature-sensor augmented omni- and unidirectional rectenna systems confirmed their predicted performance characteristics. Wireless powering of both the sensor and alarm systems was demonstrated. The omnidirectional nature of the EAD-based sensors is ideal, for example, for ceiling mounted systems in long galleries in a museum. The unidirectional nature of the HDA-based sensors make it very suitable, for example, for surface-mounted applications, e.g., as temperature and light sensors on a wall in an office building or even on wine barrels resting in a cavern. As demonstrated in [227], the NFRP HDA design can be modified for placement on the surface of such dielectrics and still maintain its unidirectional performance characteristics.

A single Rogers Duroid\textsuperscript{TM} 5880 substrate version of the LP NFRP HDA shown in Fig. 15 was developed recently and integrated with the same sensor-augmented rectifiers [283]. Like the original endfire HDA [228], this ultra-thin rectenna system had a large electromagnetic wave capture capability and achieves nearly complete conversion of the incident energy into DC power. The HDA prototype has a realized gain of 4.6 dBi and a half power beamwidth (HPBW) of 134°. The entire rectenna is electrically small with $ka = 0.98$; is low cost and easy to fabricate; and has a measured 88% peak AC-to-DC conversion efficiency. As discussed in [254], large-scale rectenna arrays are usually implemented to capture larger amounts of power. This ultra-thin HDA system is an attractive candidate for a multi-element HDA-based rectenna array. Such a system is currently under development.

![Figure 15: Ultra-thin NFRP HDA WPT system. (a) Antenna alone. (b) Antenna augmented with the sensor. [284]](image)

6.3. Pregtronics

The concept of integrating antennas into structural materials has many applications for sensor networks and communication systems. Incorporating such electromagnetic systems into, for example, the actual bodies of land, sea and space vehicles as well as in buildings, bridges, and tunnels, one could monitor many different properties of those structures and the environments in which the operate, as well as perform their electromagnetic functions. It becomes much more than an antenna problem. It necessitates the co-design of the antenna with the materials with further adjustments in the design and implementation as the materials and fabrication processes occur and evolve.

For instance, multifunction, conformal load-bearing antenna structures offer unique structural weight savings and aerodynamic advantages in composite aerospace platforms. Many aircraft communications systems fall within the HF to UHF bands. Efficient antennas in those ranges are physically large and are generally found in the form of blade/surface monopole and/or lone wire antennas. With the advent of new antenna technologies such as the NFRP ESAs, the ability to seamlessly integrate their passive and active versions into aerospace platforms has become increasingly important. They have the key capability to be downsized for integration into small aerospace platforms. This is particularly interesting in the case of smaller unmanned aerial systems (e.g., drones) where there are significant internal volume and weight restrictions [285, 286].

A version of the EAD ESA [286] and versions of the electronics that would be needed for its NF-augmentation [285] have been developed for use in a grade of composites called “pre-impregnated” (pre-preg) materials. These pre-preg materials differ from traditional textiles in that they contain a B-staged epoxy resin that must be baked in an autoclave at temperatures greater than 170° C, and under pressures upward of 700 kPa to achieve their maximum strength. Before this curing process, they can be conformably molded to any surface. Carbon fiber reinforced plastics used in tennis rackets and bicycles are now everyday examples of these composite materials.

The antenna consisted of a differentially fed dipole element integrated with a NFRP EAD element. To achieve good matching when the antenna was in situ, a meanderline-loaded version of the dipole element was found to be necessary. The system was designed and tested at the arbitrary frequency of 300 MHz. Three ESA cases were investigated to ascertain the performance of the manufacturing techniques and material properties used to build them, as well as their performance characteristics. Photos of their prototypes are shown in Fig. 16. Uniquely, an embroidered conductive thread and a new carbon fiber based, non-woven mat were investigated for use as the conducting elements. Both cases were compared with a copper variant of the EAD antenna. The embroidered version was achieved by learning how to and then sewing the components of the antenna into the pre-preg before curing. It was the original approach and required a programmable, heavy duty sewing machine to sew the desired shapes. The veil version has since become the standard. The required shape can be laser cut out from a large piece of the non-woven mat. All three prototypes were tested. Measurements confirmed that both the non-woven mat and the embroidered versions of the EAD antennas performed similarly to the copper version [286].

Microwave pre-preg electronics, i.e., “pregtronics”, was similarly established originally with embroidered transmission line studies and then by incorporating an ultrawideband (UWB) amplifier as the main component of a microwave circuit [285]. Although only a simple UWB microwave amplifier-based circuit was demonstrated, it is clear that this pathfinder prototype circuit with its passive and active components demonstrated the hybridization of composite structures and electronics. Extending the concept to incorporate digital electronics and combining all of the pregtronic concepts with the ESAs have been considered. These co-designed pregtronic-based ESAs allow for
the development of smart sensing, conformal structures/skins which would offer a significant advantage for efficiently utilizing the limited volume available on unmanned aerial vehicles (UAVs) and other mobile platforms.

### 6.4. Millimeter-wave Designs

One evolutionary technology in 5G cellular systems that is finely happening is the use of the millimeter (mmWave) frequency spectrum to realize the high data rates and system capacities that have been forecast to meet the evergrowing demands of consumers. Experimental results have proved that the 28 GHz frequency band is a suitable band for the initial rollouts of some mobile terminals. While much of the chatter about 5G antenna systems has been focused on millimeter-wave arrays, compact antennas continue to be in demand for many IoT applications.

Both LP and CP NFRP HDA ESAs have been developed for the 28 GHz band [287]. The LP model and its prototype are shown in Fig. 17(a). Only simulations of the CP model were provided. The use of both the LP and CP systems for on-body use were evaluated and it was demonstrated that the body had little effect on their electromagnetic performance characteristics. The potential of these HDA systems for on-body SWIPT applications is currently being investigated.

Omnidirectional CP (OCP) antennas with lower gain are expected to be the most suitable candidates for general device-to-device (D2D) applications in 5G wireless systems. They have much larger radiation coverage and, hence, enable diverse communication links among multi-users. An 28 GHz OCP ESA was realized in [288]. The model and its prototype are shown in Fig. 17(b). Instead of the electric and magnetic dipole elements being orthogonal, the balanced pair are parallel in this OCP design. It is believed to be a very good candidate for D2D communication applications.

As one can see from their photos, these 28 GHz ESAs are really tiny. While it is anticipated that electrically small versions of any antenna system will continue to be desired even as the operating frequencies increase, their physical sizes may be small enough for many applications. Moreover, the highly directive beams necessary for a variety of 5G and beyond millimeter-wave applications does necessitate arrays. Several examples of end-fire arrays of HDAs in the millimeter-wave bands have been reported at 30 GHz, e.g., [289] and 60 GHz, e.g., [290]. Since it has been shown that the NFRP HDA designs can be tailored for on-chip applications [227], arrays of them for millimeter-wave WPT (mmWPT) are currently under development.

### 7. Summary

While many electromagnetic, antenna and metamaterial researchers are focused on array developments for current 5G and evolving 6G beyond systems, the usefulness of efficient electrically small multifunctional, reconfigurable antennas as the ideal candidates for many of the emerging AWE-inspired IoT applications cannot be overstated. Given the concerns over how much energy will be needed to enable arrays for the anticipated 5G and beyond wireless ecosystems, any reduction of the power required by individual elements associated with high performance wireless mobile terminals and their enabling antenna systems will be welcomed. The WPT concepts discussed herein will help make 5G and beyond IoT systems more sustainable. Years of simply designing the electronic circuits and the antennas independently of each other and using intervening matching networks to enable their combinations has to stop. Co-design will only increase performance as well as save time and money. Integration of the electrically small transmitting and receiving systems directly into structural materials will decrease the weight and enhance the aesthetics of IoT devices and enable a host of applications. Co-designing compact antenna systems with novel materials to enable their functions such as reconfigurability at high millimeter-wave frequencies will have to become commonplace. Associated multidisciplinary approaches to realizing these antenna systems will become the norm as will more advanced measurement techniques to verify their performance characteristics. While you may not have been awestruck by the plethora of ESAs developed in the last two decades, I sincerely hope that the various concepts discussed and illustrated in this Overview will stimulate innovative ways
of looking at your old and new problems and, hence, prove useful to your current and future research efforts.

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