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Electrically Small Antennas for Maritime Wireless Applications

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ABSTRACT

The maritime wireless communication requires robust radio links and high throughputs for effective and reliable connectivity and networking between various vessels and offshore units. The design and development of antennas for such applications require various complex considerations to meet not only the specific application requirements but also to ensure the performance requirement within a multitude environment and compact antennas with low weight and small form factors are required. Moreover, efficient antennas are needed both at transmitter and receiver for reliable wireless links for various frequencies. However, at low operating frequencies, like VHF band, the size of the antenna is very large resulting from high operating wavelength. Such large size of antenna and its resulting weight restricts the deployment of antennas on ships and vessels etc. This necessitates the design and implementation of small, low weight and efficient antennas or apertures preferably with beam-switching or beam-scanning capabilities for efficient transmission and reception of radio signals across the required bandwidth and beamwidth for effective communication, navigation and surveillance etc. For the lower frequency bands, the dimensions of antennas become very large due to longer wavelengths. By reducing the dimensions of antenna to large extent compared to operating wavelength, it becomes electrically small antenna (ESA). Such ESA suffers from narrow impedance bandwidth due to wide variations in port impedance and low radiation efficiency resulting from reduced radiation resistance. This article will discuss the design and measurement challenges and solutions for electrically small antennas and various design versus performance trade-offs and characterization challenges for ESAs will also be discussed.

1. Introduction.

Over the last two decades, a remarkable progress in terrestrial wireless communication has been observed, paving the way for a variety of high-speed and low-latency applications [1]. More recently, the surge in maritime activities like oil exploration, ocean aquaculture, scientific research, and tourism, has highlighted the need for enhanced broadband communication services tailored for naval users. The maritime wireless communication is crucial for maintaining the data and voice connectivity at sea. Moreover, this type of connectivity facilitates the crew members to be well connected with offshore nodes. In fact, the efficient connected technology solutions impact the maritime industry significantly by providing the services like internet of things (IoT) cellular connectivity, dedicated Wi-Fi services, and fully cloud-based supported wireless access networks to cater the fleets around the globe. It employs satellite technologies including LEO and VSAT, as well as cellular networks like LTE and 5G, along with radio communication via VHF and UHF links [1]. Such type of connectivity is critical for navigation and safety, especially for the systems like GMDSS, while also increasingly accommodating the high-speed IoT applications and future 6G capabilities. However, there are various challenges to overcome, including disruptions from weather, signal loss over water, and the requirement to sustain reliable, high-throughput connections for the vessels. The reliability of connection is critical in the maritime sector, especially considering the often-unpredictable nature of the sea. Various wireless connectivity technologies, such as satel-

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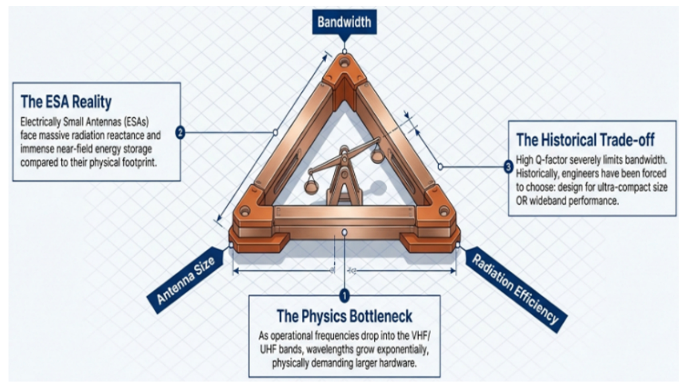
lite and cellular networks, are key to ensuring safety, efficiency, and pleasant experience for all on board. The reliable wireless communication and navigation systems enable vessels to coordinate the rescue operations, access real-time updates on weather and sea conditions, and keep both crew and passengers connected and informed. Moreover, such systems facilitate the seamless transportation of the goods across the globe. Despite ongoing technological advancements, it remains critical to carefully assess and maintain the reliability in all wireless operating environments. Designing a wireless communication system for maritime applications comes with its own unique challenges compared to those intended for terrestrial communication. This is mainly due to the high mobility of nodes such as ships and UAVs, along with the sparse scattering environments and the notable reflections off the surface of water. In this context, design parameters of wireless system must address issues like signal fluctuations or fading, ensure reliable long-range wireless connectivity, and efficiently managing the limited spectral resources available for intended application. The maritime wireless communication parameters are designed to effectively navigate the environments characterized by high latency and multipath fading/signal fluctuations. Such systems can employ VHF frequencies spanning over 156 MHz to 174 MHz for short-range safety communications, while using the 2.4 GHz and 5.8 GHz bands for high-speed broadband connectivity [2]. The antennas for such maritime wireless communication transceivers must be designed to withstand the challenges posed by a dynamic and highly reflective sea surface. Such environment can cause multipath fading, ship motion, and extreme weather conditions, all of which require robust antenna solutions. The critical parameters for required antennas include operating frequencies ranging from VHF to Ka-band, high gain for enhanced signal strength, vertical polarization to optimize the surface wave propagation, and beam-steering capabilities to ensure all-times reliable connections. The maritime wireless communication antennas are designed for high vertical placement to ensure a clear line of sight. They must be built tough to endure harsh conditions like salt, wind, and corrosion, while also featuring specific radiation patterns that accommodate pitch and roll stability. For optimal functionality, it is crucial to minimize antenna separation and to use low-loss cables that support high-frequency systems like 5G and satellite communications. In fact, very efficient, compact and low form factor antennas or antenna arrays are required to meet the challenging requirements of maritime wireless applications especially for VHF band links [3-4]. However, due to low operating frequencies, the size of the antenna is very large resulting from high operating wavelength [5-7]. Such large size of antenna and its resulting weight restricts the deployment of such antennas on vessels and ships. This necessitates the design and implementation of small, low weight and efficient antennas or apertures preferably with beam-switching or beam-scanning capabilities for the efficient transmission and reception of signals across the required bandwidth and beamwidth for effective communication, navigation and surveillance etc. For the lower frequency bands, the dimensions of antennas become very large due to longer wavelengths. By reducing the dimensions of antenna to large extent compared to its operating wavelength, it becomes electrically small antenna (ESA). Such ESA suffers from narrow impedance bandwidth due to wide variations in port impedance and low radiation efficiency resulting from reduced radiation resistance. The miniaturization paradox for ESAs can be represented as indicated in Fig.1.

Figure 1: The miniaturization paradox for the electrically small antennas (ESAs).



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The design, implementation and characterization of efficient electrically small antenna (ESA) can play a very critical role in realization of reduced size, low weight and power efficient low-cost solutions for maritime wireless communication applications including navigation systems. This necessitates the design and implementation of small, low weight and efficient antennas or apertures for efficient transmission and reception of radio signals across the required bandwidth and beamwidth for maritime wireless communication with improved connectivity.

2. Review and Analysis of Related Works.

The reduction in the form-factor of HF antennas compared to its operating wavelength results in eclectically antenna (ESA). The ESA suffers from various performance degradations including narrow impedance bandwidth due to wide variations in port impedance and low radiation efficiency resulting from reduced radiation resistance of ESA [7-9]. Designing an ESA with wider impedance bandwidth and improved efficiency across lower operation frequencies especially the HF band, is a challenging task. Various ESAs have been reported so far with small form factors but limited performance characteristics [6-7], [11-14]. For instance, the embedded shipborne antenna reported in [6] is based on slot antenna array structure which is excited through a strip line. However, the input resistance of this proposed antenna varies from 0.01 Ω to 1500 Ω over the frequency span of 7.5 MHz to 30 MHz. Consequently, this antenna cannot be matched over wider HF band to achieve nice levels of realized gains. Moreover, the slot feeding results in backward radiations to hinder its applications for high power HF communication. A dual polarized platform-based HF antenna design based on characteristic mode theory has been presented in [7]. The characteristic mode theory exploits the metallic platform to use it as main aperture and additional coupling elements were placed on other locations of platform to excite two orthogonal modes for dual polarization [7]. The simulation results for the full-scale model of the proposed antenna system with dual-polarized characteristics show operational bandwidth of 24 kHz and port to port coupling ≤ -20 dB (better than 20 dB isolation) for the frequency range of 3–10 MHz. The limitations of this antenna include narrow instantaneous impedance bandwidth of 31 KHz and realized gain of -15 dBi.

A semi?spherical antenna based on combination of loop antenna and transverse electromagnetic horn and has been reported in [15] for the frequency band spanning over 0.42 to 6 GHz focusing the ultra?wideband directional operation for 5G and beyond 5G military and commercial applications. The structure of the presented antenna fits within a sphere having radius of 30 mm or 3?cm resulting in as electrically small antenna for the lower end of its operational band (as ka = 0.5 at 0.795 GHz). Compared to the conventional design, the radiation efficiency has been improved by > 7% for ka = 0.5 and over 22% for the case of ka = 1(at 1.59 GHz). These improvements in efficiency have been realized through tuning of bowtie, transverse electromagnetic horn and resistive loading of the proposed antenna structure.

The work reported in [16] introduces an electrically small antenna designed with a metamaterial inspiration. This antenna, measuring 0.205λo by 0.205λo, features an innovative feeding method and is built with two different substrates. The simulated -10 dB impedance bandwidth for this antenna spans over 50 MHz around center frequency of 2.4 GHz. Another example of electrically small antenna is presented in [17] which employs metallic curved strips to achieve enhanced performance resulting in simulated 10 dB return loss impedance bandwidth of 22.4 MHz. A compact CPW-fed zeroth-order resonant type of antenna has been reported in [18] with dimensions of (0.201 x 0.205) λo. The expanded impedance bandwidth of 210 MHz has been achieved through an addition of chip inductors for this antenna design. A wideband compact antenna is discussed in [19], featuring antenna dimensions of (0.55 x 0.55) λo. This design is based on two arms with eight vias, resonating at 3.3 GHz and providing a 10 dB return loss bandwidth of 220 MHz. The work reported in [20] presents a compact planar monopole antenna supported by a 2 x 1 array of electromagnetic bandgap structures (EBG), with dimensions of (0.31 x 0.55) λo. Its simulated results indicate a -10 dB impedance bandwidth of 120 MHz. In [21], the reported electrically small dipole antenna utilizes a nonperiodic left-handed transmission-line structure, achieving a bandwidth of 4.8% through the optimization of series capacitors and shunt inductors. The research in [22] reports a single layer inductively coupled, capacitively loaded monopole antenna designed for 2.36 GHz applications, which achieves the simulated -10 dB impedance bandwidth of 0.4%. A CPW-fed electrically small antenna loaded with chip inductor has been reported in [23] for WLAN frequencies. The reported design incorporates an open-ended coplanar transmission line loaded with a chip inductor to achieve a compact antenna size and a 40 MHz bandwidth. In [24], the construction of an ESA using multiple coupled split-ring resonators (SRRs) is reported, revealing a six-layer antenna structure with a relative bandwidth ≤ 0.3%. The research work reported in [25] introduces a compact antenna design which incorporates a tunable inductor and an inductively coupled feed network. The measurement results for this antenna showcase the -6 dB impedance bandwidth of more than 110 MHz for 2.42 GHz applications. The gain of the electrically small antennas can be enhanced by increasing the effective dimensions of the antenna. This technique has been reported in [26] where the antenna's area has been expanded through array configuration to achieve the significant improvement in antenna gain from -15.4 dB to -5.5 dB. In summary, the reported passive type of ESAs especially those operating over lower band offer very limited form-factor versus performance characteristics [6-7]. For instance, the instantaneous impendence bandwidth for such antennas is very narrow although the operating frequency can be tuned for some of these reported antennas. Moreover, the radiation efficiencies of such antennas are not so high to enable them for lower applications.

3. Electrically Small Antennas Design Challenges and Solutions

The electrically small antennas (ESAs) are defined by their maximum dimension much smaller than the operating wavelength. For ESAs, typically $k\alpha < 0.5$ where k is the wavenumber and α is the radius of the sphere enclosing the antenna. The ESAs are characterized by their low radiation resistance, high reactance, and high Q-factors, resulting in narrow bandwidths. The performance characteristics of the ESAs are restricted by the Bode-Fano limit, which dictates a strict trade-off between size, bandwidth, and efficiency. It dictates that as bandwidth increases, the maximum attainable match (minimum reflection coefficient) decreases, restricting efficient operation to narrow bandwidths. Due to high capacitive or inductive reactance, ESAs need complex impedance matching networks/circuits, which often introduce resistive losses that further reduce the overall radiation efficiency of the antenna. As antenna size decreases, the Q increases resulting in narrower impedance bandwidth, and reduction in gain or efficiency of the antenna. The key design challenges include balancing the miniaturization with efficiency of an antenna, as they generally exhibit reduced bandwidth and gain. The electrically small antennas for the VHF applications, operating over 30 to 300 MHz, utilize innovative designs inspired by the metamaterial-based structures, meandered lines, or magneto-dielectric materials. These designs feature smaller footprints compared to the operating wavelength, often measuring dimensions of less than 0.1λo. To handle the challenges of low input impedance and narrow bandwidth, various techniques can be employed, including composite right/left-handed (CRLH) transmission lines, non-foster matching networks, and unique folded monopole geometries. In fact, there are various complexities involved in designing an ESA. The first challenge in ESA design is its impedance matching [27]. Conventionally, we might consider external impedance matching methods or techniques. However, it's crucial to realize that the matching network has an upper bound on achievable impedance bandwidth. Generally, there are two critical limits affecting the maximum bandwidth that can be achieved when passive matching circuits are used for ESA. The first limit is the minimum quality factor, which is directly defined by the maximum bandwidth of the electrically small antenna. The second one is called the Fano-Bode limit specific to passive matching circuits/networks. For an ESA, we face the challenge of matching an impedance that is comprised of very small resistance (real part of the impedance) which is frequency dependent alongside a significantly large capacitive reactance (negative imaginary part of impedance) to 50Ω. This can be accomplished through traditional methods, such as utilizing an L-section based on lumped elements, or through distributed elements like stubs. It's worth noting that such passive matching network can create an appearance of a larger antenna to the transmitter, or in other words, the resulting resonance is not realistic. The achievable bandwidth for matching a capacitive reactance to a resistance is constrained by the Fano-Bode limit. Consequently, the traditional matching networks typically offer a very narrow bandwidth for ESA. Secondly, the assumption of a lossless matching network often doesn't hold true in practice. When we use an L-section to match an electrically small antenna, it invariably introduces some losses. Therefore, it's crucial to consider these losses when designing the impedance matching circuit/network, as they can significantly influence the matching process [27]. In fact, these losses tend to overshadow the radiation resistance, consuming much of the incident power and converting it into heat rather than radiation. One approach is to create an adjustable passive matching network that can automatically tune itself to the desired frequency [27]. This would permit the antenna's bandwidth to shift as required, while ensuring that the bandwidth remains consistent whenever the center frequency is shifted. Another potential solution can be based on incorporating the non-foster elements in the matching network. These non-foster elements, which are considered active, include components like negative inductance or capacitance. By utilizing non-foster elements in the matching network, wider matching bandwidth can be achieved to overcome the limitations imposed by the Fano-Bode criterion. The implementation of these elements can be accomplished using active circuitry. A study in [28] highlighted a novel approach to achieving a negative capacitor using Negative Impedance Converter (NIC). Another effective strategy involves modifying the structure of ESA to enhance radiation resistance, enabling it to self-match to 50Ω with a design that features a low-quality factor. This approach can be termed and self-resonance. It's important to note that there is a fundamental design limit for ESA, known as the Chu limit, which determines the lowest achievable quality factor for an ESA. Designing an ESA that meets the criteria of self-resonance, self-matching to 50Ω, and nearing this minimum quality factor requires maximizing the effective volume occupied by the ESA architecture. The required volume can be compared to the volume of a hypothetical sphere that encloses the largest dimension of the antenna, which helps minimize non-propagating stored energy, thereby ensuring a lower quality factor [29]. Simultaneously, it is essential for the ESA's input impedance to be precisely 50Ω at the frequency of interest. One promising technique for achieving these objectives is the folded monopole design based on multi-arm meandered lines This technique is termed as miniaturization of antenna to enable it as electrically small structure due to lower operating frequency with reference to its electrical dimensions. In fact, various techniques have been reported in literature to tackle the ESA design challenges like its low input impedance and narrow bandwidth. These techniques include the use of composite right/left-handed (CRLH) transmission lines, distributed matching circuits, top loading, folding and meandering [30-35]. The goal of all these techniques remained to optimize the performance characteristics of an antenna which is electrically small either through improved impedance bandwidth or slowing down the wave velocity for given structure. For example, an ultra-wideband (UWB) electrically small antenna has been presented in [30] that utilizes distributed passive network loading. The structure of antenna presented in [30] is shown in Fig. 2. By using the principles from the theories of Vivaldi antenna, magnetic dipole antenna, and distributed loading, this design achieves broad bandwidth within a constrained three-dimensional planar Vivaldi antenna structure. The integration of the magnetic dipole antenna significantly enhances the low-frequency bandwidth of the small antenna without compromising its aperture size. Additionally, the implementation of distributed passive network loading enables effective wideband-conjugated matching while maintaining the compact dimensions of the antenna. As clear from Fig. 3, the antenna features a −6 dB bandwidth ranging from 0.2 GHz to 3 GHz, with overall dimensions of $(0.06 \times 0.05 \times 0.12)$ λo, where λo represents the wavelength at the lowest end of operational frequency.

Figure 2: The miniaturized ultra-wideband antenna (UWB) antenna structure reported in [30].

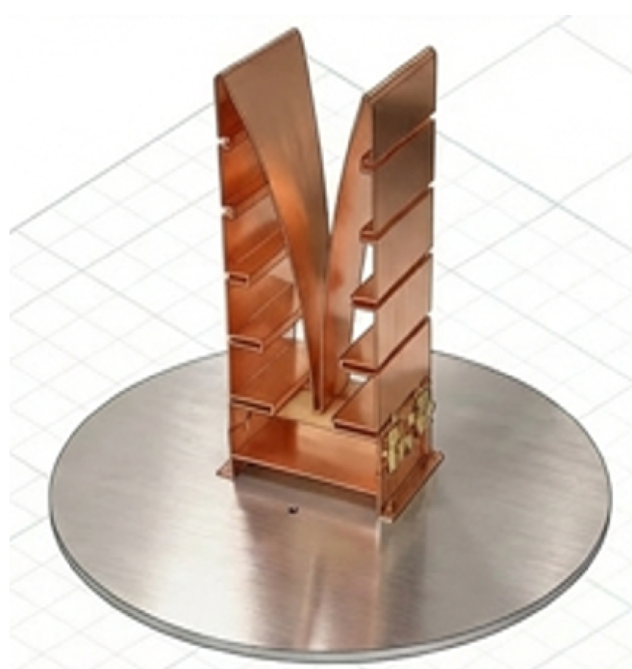

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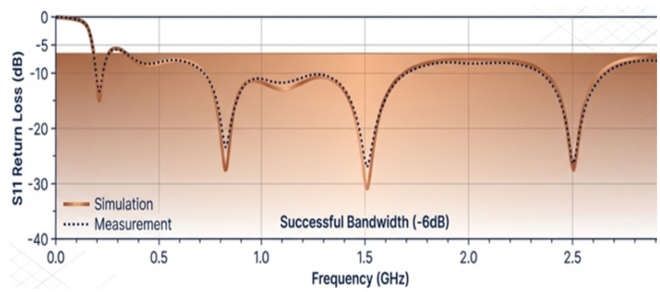
Figure 3: The simulated and measured S11 results for ultra-wideband ESA presented in [30].



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The work reported in [31] introduces a compact antenna design that utilizes a composite right/left-handed (CRLH) transmission line (TL) alongside a non-foster matching circuit as shown in Fig.4. The antenna is constructed using an interdigital capacitor (IDC) and a spiral inductor, specifically targeting the very high frequency (VHF) range. The dimensions of the antenna are $(0.025 \times 0.014 \times 0.0008)\ \lambda$ at 145.5 MHz, employing a zeroth-order resonance created by the CRLH transmission line. To further broaden its operational bandwidth, a non-foster circuit (NFC) has been incorporated featuring a pair of transistors configured in a cross-coupled arrangement. The presented antenna maintained excellent broadband characteristics despite its small size relative to its operating wavelength as clear from the impedance bandwidth characteristics shown in Fig. 5.

Figure 4: The compact antenna design that utilizes a composite right/left-handed transmission line (TL) alongside a non-foster matching circuit [31].

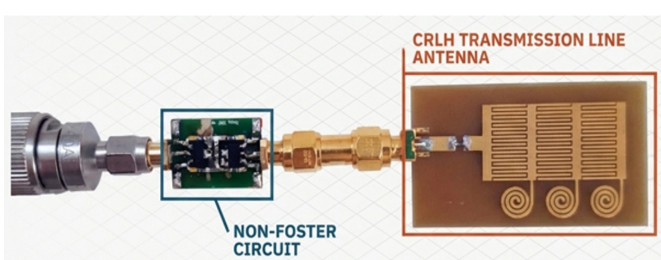

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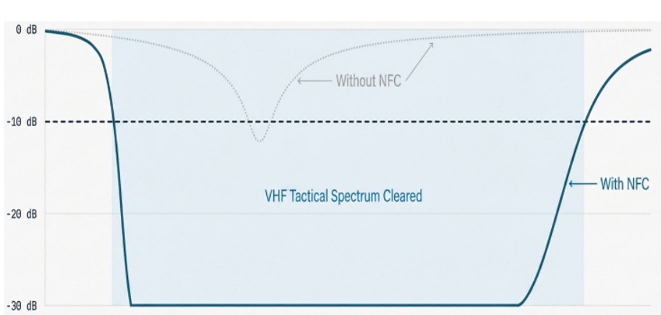
Figure 5: The operational bandwidth performance of the antenna design reported in [31].



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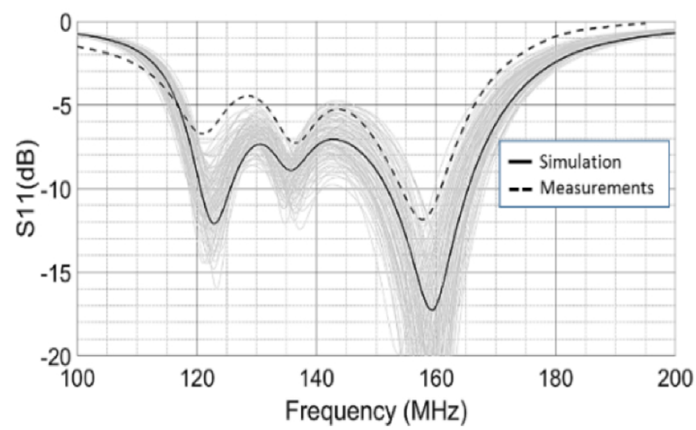
The work reported in [32] presents a miniaturized planar monopole antenna that employs a magneto-dielectric material for miniaturization purpose. The design employs slots which were partially covered by the magneto-dielectric material (MDM) resulting in high degree of optimization. By adjusting the topology and dimensions of the MDM, the antenna's performance is effectively enhanced, particularly with the addition of these slots. This monopole antenna achieves a miniaturization rate of 60%, reducing the height from 51 cm to 20 cm while utilizing only 5% of its surface area for the MDM. The measurement results for this antenna reveal that the antenna operates at a central frequency of 130 MHz, with a bandwidth increase of 30%, as shown in Fig. 6.

Figure 6: The simulated and measured S11 results for the antenna reported in [32].



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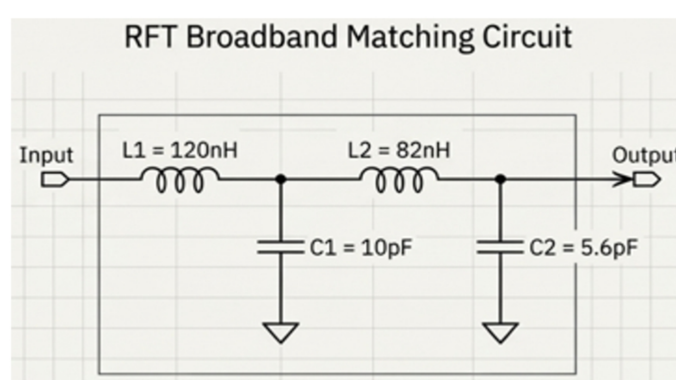
The improved impedance bandwidth for the miniaturized planar monopole antenna reported in [32], has been achieved through a broadband matching circuit designed using the Real Frequency Technique (RFT) shown in Fig.7.

Figure 7: The broadband matching circuit designed using the Real Frequency Technique (RFT) [32].



Source: Authors.

The study in [33] introduced a compact frequency-tunable monopole antenna designed for the medium frequency/high frequency (MF/HF) band, featuring an omnidirectional radiation pattern. The design incorporates a capacitive top, which enables the antenna to resonate effectively at lower frequencies, complemented by a variable inductive load. By leveraging the capacitively loaded top, notable increase in the antenna's radiation resistance was reported. The resonant frequency can be adjusted across a broad spectrum (0.974–30 MHz) while maintaining the overall size of the antenna, attributed to the loaded through tunable coil. The tuning system for this antenna is comprised of arms, motors, a contactor, a microcontroller, and remote-control capabilities. The experimental results reveal measurements with ka values of 0.01, mag(S11) ≤ −15.8 dB, gain level better than −13.9 dBi, and efficiency (?) is around 2.2% at lowest resonant frequency of the presented antenna [33].

A compact, electrically small circularly polarized (CP) quasi-Yagi antenna has been reported in [34]. The proposed design features three key elements: a compact single-feed crossed-dipole that functions as the driver, along with two parasitic elements that serve as the reflecting and directing elements. Each segment of the elements incorporates an arrowhead ended meandering line to enhance compactness. The driver is designed with double vacant-quarter printed rings that facilitate the generation of CP radiation. The addition of parasitic elements not only promotes directive radiation but also broadens the antenna's bandwidth. The validation model measures an overall dimension of 3.5 cm × 3.5 cm × 2.7 cm equivalent to (0.18 × 0.18 × 0.14) times λ_o at 1.575 GHz frequency with, ka factor of 0.93. It achieves a the measured -10-dB bandwidth of 19.23% (ranging from 1.476 to 1.790 GHz) and a 3-dB axial ratio bandwidth (ARBW) of 7.7% (from 1.505 to 1.625 GHz). Additionally, the presented antenna achieves a boresight gain of around 3.0 dBic and better than 8.2 dB front to back ratio(F/B).

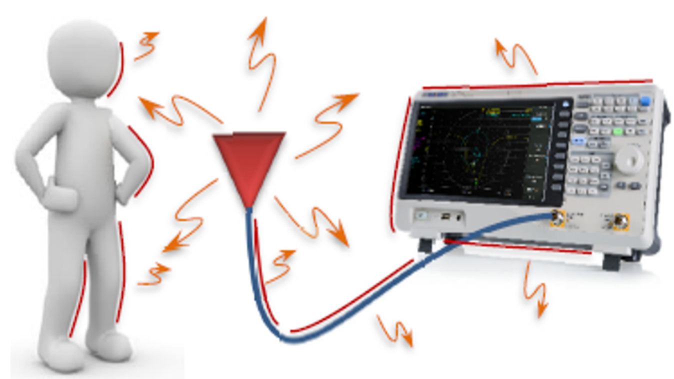
4. Electrically Small Antennas Characterization Challenges.

The process of characterizing or measuring the electrically small antennas (ESAs) also presents various challenges [35]. However, there are many measurement tools available that come with standardized instructions for antenna characterization and a wealth of supplementary resources to assist in measurements of ESAs. It's essential to put a balance among design features such as frequency bandwidth, radiation efficiency, miniaturization, and radiation pattern when working with an ESA. Wheeler's definition suggests that an ESA can fit within a sphere with a diameter of λ/π or smaller; this also serves as a rough measure for its reactive nearfield. This means that any interference, whether it stems from the feeding network, environmental factors, or materials like the human body, can significantly influence the ESA's current distribution. As a result, anything connected to the ESA or present within its reactive nearfield can notably affect its characteristics, including resonant frequency, input impedance, radiation pattern, and operating bandwidth.

The radiation efficiency of ESAs is relatively poor. For transmission, we primarily consider radiation efficiency, which includes ohmic loss and return loss, along with the operating bandwidth. On the receiving end, the signal-to-noise ratio (SNR) becomes just as crucial as the frequency bandwidth itself. While a mismatched antenna might enhance the frequency bandwidth for a specific quality factor, it doesn't improve the SNR because it simultaneously re-radiates both the signal and noise. This highlights the importance of the noise figure (NF) of the front-end components, like the low noise amplifier and filter, in the receiving antenna's performance. The design criteria for transmitting and receiving ESAs often conflict, suggesting that creating two separate ESAs for each function would be the most effective approach.

Due to the intensive reactive environment surrounding the antenna, traditional shielding methods for the feeding cable, like using balanced-unbalanced (balun) circuits, are not suitable for Electrically Small Antennas (ESAs). When dealing with electric or magnetic ESAs, such as monopole or loop antennas, the electric and magnetic fields can couple with the balun structure, leading to inaccurate readings caused by the cable connected to the balun. This interaction transforms both the feeding cable, and the instrument linked to it into parts of the radiating structure. Consequently, the input impedance or radiation pattern measured cannot be attributed solely to the ESA itself. Therefore, various efforts have been made to accurately determine the input impedance and bandwidth of an ESA.

Figure 8: The depiction of the impedance measurement challenge for ESA with presence of near field objects.



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The radiation pattern of a standalone ESA typically follows the spherical harmonic pattern or simply sin θ, which is related to the TE01/TM01 modes for magnetic or electric ESAs. However, there are instances where it's necessary to measure the ESA's radiation pattern and polarization. For instance, while determining the axial ratio of a circularly polarized ESA can be quite challenging, one effective method involves using a miniatured source, such as an oscillator, connected to the antenna under test (AUT)'s port. This setup allows the radiated field to be measured within an anechoic chamber, with the condition that the source and its battery are significantly smaller than the AUT to prevent any alterations to the radiation pattern. Alternatively, another approach utilizing frequency mixing can be employed where a compact low-frequency source and its battery are connected in parallel with a nonlinear device, like a diode, to the AUT's port. An external RF source then illuminates the antenna through a measuring probe as it rotates, while a spectrum analyser captures the probe's readings to evaluate the magnitude of the offset frequency, which corresponds to the square of the radiation pattern.

Conclusions.

The efficient electrically small antennas (ESAs) are critical for maritime wireless applications. The design and realization of compact and low weight ESAs for maritime applications is a challenging task. The design criteria for the transmitting and receiving ESAs is different and must be followed for the efficient design of ESA for the specified application. The characterization of the ESAs is also a challenging task. Several techniques have been reported for impedance and radiation pattern measurements of ESAs. One way to characterize the ESAs is to implement the scaled model/prototype of ESA to facilitate the required measurements through state-of-the-art impedance measurement and radiation measurement facilities used for conventional antennas.

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