

Applications of Electromagnetic Sensing Technologies in Complex Electromagnetic Environment

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Abstract:

The increasingly complex electromagnetic environment (CEME), characterized by dense signal occupancy, intentional interference, and dynamic spectral congestion, poses significant challenges to electromagnetic (EM) sensing technologies. This review comprehensively surveys the theoretical foundations and practical applications of EM sensing within such challenging environments. Key theoretical principles underpinning robust sensing in CEME are elucidated. The topics include wave propagation fundamentals, advanced modeling and characterization of CEME, detection and estimation theory under interference, and electromagnetic compatibility coupled with dynamic spectrum management. The practical deployment of EM sensing technologies is examined across critical sectors including defense (leveraging cognitive radar, multi-sensor fusion), communications (spectrum sensing for cognitive radio/dynamic access), and aerospace (addressing interference threats like 5G to altimeters). Emerging trends such as AI/ML-enhanced sensing, integrated sensing and communication, and collaborative/distributed sensing networks are highlighted as pivotal for future advancements. The review concludes by outlining key challenges and research directions aimed at enhancing sensor adaptability, resilience, and spectral efficiency in the face of ever-growing EM complexity.

Keywords: Complex electromagnetic environment; Electromagnetic sensing; Sensing resilience.

1. Introduction

Electromagnetic sensing technologies, encompassing radar, wireless signal sensors, passive radio frequency (RF) receivers, and more, play a crucial role in

modern defense, communications, transportation, and aerospace systems. These sensors operate by transmitting or receiving electromagnetic (EM) waves to detect objects or analyze the environment. However, today's electromagnetic environment has grown ex-

traordinarily complex and congested (CEME). A CEME arises from the superposition of numerous electromagnetic emissions from ubiquitous sources like communication devices (Wi-Fi, Bluetooth, 4G/5G, IoT), radars, jammers, alongside natural EM phenomena, all interacting within shared spatial and spectral domains [1]. This dense coexistence leads to significant mutual interference, elevates the ambient RF noise floor, and creates intricate spectral-temporal-spatial landscapes [2, 3]. Consequently, effective sensing becomes vastly more challenging: signal-to-noise ratios degrade, detection probabilities diminish for weak or distant targets, and the reliability of sensing and communication links is strained. The proliferation of civilian wireless devices, particularly in popular bands like 2-4 GHz, exemplifies this growing congestion and its impact. Therefore, understanding and overcoming the challenges posed by CEME is paramount for the continued effectiveness and evolution of EM sensing technologies across their critical application domains [4].

This review aims to comprehensively survey the applications of electromagnetic sensing technologies within such CEME. It begins by outlining the theoretical foundations underlying electromagnetic sensing, focusing on fundamental principles and analytical frameworks. Subsequently, it delves into practical applications and examines how electromagnetic sensing technologies are being effectively implemented across key sectors, including defense, communications, and aerospace. Following this, it discusses the primary technical challenges posed by CEME. It highlights critical issues such as interference mitigation, clutter suppression, signal classification, and electromagnetic compatibility. Additionally, it addresses emerging trends and developments shaping the future of electromagnetic sensing technologies. The review emphasizes innovations in artificial intelligence, integrated sensing and communication (ISAC), reconfigurable hardware, and distributed sensing networks.

2. Theoretical Foundations of Electromagnetic Sensing Technologies

Effective deployment and operation of EM sensing systems within CEME demand a solid grounding in core theoretical principles. These principles govern how sensors interact with targets and, critically, how they contend with the myriad interfering signals and noise inherent in such environments. This section outlines key theoretical foundations, focusing on their relevance and adaptation for CEME.

2.1 Basic Principles of Electromagnetic Sensing

At its core, electromagnetic sensing involves detecting or measuring phenomena via the transmission and/or reception of electromagnetic waves. Modalities include active systems like radar and lidar, which emit energy and analyze the returned signal, and passive systems like RF receivers, radiometers, and electronic support measures (ESM), which solely receive ambient or target-emitted radiation [5]. All EM sensors fundamentally rely on Maxwell's equations and wave propagation principles. Sensors are broadly categorized as active and passive.

Active Sensors such as Radar transmit EM pulses and analyze the echo reflected from targets. A cornerstone theoretical model is the Radar Equation:

$$P_r = \frac{(P_t G_t G_r \lambda^2 \sigma)}{(4\pi)^3 R^4 L} \quad (1)$$

Where: P_r is the received power at the radar, P_t is the transmitted power, G_t is the transmit antenna gain, G_r is the receive antenna gain, λ is the operating wavelength, σ is the target radar Cross-Section (RCS, a measure of reflectivity), R is the range (distance) to target, and L is the system losses.

This equation quantitatively shows that received power (P_r) decreases with the fourth power of the range and is directly proportional to the target RCS (σ) and the square of the wavelength. In CEME, the presence of clutter (unwanted echoes) and elevated noise floor further diminishes the effective P_r , making detection of distant or low-RCS targets exceptionally difficult.

Passive Sensors such as Spectrum Analyzers and ESM Receivers do not transmit; they detect signals emitted by targets or other sources. Their performance hinges on high sensitivity to capture weak signals. In CEME, their fundamental limitation is the ambient noise floor and the level of co-channel and adjacent-channel interference, often quantified by metrics like Noise Figure (NF), Signal-to-Noise Ratio (SNR), and Signal-to-Interference-plus-Noise Ratio (SINR). High interference levels in CEME can easily mask signals of interest for passive sensors.

2.2 Modeling and Analysis of Complex EM Environments

Traditional models assuming isolated sensor-target interactions are inadequate in CEME. Here, the environment is dominated by numerous simultaneous emitters and natural sources, coexisting and interacting within shared spatial and spectral domains. Accurately modeling and characterizing CEME is therefore critical for designing robust sensing systems.

Modern approaches characterize CEME as a multidimen-

sional phenomenon across the domains of time, frequency, space, and amplitude. Conceptually, the EM environment can be viewed as a high-dimensional surface, where each point represents the power density or field strength at a specific frequency, location, and time instant. For example, spatio-temporal spectral snapshots can capture the variation of signal strength over time across multiple frequency bands within a geographical area. These representations form the basis for data-driven modeling using techniques like machine learning, statistical pattern recognition, and dynamic environment mapping [6].

Key quantitative metrics derived from this multidimensional analysis include:

Spectral Occupancy: The fraction of time a specific frequency band is utilized above a defined power threshold within an observation period.

Interference Density: A measure quantifying the number and aggregate power of overlapping or co-channel transmissions within a specific region and frequency band.

Temporal Variability: The rate and pattern of fluctuations in signal or interference levels over time, caused by user mobility, signal fading, or bursty transmissions.

Spatial Field Distribution: The geographical variation of signal strength, noise floor, or interference levels.

These metrics are fundamental for simulating CEME scenarios, predicting sensor performance, analyzing vulnerabilities, and designing mitigation strategies. Furthermore, they enable real-time environmental awareness for adaptive sensing systems, particularly crucial in contested spectrum or spectrum-sharing contexts.

2.3 Detection and Estimation Theory

Sensors operating in CEME face significantly degraded signal environments due to high levels of noise, clutter, and structured interference. Classical detection and estimation theory, often built on assumptions like Gaussian noise and known signal parameters, requires substantial extension to remain effective under these non-ideal CEME conditions.

Key challenges necessitating advanced theoretical approaches include:

Non-Gaussian Noise and Clutter: Background noise and clutter in CEME often exhibit heavy-tailed distributions (e.g., K-distribution, Weibull) that violate Gaussian assumptions, leading to suboptimal performance of classical detectors like the matched filter.

Non-Stationary Interference: Interfering signals may appear, disappear, or change characteristics rapidly over time and frequency, violating stationarity assumptions.

Multiple Simultaneous Signals: The presence of numerous signals overlapping in time, frequency, and space compli-

cates the separation and detection of the desired signal.

To address these challenges, detection and estimation theory for CEME incorporates:

Robust Detection: Designing detectors that maintain performance despite deviations from assumed noise/clutter models, such as Constant False Alarm Rate (CFAR) detectors adapted for non-Gaussian clutter.

Adaptive Filtering: Techniques like adaptive beamforming and adaptive temporal filtering to nullify or suppress interference directions or frequencies.

Subspace Techniques: Methods that exploit the underlying structure of the signal and interference in high-dimensional spaces to separate sources.

Learning-Driven Methods: Leveraging machine learning, particularly deep learning classifiers, to learn complex patterns of signals and interference directly from data. These methods show promise in classifying signals in dense environments, identifying interference types, and suppressing clutter in non-linear and non-stationary scenarios. Deep reinforcement learning is also explored for adaptive sensing control under interference [7].

These advanced theoretical frameworks are essential for developing sensors capable of reliable target detection, parameter estimation, and signal classification amidst the complexities of CEME.

2.4 Electromagnetic Compatibility and Spectrum Management

Ensuring reliable sensor operation in CEME fundamentally relies on the principles of Electromagnetic Compatibility (EMC) and Spectrum Management. EMC focuses on the ability of different electronic devices and systems to function correctly in their shared EM environment without causing or experiencing unacceptable interference. Core EMC concepts include:

Emissions Control: Limiting the unintentional radiation (conducted and radiated) from a device.

Immunity: The ability of a device to operate as intended in the presence of electromagnetic disturbances.

Mitigation Techniques: Employing strategies like shielding, filtering, grounding, isolation, and careful circuit design to minimize both emissions and susceptibility.

While EMC provides the foundational principles for coexistence, Spectrum Management provides the operational framework for coordinating the use of the radio frequency spectrum to minimize harmful interference between systems. In the static sense, this involves regulatory allocation of frequency bands to specific services. However, in dynamic CEME, Dynamic Spectrum Management (DSM) becomes paramount.

DSM requires sensing technologies to continuously moni-

tor spectrum usage and adapt accordingly:

Cognitive Sensing Principles: Systems like Cognitive Radio (CR) and Cognitive Radar embody DSM. A CR intelligently senses its spectral environment, identifies spectrum holes, and dynamically accesses these holes without causing harmful interference to primary users. Similarly, cognitive radar adapts its transmit waveform, frequency, and other parameters based on the perceived environment and target scene to optimize performance, avoid interference, and reduce mutual interference with other systems. These systems treat the EM spectrum as a dynamic resource that must be sensed and managed in real-time for efficient and non-disruptive operation within CEME.

Spectrum Sharing Frameworks: Regulatory models like Licensed Shared Access (LSA) and the Citizens Broadband Radio Service (CBRS) in the US explicitly rely on robust sensing to enable dynamic sharing of spectrum between incumbents and commercial users.

Thus, EMC theory and spectrum management science, particularly through the lens of dynamic adaptation and cognitive sensing, provide crucial theoretical underpinnings for designing sensors that can not only survive but effectively operate within the constraints and opportunities of CEME.

3. Practical Applications in CEME

These theoretical foundations are put into practice across critical sectors where sensing technologies must contend with increasingly complex electromagnetic environments.

3.1 Defense and Electronic Warfare

In the defense sector, electromagnetic sensing technologies are indispensable for surveillance, targeting, and threat detection. However, they must operate in electromagnetically contested battlefields where adversaries and friendly forces alike emit a multitude of signals. Modern militaries field active sensors like radars. They also use passive sensors such as ESM receivers that listen for enemy communications or radar emissions. These systems now face environments with both inadvertent interference and deliberate jamming by adversaries. A 2021 analysis highlighted that Western forces' historical "electromagnetic supremacy" is eroding. This is happening as competitors field advanced jammers and as civilian spectrum congestion encroaches on military uses [8]. For example, in coalition operations, dozens of high-power emitters on land, sea, and air can inadvertently jam each other if not properly managed [9]. In fact, U.S. forces recorded over 261 satellite communication jamming incidents in 2015. It turned out many were self-inflicted due to the proliferation of emitters sharing bands [10]. This underscores that

even without enemy action, the complexity of our own electromagnetic order of battle can be a hazard.

Sensing technologies in defense are evolving to meet these challenges in several ways. Firstly, there is a push towards agile, cognitive radar and EW systems. Cognitive radars employ smart waveforms and dynamic spectrum selection to evade jamming and reduce mutual interference. For instance, in 2020 Wang et al. proposed intelligent anti-jamming decision-making for cognitive radar using deep reinforcement learning [11]. The radar learns to sense the spectral scene, including jamming signals. It then chooses transmit parameters that maximize detection probability while minimizing the jammer's effectiveness [12]. These approaches essentially treat the EM environment as an adversarial "game" in which sensor and jammer strategies co-evolve. By perceiving and learning about the environment, cognitive sensors can exploit spectral gaps or adjust tactics faster than fixed, rule-based systems.

Secondly, defense applications increasingly rely on multi-sensor fusion and distributed sensing to overcome environment complexity. Therefore, networked sensors share data to enhance overall situational awareness. A notable example is using multiple passive RF sensors to geolocate an enemy emitter in a cluttered urban environment. Individually, each sensor's view may be confounded by reflections or partial coverage. Cooperatively, however, they can triangulate the source. In 2023 Huang et al. demonstrated a multi-UAV system that uses distributed cooperative sensing with a reinforcement learning algorithm to locate radio sources in a city [13]. The UAVs share signal information and adapt their flight/sensor configurations in real time. The study found that a team of cooperating UAV sensors could learn and adapt in a challenging adversarial environment. They ultimately gained a higher detection success rate against the complex EM background [14]. This validates the effectiveness of multi-agent cooperation and algorithmic intelligence for spectrum sensing in military scenarios [15]. In essence, the trend is toward network-centric sensing and each sensor node contributes to a holistic picture of the EM battlespace, allowing the system to see through interference via diversity and redundancy.

3.2 Communications and Spectrum Monitoring

Wireless communication networks are a second major domain where electromagnetic sensing is crucial in congested environments. Communications systems are traditionally users of the spectrum. Now, however, they increasingly incorporate sensing functionalities to monitor and manage spectrum usage in real time. This is largely driven by the explosive growth of wireless devices and

services, which has led to near-saturation of many frequency bands. As noted earlier, unlicensed bands like 2.4 GHz or 5 GHz host countless Wi-Fi and IoT devices. This creates interference and raises the noise floor. To maintain reliable connections, networks must dynamically sense and respond to the environment. For example, they might do this by switching channels, adjusting power, or using error correction when interference is detected [16].

A prime concept here is the Cognitive Radio (CR). Cognitive radios perform spectrum sensing to detect which frequency bands are occupied and which are spectrum holes. This enables opportunistic use without disturbing primary users. They continuously scan the radio environment and can change their transmission parameters on the fly. Research over the past decade has produced many spectrum sensing algorithms. These range from energy detection and matched filtering to advanced techniques using machine learning to identify signal patterns. A 2022 overview by Dai et al. highlights that cognitive radio and dynamic spectrum access are considered promising solutions to spectral congestion. They introduce opportunistic usage of under-utilized frequencies. Regulatory developments like the Citizens Broadband Radio Service (CBRS) in the 3.5 GHz band (USA) explicitly rely on spectrum sensing and database assistance. This allows shared use of military radar bands by commercial devices, but it is contingent on sensing the presence of priority users [17].

In summary, communications systems rely on electromagnetic sensing both internally and externally. Internally, each device senses for interference or idle spectrum. Externally, networks of sensors monitor the environment. Spectrum sensing and dynamic adaptation are fundamental to next-generation wireless networks operating in congested RF scenarios. This trend also aligns with regulatory moves toward more flexible spectrum allocation. Such frameworks demand trustworthy sensing to prevent harmful interference. In a complex EM environment, a communication device must essentially behave like a sensor as much as a transmitter. It must continually observe its spectral surroundings and adjust to maintain connectivity.

3.3 Aerospace and Remote Sensing

In aerospace, electromagnetic sensing technologies include aircraft radars and aircraft navigation aids. They also include a wide array of space-based sensors, such as remote sensing satellites, radar imaging satellites, and communication satellites that also perform spectrum monitoring. These systems often operate in environments with both natural and man-made EM complexities. Two prominent examples have garnered much attention in recent years. These are interference to aircraft radio altimeters

from 5G phones/towers and radio-frequency interference (RFI) to satellite-based remote sensors.

Aircraft Radio Altimeters (RAs) are short-range radars that operate at 4.2–4.4 GHz. They provide critical altitude-above-ground data during takeoff and landing. In 2021–2022, Chinese telecommunication companies began deploying 5G cellular networks in the adjacent 3.7–3.98 GHz C-band. In response, aviation authorities raised alarms that some older altimeters could suffer interference. The concern was that high-power 5G base station signals might overload altimeter receivers. This could happen even though the signals are out-of-band, due to insufficient filtering or non-linear effects. Research by Duan et al. (2023) confirmed that 5G signals can indeed induce nonlinear gain compression in an RA's receiver front-end, effectively desensitizing it. Furthermore, the closer the 5G frequency is to the altimeter's operating frequency, the lower the interference power needed to cause issues [18]. Many planes in service have legacy altimeters with broad receive filters and no modern EM shielding. Some are 20–30 years old, making them quite susceptible to out-of-band interference [19]. This has been validated by reports of altimeter anomalies in the presence of new 5G cell sites. This episode underscores how introducing a new emitter into an already utilized spectrum created a complex EM environment. This required a re-evaluation of sensor resilience.

Finally, we note that aerospace use of EM sensing extends to applications like radar-based collision avoidance in spacecraft, air traffic control radars in congested airspace, and secondary surveillance radar. These systems must handle thousands of aircraft replies without confusion. All of these rely on managing a high volume of EM signals. For example, the TCAS in aircraft actively interrogates nearby transponders. In busy airspace, TCAS must sort through many replies, which is a classic complex environment issue of signal sorting and avoiding garble. Techniques from radar signal sorting in EW are applied here as well.

4. Development Trends and Future Outlook

4.1 Artificial Intelligence and Machine Learning in Sensing

Indeed, the most sweeping trend is the incorporation of AI/ML techniques at various levels of sensor systems. Traditional model-based approaches (e.g., analytical detection filters) give way to data-driven learning approaches. These can better handle complexity and uncertainties.

For example, reinforcement learning is used for cognitive radar control and dynamic spectrum access, as discussed. This enables sensors to learn optimal strategies in complex EM scenarios. Deep learning methods are being applied to RF signal classification, interference identification, and clutter suppression. It has been reported that the metasurface was guided by a neural network to direct wireless signals through a chaotic environment, which improved communication channel reliability [20].

4.2 Integrated Sensing and Communication

Furthermore, ISAC is a key trend worth emphasizing on its own. In 5G, and more so in 6G visions, the boundary between communication infrastructure and sensing infrastructure blurs. Future wireless networks might serve as wide-area radar/sonar networks in addition to providing connectivity. This is motivated by spectrum scarcity and by new applications. For example, one could use 6G base stations to sense the environment for smart city applications or use vehicle communications to collectively map surroundings. Achieving ISAC requires advanced waveform design so that information and sensing metrics can be embedded in the same waveform. It also requires sophisticated receivers that can decode data while measuring channel properties for sensing. Future standards might include explicit sensing performance requirements alongside communication specs. We are already seeing preliminary steps, like 5G NR allowing radar-like measurements. In some implementations, 5G signals are used for passive localization of users.

4.3 Collaborative and Distributed Sensing

The power of networked sensors over individual sensors is a growing trend. In military terms, this appears as sensor fusion and cooperative engagement, where multiple platforms share sensor data to form a single integrated picture. In civilian terms, one sees crowd-sourced spectrum sensing, where many devices contribute measurements to map spectrum usage. Distributed sensing can significantly improve detection in complex environments by leveraging spatial diversity. If one sensor is in a fade or heavy interference, another might not be. Future systems will likely employ swarm sensing and edge computing to combine data in real time. The trend extends to multi-static radar and passive radar systems. For instance, these systems might use communication signals as “illuminators of opportunity” and have sensors passively receive reflections. This approach avoids adding new emissions to the environment and shares infrastructure. Many research projects are underway on passive radar that exploits FM, DVB-T, or cellular signals to detect aerial objects. This offers a

covert sensing capability that inherently coexists with the communication signals.

In conclusion, the future of electromagnetic sensing in complex environments will likely be characterized by intelligent, adaptive, and integrated systems. Sensors will not be static devices. Instead, they will be fluid components of a larger, networked, partially self-learning organism that continuously manages the electromagnetic spectrum. They will collaborate with each other and even with communication infrastructure. This collaboration will ensure that both sensing and communications can cohabit the spectrum effectively. Challenges remain, especially in guaranteeing reliability and safety when AI and autonomy are given more control. However, the trajectory is set by necessity: the EM environment’s complexity will only increase, so our sensing technologies must become commensurately more sophisticated to keep up.

5. Conclusion

In conclusion, the field of electromagnetic sensing stands at a critical juncture, shaped by the growing intricacy and adversarial character of modern electromagnetic environments. As this review has illustrated, the last decade has witnessed profound developments across theoretical models, algorithmic strategies, and hardware systems—developments that collectively signal a shift from traditional deterministic sensing paradigms toward more adaptive, intelligent, and resilient architectures. These advances are not merely responses to escalating challenges such as spectrum congestion, intentional interference, and multi-domain signal conflicts; they are proactive strides toward reimagining sensing as a dynamic, cognitive process—one that learns, collaborates, and adapts in real-time.

Looking forward, the convergence of artificial intelligence, distributed sensor networks, and advanced materials science heralds a new generation of electromagnetic sensing systems. These future systems will likely be capable of operating autonomously in complex, contested environments while maintaining high fidelity, low latency, and mission-specific responsiveness. Crucially, they will not only survive in cluttered spectral terrains but thrive—transforming environmental volatility into a driver of sensing innovation.

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