frontiers | Frontiers in Signal Processing

TYPE Editorial
PUBLISHED 13 February 2026
DOI 10.3389/frsip.2026.1792985

OPEN ACCESS

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RECEIVED 21 January 2026
ACCEPTED 23 January 2026
PUBLISHED 13 February 2026

CITATION
Han C and Ostrometzky J (2026) Editorial: MmWave technologies as opportunistic ISAC for environmental monitoring.
Front. Signal Process. 6:1792985.
doi: 10.3389/frsip.2026.1792985

Editorial: MmWave technologies as opportunistic ISAC for environmental monitoring

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KEYWORDS

commercial microwave links, environmental monitoring, integrated sensing and communication, iot, mmwave, opportunistic ISAC, precipitation

Editorial on the Research Topic
MmWave technologies as opportunistic isac for environmental monitoring

1 Introduction

Integrated Sensing and Communication (ISAC) is rapidly evolving from a forward-looking concept into a practical design principle for modern wireless systems. This Research Topic focuses on *opportunistic* ISAC, where sensing functionality is extracted from existing communication infrastructure, including commercial microwave links (CMLs), satellite channels, and automotive radars, to monitor the environment without deploying dedicated, costly hardware. By treating ambient radio signals as "opportunistic" sensors, one can retrieve high-resolution environmental information from networks that already exist. This capabilities expands the capabilities of the standard ISAC paradigm, as it uses an already deployed communication hardware, which was not originally designed for ISAC.

Environmental information is often already embedded in radio measurements. For example, rainfall and water vapor affect microwave signlas, and can cause extra attenuation on microwave links channels. By processing the attenuation of these links, rainfall and water vapor monitoring can be realized. In addition, mmWave sensing also captures aspects of the physical environment, where robust processing of sparse radar point clouds can reveal structured features such as road boundaries. Turning these diverse sources of information into reliable weather and environmental products requires careful modeling, robust detection and estimation under non-stationary conditions, and principled fusion with complementary sensors and data sources.

2 Contributions of this Research Topic

The five articles in this Topic reflect these capabilities from a few different angles. They show how opportunistic measurements can be turned into rainfall and humidity products, how algorithmic choices can be made with the end metric in mind, and how mmWave sensing methods can be advantageous for smart-city monitoring and transportation safety. In this short editorial, we summarize each article in turn and discuss its context and importance within the broader field.

2.1 Point and line sensing with CMLs

Messer et al., "Rain Field Retrieval by Ground-Level Sensors of Various Types" provides a focused comparison of rain-field retrieval using networks of point sensors (e.g., rain gauges) with networks of commercial microwave links (CMLs) that measure the attenuation (and thus, the rain) as a set of line-integration. By examining how different sensor types and single/mixed deployment schemes sample the same underlying fields, the study clarifies when the line-averaging nature of links becomes an asset rather than a drawback. Their work addresses a fundamental question: how does the sampling geometry affect reconstruction accuracy? By analyzing performance bounds (Cramér-Rao) and practical interpolation methods, they demonstrate that line sensors (CMLs) can outperform point sensors in detecting certain rain fields (such as "spotty" or high-variability ones). Their findings provide useful information for the design of hybrid sensor networks, taking into consideration the rain cell size and the sensor network properties.

2.2 Improving accumulated rainfall estimation through wet–dry detection

Weiss et al., "Intensity Estimation After Detection for Accumulated Rainfall Estimation" addresses the specific challenge of accumulated rainfall estimation by selecting the wet/dry detection threshold to minimize a post-detection estimation criterion, effectively optimizing the full estimation-after-detection chain. Many methods often treat the detection of rain (wet/dry classification) and the estimation of its intensity as separate problems. The authors argue that this separation introduces bias. They propose a novel approach that optimizes the detection threshold using a joint risk function, which accounts for both detection errors (false alarms/ misdetections) and estimation errors. Using real attenuation measurements from a cellular network in Sweden, the authors demonstrate that a decision-aware threshold can improve accumulated rainfall accuracy compared to the standard choices.

2.3 Water vapor mapping using CML attenuation and auxiliary temperature data

Beyond precipitation, atmospheric moisture is a high-impact target for opportunistic sensing. Near-ground humidity is a vital parameter for weather prediction but is difficult to map at high resolution. Commercial microwave links, sensitive to absorption and refractivity effects, offer a complementary view with wide spatial coverage.

Bragin et al., "Water Vapor Density Field Estimation Using Commercial Microwave Link Attenuation Combined With Temperature Measurements" proposes a data-driven approach for estimating water vapor density (WVD) fields by combining CML attenuation with temperature measurements. The authors develop an enhanced machine learning model that fuses attenuation data from CMLs with temperature measurements. A key innovation in their work is the incorporation of a "humidity-elevation profile," allowing their model to estimate WVD at various altitudes and locations where no physical weather stations exist. Tested across a real cellular network, their approach achieved great accuracy improvements.

2.4 GNSS-PWV analysis of heavy rainfall over Cyprus

In addition to terrestrial communication infrastructure, satellite navigation signals and especially the global navigation satellite systems (GNSS) routinely used for positioning, also encode tropospheric delays that can be converted into precipitable water vapor (PWV). High-temporal-resolution PWV knowledge is a contributing factor to the studies of heavy rainfall precursors, and can also complement conventional meteorological observations.

Giannadaki et al., "Correlation of Precipitable Water Vapor and Heavy Rainfall Over Cyprus Using GNSS Sensors Network" analyzes the relationship between PWV and heavy rainfalls over Cyprus using a GNSS sensor network, ERA5 (the fifth generation ECMWF atmospheric reanalysis), and meteorological station data. By examining a large set of heavy and extreme precipitation events, the authors report systematic PWV increases prior to many heavy-rain onsets and quantify correlations that vary across regions (for example, mountainous versus coastal).

2.5 mmWave sensing for autonomous driving

While weather monitoring represents a macroscopic application of OISAC, mmWave technologies are equally transformative for local, high-precision environmental mapping for modern smart-city applications, such as autonomous systems.

Wu and Noh, "4DRadarRBD: 4D mmWave Radar-Based Road Boundary Detection in Autonomous Driving" introduces 4DRadarRBD, a 4D mmWave radar-based road boundary detection method that estimates accurate boundary curves from sparse and noisy radar point clouds. Unlike cameras or LiDAR, which can fail in poor lighting or adverse weather, mmWave radar remains robust. The authors overcome the inherent noise and sparsity of radar point clouds by implementing physical constraints and a distance-based loss function. Their work highlights the "dual-use" potential of mmWave technology—ensuring vehicle safety by mapping the static physical environment (road edges, fences) while operating under conditions where other sensors fail. This approach is yet another example to the essence of OISAC.

3 Outlook

Collectively, the contributions in this Research Topic present several novel directions that are shaping OISAC for environmental monitoring: An analysis of the *information and geometry*, where point sensors, CMLs based line-integrated measurements, and a mixture of both, each have distinct strengths, with their respective performance depends strongly on both the network topology as well as on the rainfall type and structure. In addition, the importance of *hybrid modeling*, that is, the combination of physical insight and models, side information (terrain, temperature, diurnal patterns), with data-driven methods is demonstrated, as this hybrid approach can achieve excellent performance, and to handle challenging scenarios such as different scales and nonstationarity. Finally, from the collection of studies in this Research Topic it is clear: *Multi-modality is becoming the norm*, as OISAC can draw on a broad range of opportunistic measurements, including terrestrial commercial microwave/mmWave links, satellite microwave links, GNSS-derived weather products, and mmWave radar observations. We see a clear trajectory from theoretical validation to real-world deployment, driven by increasingly sophisticated signal processing and machine learning techniques.

As these OISAC techniques mature, they are expected to offer new tools for many applications in meteorology and hydrology, smart-city environmental resource management, and large scale climate studies. Thus, today's opportunistic measurements will be transformed into an operational, globally harmonized source of high-resolution environmental intelligence.

Author contributions

CH: Writing – original draft. JO: Writing – review and editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. H. Messer's work was supported by the Israel Science Foundation (Grant 535/23); I. Bragin's work was supported by the European Union under Grant 101037193; D. Giannadaki's work was supported by the Cyprus RESTART 2016-2020 programme (ENTERPRISES/0223/Sub-Call1/0255); Y. Wu's work was supported by the Stanford CEE Fellowship and the Stanford Blume Center.

Acknowledgements

We thank all authors and reviewers for their time and effort, and the journal editorial office for supporting the organization and publication of this Research Topic.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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