VaporISAC: Integrated Sensing and Communication via Molecular Signals

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***Abstract*—Conventional electromagnetic (EM)-based integrated sensing and communication (ISAC) systems degrade in cluttered, obstructed, and radio-frequency-hostile environments, while macroscopic molecular communication (MC) remains largely unexplored as an ISAC medium. This article introduces VaporISAC, a molecular ISAC framework in which chemical vapor pulses simultaneously convey information and probe the propagation environment, enabling a *one signal, two outputs* paradigm. The same received waveform is jointly processed to recover transmitted information and infer environmental properties such as airflow, turbulence, smoke, and chemical conditions. Rather than replacing conventional EM-based ISAC, VaporISAC complements existing approaches in chemically dynamic, infrastructure-limited, and EM-challenged environments. The sensing principles, system architecture, proof-of-concept demonstrations, emerging applications, and open research challenges of VaporISAC are presented, positioning it as a promising new paradigm for resilient communication and environmental sensing.**

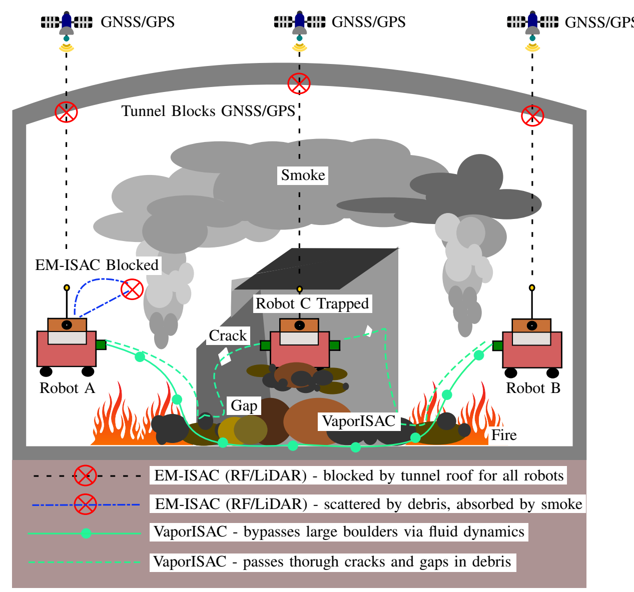

Fig. 1: Disaster scenario with communication layers.

I. Introduction

Integrated sensing and communication (ISAC) is widely recognized as a key enabler of sixth generation (6G) networks, integrating communication and sensing through shared waveforms and hardware resources. By jointly enabling data transmission and environmental perception, ISAC improves spectral efficiency and supports context-aware applications such as autonomous systems, smart infrastructure, and industrial automation [1]. However, existing ISAC frameworks rely on electromagnetic (EM) signaling, limiting their effectiveness in environments where signal propagation is severely impaired.

Disaster and industrial environments, such as collapsed tunnels, burning buildings, underground pipelines, and smoke-filled facilities, present significant challenges for conventional sensing and communication. Radio frequency (RF) signals suffer from severe attenuation and multipath effects, optical sensors degrade in smoke and particulate matter, and global navigation satellite systems (GNSS)/global positioning system (GPS) is unavailable in enclosed spaces [2]–[4]. These limita-

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tions motivate the exploration of alternative physical modalities for ISAC, cf. Fig. 1.

In this article, we introduce VaporISAC (cf. Fig. 1), a framework that brings the ISAC paradigm to the chemical domain by using controlled vapor releases as both information carriers and environmental probes. Instead of replacing RF systems, VaporISAC complements existing approaches by enabling communication and situational awareness in places where EM-based methods become unreliable. To our knowledge, this is the first framework to unify macroscale molecular communication (MC) with ISAC, establishing a new direction for unified communication and sensing in extreme environments.

II. EM-ISAC Capabilities and Limits

EM-ISAC integrates communication and sensing within a common RF platform by sharing spectrum, hardware, and signal processing resources. Using wireless waveforms, such as orthogonal frequency division multiplexing, EM-ISAC enables simultaneous data transmission and environmental perception, including object detection, localization, motion estimation, and channel characterization. Recent advances in sub-6 GHz, mmWave, and massive multiple-input multiple-output (MIMO) systems have demonstrated high-rate communication with accurate sensing capabilities [5], establishing EM-ISAC as a key technology for 6G applications such as autonomous systems, smart infrastructure, and industrial automation [6].

However, the effectiveness of EM-ISAC decreases in extreme environments where the propagation medium is highly dynamic or obstructed. Concrete, debris, and metal introduce severe attenuation, scattering, and multipath effects, degrading communication reliability and sensing accuracy [2]. Although lower-frequency RF signals provide improved penetration, they offer limited sensing resolution, whereas mmWave systems are more susceptible to blockage and environmental variations [7]. Similarly, optical modalities such as cameras and light detection and ranging (LiDAR) suffer from degradation under smoke, dust, and aerosols, while thermal imaging provides only limited robustness [3], [8]. Furthermore, infrastructure failures can disrupt GNSS/GPS, cellular, and Wi-Fi connectivity, requiring autonomous platforms to rely on local sensing and navigation mechanisms such as simultaneous localization and mapping (SLAM) [4].

Beyond these propagation limitations, EM-ISAC is inherently constrained by its sensing modality. Radio signals primarily capture EM interactions with objects, enabling estimation of parameters such as range, angle, and velocity, but cannot directly measure physical quantities such as airflow, gas concentration, smoke density, or turbulence. These limitations motivate the exploration of VaporISAC in extreme environments.

III. Sensing Principles of MC

MC uses molecules or particles as information carriers instead of EM waves. In air-based systems, signaling molecules are transported through advection and diffusion, causing the received waveform to depend on both the transmitted symbols and environmental factors such as airflow, turbulence, smoke, and obstacles [9]. Therefore, molecular signals inherently contain information about both the transmitted message and the surrounding environment.

Despite this dual dependency, most MC research has focused primarily on communication, where environmental effects are typically modeled as channel impairments that degrade information transfer [10], [11]. However, waveform characteristics such as attenuation, delay, dispersion, and concentration variations also provide valuable information about the propagation environment.

VaporISAC leverages this property by treating molecular waveforms as combined communication and sensing signals. The received signal can be used not only for data recovery, but also to infer environmental properties, including airflow, turbulence, obstacle-induced flow variations, and aerosol or smoke conditions. Thus, communication and sensing are extracted from the same molecular propagation process instead of requiring separate sensing modalities.

This concept is supported by recent experimental work that demonstrates alcohol-based MC for simultaneous binary decoding and localization of odor-sources using a mobile robot [12]. The robot navigates toward an odor source while decoding messages encoded using alcohol molecules and an on-off keying (OOK) scheme. However, the sensing capability in this work is mainly limited to source

TABLE I: Capabilities of electromagnetic- and chemical vapor-based integrated sensing and communication.

Feature	**EM-ISAC (RF/mmWave/LiDAR)**	**VaporISAC (Chemical Vapor)**
Propagation	EM wave propagation	Molecular diffusion and/or advection
Communication Range	Long range (10–500 m)	Short range (0.5–5 m)
Data Rate	High (Mbps–Gbps)	Low (bps)
Smoke and Debris	Strong attenuation and multipath	Naturally robust
Penetration	Blocked by sub-wavelength gaps	Diffuses freely through cracks and gaps
Environmental Sensing	Geometry, motion, range, velocity	Airflow velocity, turbulence, smoke density, chemical hazards
Infrastructure	Base stations/GNSS/GPS	Fully ad hoc
Power Consumption	High (W)	Low (mW–W)
Best Use Case	Wide-area communication	Front-line disaster zones

localization and does not explicitly estimate environmental parameters.

Beyond passive environmental observation, VaporISAC can also support reactive sensing, where emitted probe molecules interact with ambient chemical species and generate measurable secondary signatures. These reactions could enable inference of chemical concentration, spatial distribution, and reactivity, extending sensing beyond physical transport phenomena to chemical state estimation. In this way, vapor waveforms become active probes of the environment, transforming MC from a communication-centric paradigm into a unified framework for communication, environmental sensing, and chemical inference. A comprehensive comparison between the capabilities of EM-ISAC and VaporISAC is listed in Table I.

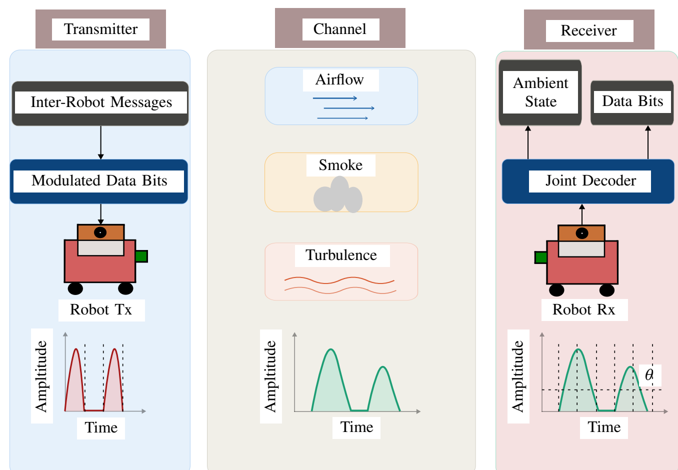

Fig. 2: Proof-of-concept idea of chemical vapor-based integrated sensing and communication with the transmitter, the channel, and the receiver side components, methods, and influences.

IV. VaporISAC System Architecture

In the following, we present the proposed VaporISAC architecture, consisting of a chemical vapor transmitter (Tx), a diffusion–advection propagation medium, and a combined communication–sensing receiver (Rx). An exemplary proof-of-concept scenario is illustrated in Fig. 2.

A. *Transmitter*

Tx consists of a low-power microcontroller, a controllable vapor release mechanism (e.g., a micropump or spray actuator), and a reservoir containing chemically safe tracer agents. The microcontroller generates symbol sequences and controls vapor emission timing and quantity using MC modulation schemes such as OOK, concentration shift keying, molecular shift keying, or their hybrids [13]. Each information symbol is realized as a controlled vapor burst characterized by its release time and emitted mass. In this sense, Tx is analogous to a baseband waveform generator in conventional ISAC systems, except that the waveform is physically realized through chemical release rather than EM radiation.

B. *Propagation Medium*

Vapor propagation is governed by molecular diffusion and bulk airflow, which transform emitted pulses into time-varying concentration waveforms. Airflow affects arrival time, diffusion and turbulence introduce temporal spreading, and attenuation modifies signal amplitude. These propagation effects create physically meaningful waveform variations that enable environmental inference.

Unlike conventional sensing systems, VaporISAC does not explicitly require dedicated sensing pilots or preambles, since each transmitted vapor pulse simultaneously conveys information and probes the environment. This creates an inherent communication-sensing tradeoff: higher symbol rates improve throughput but reduce sensing resolution, whereas longer symbol intervals enhance environmental estimation at the cost of communication rate.

C. Receiver

Rx employs a chemical sensing front-end, such as a metal-oxide semiconductor sensor or an eNose, to measure time-varying vapor concentrations and convert them into electrical signals containing communication symbols and environmental signatures. The received waveform is influenced by vapor transport as well as sensor characteristics, including response time, memory, and saturation.

Using a shared sensing and processing pipeline, Rx is designed to jointly decode the transmitted information and to estimate effective environmental parameters such as airflow, dispersion, turbulence, and attenuation. Physics-aware propagation models, statistical methods, or lightweight machine learning (ML) approaches can be used to interpret waveform variations as structured environmental information rather than noise. The proposed framework focuses on low-dimensional environmental inference instead of full spatial reconstruction, enabling efficient operation on resource-constrained platforms and infrastructure-free deployments.

V. Proof-of-Concept Demonstrations

Based on the proposed architecture, this section demonstrates the feasibility of VaporISAC through complementary analytical and experimental results.

Fig. 3 shows the dual-purpose operation of VaporISAC, where a single molecular waveform supports both communication and environmental sensing. The concentration profiles are generated using the one-dimensional diffusion–advection channel model [15] for the transmitted OOK sequence "101101", assuming a symbol duration of $T_\mathrm{s} = 2\,\mathrm{s}$ and a Tx–Rx distance of $x = 1\,\mathrm{m}$. The red and blue waveforms correspond to airflow velocities of $v_1 = 1\,\mathrm{m/s}$ and $v_2 = 0.75\,\mathrm{m/s}$, respectively, with a common diffusion coefficient of $D = 0.01\,\mathrm{m}^2/\mathrm{s}$.

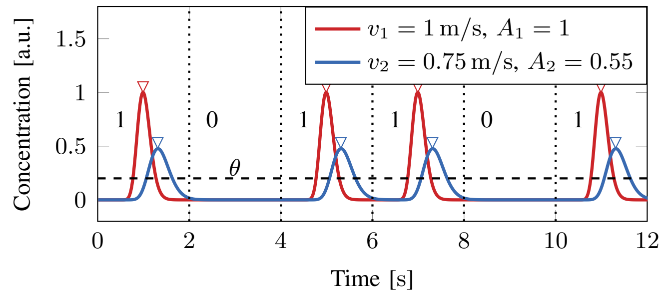

Fig. 3: On-off keying modulated analytical molecular waveform exploited for both data transmission and environmental sensing.

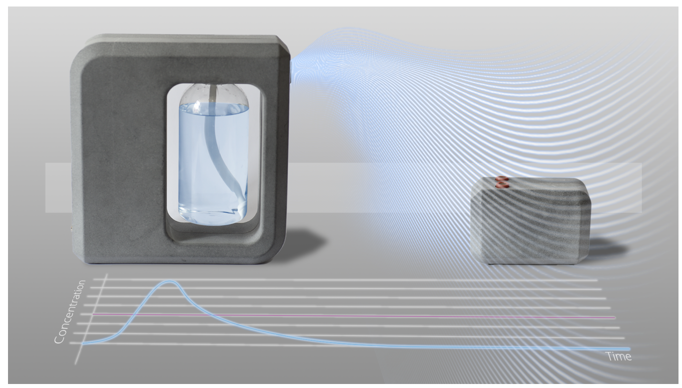

Fig. 4: Experimental setup of the macroscopic molecular communication testbed used for chemical vapor-based integrated sensing and communication. Extracted from [14].

The blue waveform additionally includes attenuation ($A_2 = 0.55$) to emulate propagation losses caused by environmental obstructions.

Despite the different propagation conditions, a fixed detection threshold (θ) can demonstrably recover the transmitted OOK symbols in both cases. At the same time, peak arrival times (marked by inverted triangles) reveal airflow velocity, while peak amplitudes indicate propagation losses. Changes in waveform spreading and inter-symbol interference (ISI) can further provide information about medium dispersion and turbulence. These results indicate that communication and environmental sensing can, in principle, be performed simultaneously using the same received waveform.

To experimentally validate this concept, we consider the macroscopic MC testbed reported in [14], shown in Fig. 4. The setup employs a spray-based ethanol Tx and an MQ-3 chemical sensor operating with OOK modulation. Fig. 5 shows the normalized received concentration for the same transmitted sequence ("101101") under diffusion-assisted and drift-dominated propagation.

Compared with diffusion-assisted propagation,

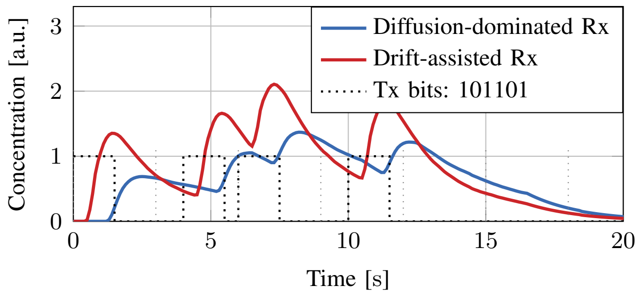

Fig. 5: Received concentration response for the transmitted bitstream under diffusion-dominated and drift-assisted propagation.

airflow produces concentration peaks that arrive approximately 44% earlier and are 66% stronger. Using the measured peak shift together with the known Tx–Rx separation of one meter, an effective drift velocity of approximately $0.314\,\mathrm{m/s}$ can be estimated. These results suggest that environmental parameters can be inferred directly from communication waveforms without dedicated sensing transmissions.

VI. VaporISAC Use Cases

To illustrate the relevance of VaporISAC, we present applications in indoor robotics, industrial systems, emergency response, and chemically active environments.

GNSS/GPS-Denied Indoor Robotics: A primary application of VaporISAC lies in indoor environments where GNSS/GPS is unavailable and radio-based localization suffers from multipath fading, blockage, or attenuation, including basements, warehouses, parking structures, tunnels, and multi-room buildings. In such settings, robots can exchange navigation commands, localization updates, and map information through molecular signaling while simultaneously exploiting distortions in vapor propagation to infer directional airflow and coarse spatial structure. These propagation signatures could effectively enable vapor-assisted SLAM or "sniffing out the path", where the same vapor waveform supports both inter-robot communication and environmental awareness. This capability is particularly valuable for multi-robot coordination in environments lacking reliable positioning infrastructure.

Airflow Monitoring: Industrial facilities such as chemical plants, refineries, storage units, and manufacturing sites, as well as modern smart buildings, contain complex ventilation systems and enclosed airflow networks that are often difficult to monitor in real time. VaporISAC could enable autonomous agents to exchange inspection status, leak alerts, airflow maps, occupancy information, and control updates while simultaneously sensing environmental conditions through the same molecular channel. Variations in vapor propagation delay, attenuation, and dispersion can potentially reveal anomalies such as duct blockages, leakage points, irregular airflow patterns, stagnant air regions, and poorly ventilated zones. This dual communication–sensing capability could effectively enable coordinated inspection, environmental diagnostics, and airflow characterization without relying on dense sensor deployments or communication infrastructure, supporting applications ranging from industrial monitoring to energy-efficient building management and indoor air quality optimization.

Search and Rescue Operations: Search-and-rescue operations in confined or partially collapsed environments, including disaster sites, tunnels, mining accidents, and fire-affected buildings, are often challenged by obstructed visibility, disrupted communication infrastructure, and irregular airflow. VaporISAC could enable autonomous agents to maintain communication links for sharing survivor locations, hazard alerts, and navigation instructions while simultaneously using vapor propagation distortions to infer environmental structure and hazard conditions. Airflow pathways derived from vapor dynamics can also indicate open voids, navigable spaces, smoke-laden regions, and potentially dangerous areas during fire incidents, supporting the localization of trapped individuals, identification of survivable zones, and safer navigation. Unlike optical or EM systems, VaporISAC is expected to remain more robust in heavily obstructed and smoke-filled environments.

Chemical Environments and Swarms: In chemically dynamic environments such as agricultural fields, laboratories, bio-reactive zones, and industrial facilities, VaporISAC can be used to exchange coordination messages and sense environmental conditions through a shared molecular channel. Vapor waveforms used for inter-agent communication can also be designed as reactive probes that interact with ambient chemical species, producing secondary signatures that could potentially reveal chemical composition, transport dynamics, and potential leakage sources. The communication–sensing framework and reactive inference capability can enhance environmental awareness, source localization, and coordination efficiency, enabling more adaptive and resilient swarm behavior.

VII. Open Research Challenges

We finally discuss key open research challenges in realizing practical VaporISAC systems, spanning modeling, algorithms, hardware, and system integration.

Communication–Sensing Tradeoff: VaporISAC inherently couples sensing and communication, creating a tradeoff between transmission performance and environmental estimation accuracy. Higher data rates require more frequent emissions and shorter symbol intervals, increasing interference and reducing sensing fidelity. Conversely, accurate sensing often requires sparse transmissions and longer observation windows, limiting throughput. Characterizing this tradeoff and developing adaptive strategies that balance sensing and communication under dynamic conditions remain important open challenges.

Realistic Channel Modeling: A major challenge is developing realistic yet tractable models for three-dimensional turbulent molecular propagation. Simplified diffusion–advection models fail to capture buoyancy, obstacles, thermal gradients, and resulting non-Gaussian plume behavior in disaster environments. Although computational fluid dynamics (CFD) tools provide high accuracy, their cost prevents real-time use. Surrogate models trained on CFD data could enable real-time inference from sparse measurements on resource-limited platforms.

Chemical Multiple Access: A critical scalability challenge in VaporISAC is the lack of a multiple access framework for multi-agent MC. In disaster scenarios, simultaneous emissions create overlapping plumes with spatial-temporal interference. Unlike RF systems, MC channels lack frequency orthogonality, with interference worsened by nonlinearities, ISI, and adsorption-desorption dynamics. This requires chemical multiple-access strategies, including time scheduling, spatial separation, orthogonal species, and code division multiple access-inspired coding, which are validated in realistic turbulent flows.

Hybrid Architecture: A key challenge in VaporISAC is designing hybrid EM-optical-MC systems where modalities operate cooperatively rather than independently. While EM sensing primarily provides information such as range, velocity, and obstacle geometry, VaporISAC is designed to infer environmental properties including airflow, smoke, and chemical hazards from the received molecular waveform. The core open problem is how to dynamically allocate sensing, communication, and decision-making across modalities. This motivates adaptive fusion frameworks that select or combine channels based on environmental conditions and mission needs, enabling robust operation and improved situational awareness in degraded disaster environments.

Decision-Directed Tracking: VaporISAC relies on decision-directed channel tracking, where parameters are updated from detected emissions for shared communication and environmental estimation. Its convergence and stability in MC channels remain largely unexplored. Unlike RF equalization, it involves stochastic plume evolution, strong nonstationarity, and asymmetric updates. Decision errors cause cascading effects, e.g., missed detections skip updates, while false alarms corrupt estimates via noise fitting. Key challenges include stability under airflow dynamics, rapid changes, and uncertainty, as well as soft-decision probabilistic updates.

Communication Limits, Coding, and Reliability: Although current macroscopic MC systems achieve only modest data rates suitable for low-rate inter-agent coordination, improving communication reliability and spectral efficiency remains a key research challenge for VaporISAC. This requires rethinking diffusion-based modulation and coding, including burst-based schemes, molecular multicarrier signaling, spatial MIMO arrays, and error-correcting codes that account for correlated molecular noise, while operating under stringent ultra-low-power constraints.

Hardware, Safety, and Validation: A major barrier to VaporISAC maturation is the lack of experimental validation. Deployment requires addressing emission variability, sensor drift, nonlinear sensor response, and strong temperature dependence under extreme conditions. Additionally, mobile robotic integration imposes strict size, weight, and power constraints for emission, sensing, and communication modules. Safety limits volatile organic compounds below flammability thresholds, motivating non-flammable, low-toxicity alternatives. A controlled testbed with turbulence, thermal gradients, and smoke is needed to validate models, benchmark performance, and generate reproducible datasets.

VIII. Conclusion

This article introduced VaporISAC, a new combined sensing and communication paradigm that extends ISAC beyond the EM domain by exploiting chemical vapor propagation. Unlike conventional EM-based approaches, VaporISAC leverages the propagation dynamics of molecular signals to simultaneously support reliable data exchange and environmental sensing, making it particularly attractive for cluttered, smoke-filled, infrastructure-denied, and chemically dynamic environments.

We presented the sensing principles underlying MC, proposed a collective communication–sensing system architecture, and demonstrated through analytical and experimental proof-of-concept demonstrations that a single molecular waveform can simultaneously convey digital information and reveal environmental properties such as airflow and propagation losses. Potential applications in autonomous robotics, industrial monitoring, search-and-rescue operations, and chemically active environments further illustrate the versatility of the proposed framework.

Although many challenges remain, including realistic channel modeling, scalable multi-agent communication, hybrid EM–molecular architectures, and experimental validation, VaporISAC establishes a new research direction at the intersection of MC and ISAC. We envision future autonomous systems employing multiple complementary physical modalities, where EM and molecular signaling operate cooperatively to provide resilient communication and richer environmental awareness in situations where either modality alone would be insufficient.

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