From Nature to Network: Expanding Connectivity with Odor-Based Molecular Communication

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Abstract

Odors serve as a natural medium for communication, enabling the exchange of complex information across biological systems through mechanisms evolved over millennia. Inspired by these biological processes, this research investigates odor-based molecular communication (OMC), which utilizes volatile molecules to encode and transmit information, as a novel communication paradigm. The study focuses on four key objectives: (1) developing advanced mathematical models to capture the intricate dynamics of odor propagation in dynamic environments, (2) designing and prototyping scalable transceivers integrating microfluidic systems and biosensors, (3) establishing AI-driven security frameworks to mitigate vulnerabilities inherent in diffusion-based communication, and (4) integrating OMC with other sensory modalities like visual and auditory systems to create cohesive multi-sensory communication systems. This research positions OMC as a low-energy, biocompatible alternative to traditional electromagnetic communication, particularly in scenarios where conventional methods are impractical. By transforming the natural principles of olfaction into engineered solutions, this study aims to establish OMC as a foundational technology for applications in healthcare, environmental monitoring, and the Internet of Everything, advancing the frontiers of communication science.

Keywords: olfactory system, odor information, molecule communication, internet of everything

1 Background Review

From the fragrance of blooming flowers signaling pollinators to the pheromones guiding the behavior of entire colonies, odors have been silent yet powerful communicators in nature for millennia. Living organisms, from the simplest bacteria to complex mammals, have evolved intricate olfactory systems capable of detecting and interpreting chemical signals in their environments. These signals serve as messengers of survival, coordinating actions such as mating, territory marking, and predator avoidance (Stensmyr et al., 2002). In humans, the sense of smell is intricately linked to the limbic system, the brain region responsible for emotions and memory, granting odors the remarkable ability to evoke vivid recollections and influence moods with extraordinary immediacy (Welberg, 2024). Despite its profound role in ecological interactions and human experience, olfaction's potential as a foundation for engineered communication systems remains largely unexplored (Aktas et al., 2024). The natural mechanisms of odor signaling present a compelling blueprint for innovations that transcend biological boundaries, paving the way for novel pathways in information exchange and connectivity.

Inspired by biological communication strategies observed in nature, molecular communication (MC) has been proposed as a revolutionary paradigm that uses molecules as carriers of information (Akyildiz et al., 2008). Mimicking the biological exchanges that facilitate communication across living organisms, MC offers an compelling alternative to traditional electromagnetic-based systems. By transmitting information through chemical signals, it exhibits advantages such as biocompatibility, energy efficiency, and the ability to operate in environments hostile to conventional methods (Söldner et al., 2020). From enabling nanoscale networks in healthcare to real-time monitoring of biological processes in enclosed or hazardous environments, MC has already been successfully deployed across diverse application scenarios (Akan et al., 2016; Yang et al., 2020).

While MC has been applied in nanoscale networks and biochemical signaling, its reliance on traditional molecular carriers like ions or proteins limits its operational range and adaptability in open, unbounded environments (Jamali et al., 2023). To overcome these limitations, odor-based molecular communication (OMC) emerges as a complementary paradigm, utilizing volatile organic compounds as information carriers to enable effective propagation through air. This capability addresses the range and diffusion constraints inherent in traditional MC systems, extending communication to scenarios requiring ambient long-range

Table 1: Comparative Analysis of Molecular Communication, Natural Olfaction, and OMC Systems

Features	**Molecular Communication**	**Natural Olfaction**	**Odor-Based Molecular Communication (OMC)**
Information Carrier	Synthetic pharmaceuticals, ions, nucleic acids, proteins (Kuscu et al., 2019)	Natural odor molecules, e.g., pheromones (Mcguiness et al., 2019)	Odor molecules and mixtures
Transmission Medium	Liquid or gas medium	Gas medium	Liquid or gas medium
Encoding Mechanism	Concentration, type, release time	Modulation via chemical reactions, air flow	Modulation of both concentration and types, i.e., mixture
Reception	Passive/Absorbing receiver, reactive receiver (Akan et al., 2016)	Odorant-binding proteins, neural processing, E-Noses (Manzini et al., 2022)	Cross-reactive receptors, chemical detectors (Jamali et al., 2023)
Practical Apps. and Use Cases	Drug delivery, lab-on-a-chip systems, nanonetworks	Interkingdom communication, ecological interactions	Chemical sensing, environmental monitoring, healthcare, virtual reality

diffusion (Giannoukos et al., 2017). Additionally, OMC aligns with natural olfactory processes, where odors transmit intricate messages across biological systems, making it particularly suited for applications that benefit from ambient diffusion and multi-sensory integration (Bolding and Franks, 2018). As illustrated in Table 1, OMC integrates the strengths of natural olfaction and molecular communication, enabling novel applications such as augmented reality, spatiotemporal tagging, and real-time environmental monitoring in domains previously inaccessible to traditional MC approaches.

Despite the promising potential of OMC, significant research gaps remain. Existing studies primarily focus on traditional molecular carriers, such as proteins and ions, or isolated aspects of odor transmission and detection, without developing comprehensive frameworks for end-to-end OMC systems (Sagar et al., 2023; Yue et al., 2024). As shown in Figure 1, an end-to-end OMC system involves intricate processes, including odor molecule release, propagation through cascaded airborne channels, and reception via olfactory mechanisms. Such systems are essential for translating theoretical advancements into real-world applications, as they ensure the seamless integration of all components, enabling reliable and scalable communication in diverse scenarios (Kuscu et al., 2019). However, critical research gaps remain, such as accurately modeling odor propagation in dynamic environments, designing scalable and biocompatible transceivers, and securing OMC channels against potential vulnerabilities (Aktas et al., 2024). Moreover, the broader potential of OMC, particularly in enabling multi-sensory integration and real-time adaptability, remains underexplored due to the absence of systematic research and interdisciplinary collaboration (Cornelio et al., 2021).

To address these gaps, this study aims to establish a comprehensive theoretical and experimental foundation for OMC as an innovative communication modality. Through the development of advanced mathematical models, scalable device architectures, AI-powered security frameworks, and the integration of OMC with other sensory modalities, this research seeks to enable seamless adoption across diverse applications, including healthcare, environmental monitoring, and augmented reality. Ultimately, it strives to bridge the gap between natural olfactory mechanisms and engineered solutions, positioning odor-based molecular communication as a pivotal technology in the Internet of Everything.

2 Research Objectives

This study proposes to establish odor-based molecular communication (OMC) as a viable and impactful communication modality by addressing its core challenges and enabling its application across diverse domains. The research is structured around four objectives, progressing logically from foundational modeling to practical implementation and integration, ensuring coherence and addressing critical research gaps.

The first objective is to develop precise models for odor molecule propagation in dynamic environments. Existing models simplify complex factors, such as turbulence, temperature fluctuations, and chemical reactions, by assuming isotropic diffusion or steady-state conditions, which limits their applicability (Powari and Akan,

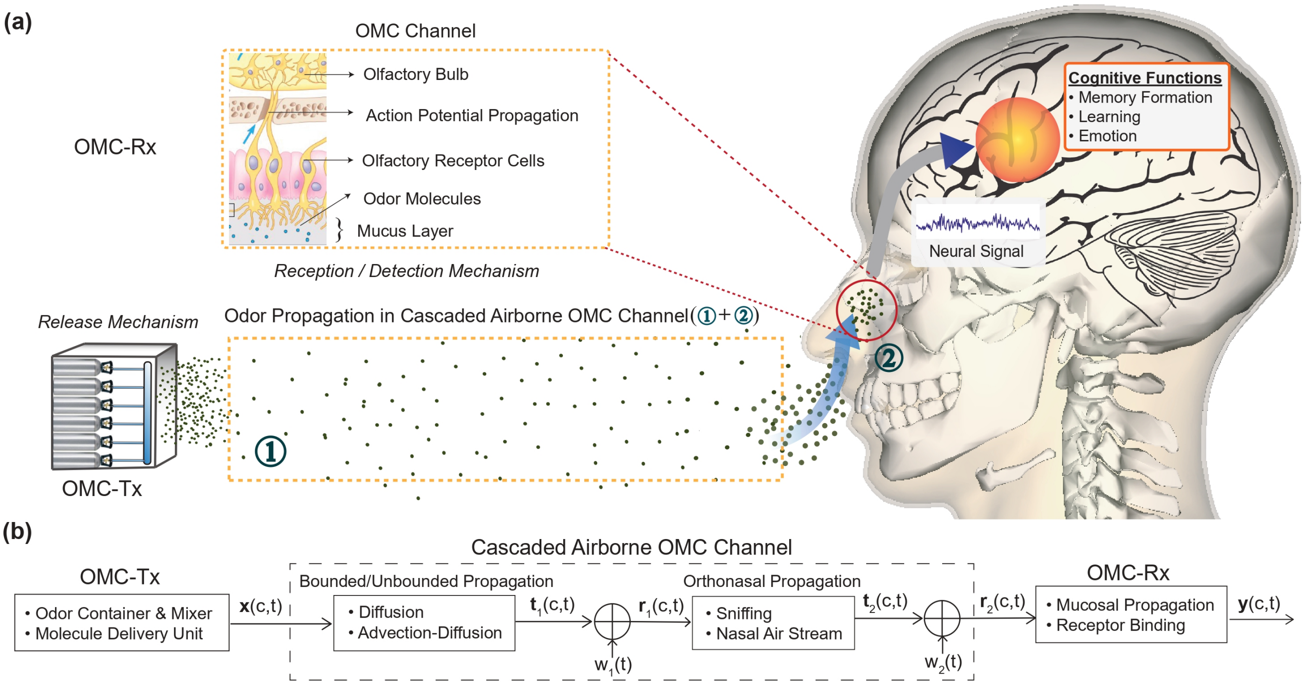

Figure 1: Odor-based molecular communication: (a) Holistic view, (b) System modeling (Aktas et al., 2024).

2024; Bilgen et al., 2024). To address this limitation, this study will construct advanced mathematical frameworks that incorporate fluid dynamics and stochastic processes to capture the non-linear and time-varying nature of odor transport. As shown in Figure 1(a), an end-to-end OMC system involves the release of odor molecules, their propagation through dynamic airborne channels, and their detection by a receiver, with processes such as diffusion, advection, and receptor binding playing pivotal roles. By modeling these processes comprehensively, the proposed framework will ensure applicability across both controlled and natural environments. Validation through computational simulations and experimental data will ensure the robustness of these models, laying a solid foundation for the design of reliable and efficient end-to-end OMC systems and enabling future experimental innovations.

Building on the foundational models, the next objective focuses on developing scalable and biocompatible architectures for OMC transceivers. These devices must be designed to reliably generate, transmit, and detect odor signals, while overcoming critical challenges such as miniaturization, energy efficiency, and adaptability to dynamic environments (Bi and Deng, 2022). As illustrated in Figure 1(b), the OMC transceivers comprises essential components, including an odor container and mixer for molecular synthesis, as well as a molecule delivery unit to enable precise and controlled release. To achieve precise and reliable operation, this study will incorporate microfluidic systems that enable accurate synthesis and controlled release of odor molecules, facilitating the precise encoding of information (Walter et al., 2023). On the detection side, receptor-inspired sensing mechanisms will be integrated to enhance both sensitivity and selectivity, ensuring robust signal decoding even in noisy or fluctuating environments. By bridging theoretical advancements and practical implementation, these prototypes will demonstrate the feasibility of OMC transceivers in diverse real-world contexts, such as healthcare diagnostics and environmental monitoring.

The third objective focuses on addressing the critical security challenges inherent in OMC systems. The diffusion-based nature of OMC channels exposes them to vulnerabilities such as passive eavesdropping, where adversaries extract sensitive information by monitoring ambient odor concentrations, and active interference, which manipulates concentration patterns to disrupt communication or mislead receivers (Shahbaz et al., 2024). To counter these threats, this study will develop advanced coding and modulation techniques that enhance signal robustness and maintain data integrity under adversarial conditions. Furthermore, machine learning-driven anomaly detection algorithms will be designed to analyze real-time odor signal patterns, effectively identifying deviations indicative of security breaches (Cai, 2024). By integrating these measures, the research aims to establish a comprehensive security framework that safeguards OMC systems, ensuring their reliability and confidentiality in high-stakes applications such as medical diagnostics and defense.

Finally, the study aims to explore the integration of OMC with other sensory modalities, creating cohesive multi-sensory communication systems. By developing synchronization methods to align OMC signals with

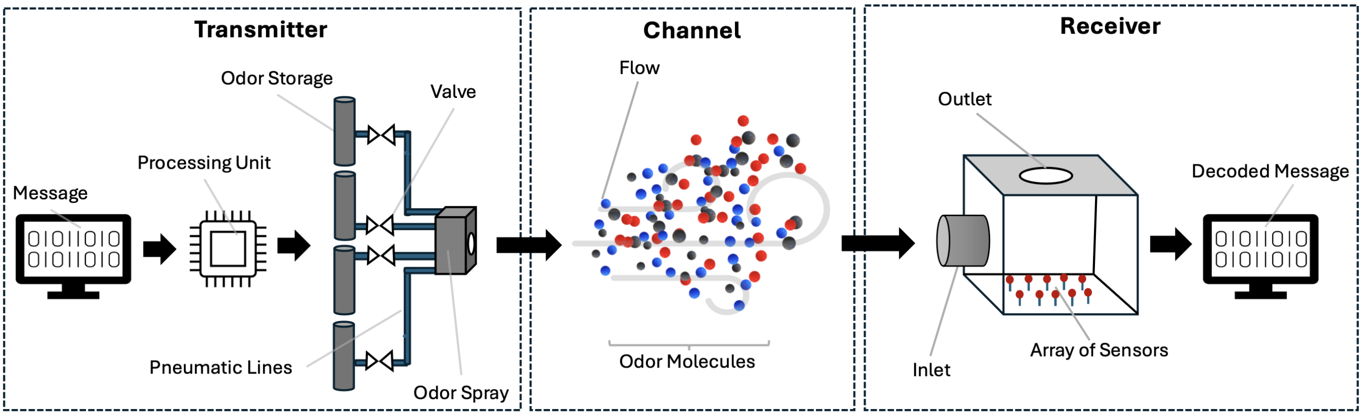

Figure 2: A generalized operational design of an end-to-end OMC system.

visual, auditory, and haptic systems, this study seeks to enable practical applications in augmented reality and environmental monitoring. Validation will be conducted through case studies, where olfactory cues enhance user immersion in augmented reality and provide critical situational awareness in environmental monitoring (Egan et al., 2023). Adaptive mechanisms will also be designed to enable dynamic adjustments in response to environmental changes and user needs, ensuring the versatility of OMC in diverse scenarios. These efforts will position OMC as a cornerstone technology within the Internet of Everything framework.

Through these interrelated objectives, This study will advance the theoretical and experimental understanding of OMC, bridging natural olfactory mechanisms with engineered communication solutions.

3 Research Methodology

This study employs a structured, interdisciplinary approach to address the key challenges in odor-based molecular communication (OMC), focusing on mathematical modeling, prototyping, and evaluation phases with advanced computational tools and experimental validation.

(1) Mathematical Modeling and Simulation: This study will develop advanced mathematical frameworks that integrate fluid dynamics, advection-diffusion equations, and stochastic processes to accurately model odor transport, accounting for dynamic factors such as turbulence, chemical reactions, and temperature variations in diverse environments. MATLAB will be employed for solving partial differential equations and stochastic modeling, while Smoldyn, a particle-based molecular simulator, will simulate molecular diffusion and reaction processes at the micro-scale. COMSOL Multiphysics will address multi-physics problems, enabling the integration of diffusion and turbulence effects in real-world scenarios. Figure 2 illustrates the end-to-end system components targeted in these models, encompassing release mechanisms, propagation channels, and detection systems. These models will undergo validation and iterative refinement through experimental data, ensuring their accuracy and applicability in practical settings.

(2) System Design and Prototyping: This phase employs a systematic approach, starting with simulation-driven optimization and advancing to experimental validation to design scalable and biocompatible OMC transceivers. MATLAB will be used for parameter optimization, while Ansys Fluent, a computational fluid dynamics tool, will simulate odor molecule synthesis, controlled release, and detection processes in dynamic environments. Soft-lithography will facilitate the fabrication of microfluidic components, providing a cost-effective and flexible method for prototyping odor synthesis and release mechanisms. Receptor-inspired sensing mechanisms, informed by biosensor and E-Nose datasets (Al-Dayyeni et al., 2021; Yang et al., 2023), will be integrated to enhance detection accuracy and robustness under varying conditions. Collaboration with microfluidics and wet lab researchers will ensure that theoretical designs translate effectively into experimental prototypes, while generating critical experimental data for model validation and refinement. Controlled testing will evaluate performance metrics such as signal precision, energy efficiency, and system stability, refining the designs for optimized functionality.

(3) Security Framework Development: To address the vulnerabilities of OMC systems, this phase focuses on developing a robust security framework capable of mitigating threats like eavesdropping and interference. Advanced coding and modulation techniques will be designed to enhance signal integrity, while machine learning models, such as LSTM-based anomaly detectors, will identify deviations in odor signal patterns indicative of adversarial activities. These models will be trained using synthetic datasets from simulation tools like Smoldyn and Ansys Fluent, alongside experimental data from controlled lab environments. Additionally, encryption-inspired strategies, such as randomized molecular release patterns, will be implemented to prevent unauthorized decoding of signals. The framework's robustness will be evaluated through controlled tests simulating various attack scenarios, with performance metrics including detection accuracy, false positive rates, and computational overhead guiding iterative improvements.

(4) End-to-End System Validation: The final phase consolidates the developed mathematical models, transceiver prototypes, and security frameworks into a cohesive OMC system for comprehensive evaluation. Synchronization methods will be implemented using time-stamped encoding and real-time feedback mechanisms to ensure alignment of odor signals with other sensory modalities under dynamic conditions. The integrated system will undergo rigorous testing in controlled and semi-realistic environments to evaluate key performance metrics, including transmission accuracy, latency, energy efficiency, and resilience to environmental variability such as turbulence and temperature fluctuations. Experimental setups will combine microfluidic prototypes with receptor-inspired detection mechanisms and security features to assess system robustness. Collaborative efforts with experts in chemistry, microfluidics, and system engineering will guide iterative improvements, ensuring practical scalability and readiness for real-world applications.

Table 2: Timeline for my current MPhil and future PhD research

Gantt chart	**MPhil year**				**PhD year 1**				**PhD year 2**				**PhD year 3**			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Literature review																
Develop OMC mathematical models																
Design and fabricate OMC transceivers																
Test and validate transceiver prototypes																
Develop security mechanisms for OMC system																
Integrate OMC with multi-sensory modalities																
Analyze experimental data and refine OMC system																
Write and finalize thesis																

4 Current Progress and Research Plan

At this stage, under the guidance of Prof. Özgür Akan, I have made significant progress in encoding odor information through the modulation techniques of intensity and frequency shift keying, providing a solid foundation for digitizing odors for reliable communication. Through computational modeling and simulation using MATLAB and Smoldyn, I have developed insights into odor transmission dynamics, including signal robustness and decoding accuracy. Additionally, my previous publications in AI-driven system have equipped me with valuable expertise in implementing machine learning methods (Cai, 2024), which directly contributes to my objective on establishing AI-based secure frameworks to address vulnerabilities inherent in OMC systems. For the remainder of my MPhil year, I will focus on completing advanced frameworks for odor propagation in dynamic environments, culminating in a thesis and a research paper, ensuring a seamless transition into PhD stage and reinforcing my suitability as a highly capable and dedicated PhD candidate.

Building upon this progress, my PhD research will systematically address the broader objectives of OMC development through distinct phases, as outlined in Table 2. Using the connections established during my MPhil studies at the University of Cambridge and the advanced research facilities within the Department of Engineering, I will actively explore collaborative opportunities to enrich and expand the scope of my research. The first year, as the most tangible phase, will focus on refining OMC mathematical models and developing simulation-driven transceiver prototypes, with experimental validation closely integrated into the process.

To support my research, I plan to explore potential collaboration with Professor Luigi Occhipinti's team, whose expertise in bioinspired sensor design will aid in developing advanced receivers that mimic olfactory receptor behavior, crucial for testing and optimizing OMC systems. Additionally, I aim to collaborate with

Dr. Stephan Goetz's team to draw on their extensive experience in neuroscience system modeling. This collaboration will not only provide valuable insights into how olfactory signals are processed in the brain but also enhance the alignment of odor signals with other sensory modalities under dynamic conditions. By incorporating these interdisciplinary insights, my research will seamlessly connect technical innovation with practical applications, effectively tackling both theoretical challenges and real-life demands.

5 Contributions to Knowledge

From the fragrance of blooming flowers guiding pollinators to the pheromones orchestrating the behavior of entire colonies, natural olfactory systems reveal the profound potential of odors as carriers of complex information. Drawing inspiration from these mechanisms, this study transforms the untapped potential of odor signaling into a structured communication modality through the development of odor-based molecular communication (OMC). By bridging nature's elegant design with engineering innovation, this study establishes OMC as a practical, scalable, and secure technology for various real-world applications.

Imagine low-cost, energy-efficient OMC devices monitoring urban air quality, transmitting real-time pollution data to inform public health strategies and policy decisions. In healthcare, wearable OMC transceivers could non-invasively detect biological changes in a patient's body, enabling early diagnosis of conditions like diabetes or infections. These applications highlight the transformative potential of this study in addressing critical societal challenges, ranging from advancing environmental sustainability to enhancing healthcare outcomes through innovative OMC systems.

Overall, this study will contribute the field of communication by establishing OMC as a robust and scalable modality through the development of mathematical models, experimentally validated prototypes, secure communication frameworks, and the integration of OMC with other sensory modalities, to enable cohesive multi-sensory communication systems. By enabling reliable and adaptive information exchange, it achieves the ambitious goal of harnessing and engineering olfactory communication as an innovative modality within the Internet of Everything, significantly expanding the horizons of connectivity.

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