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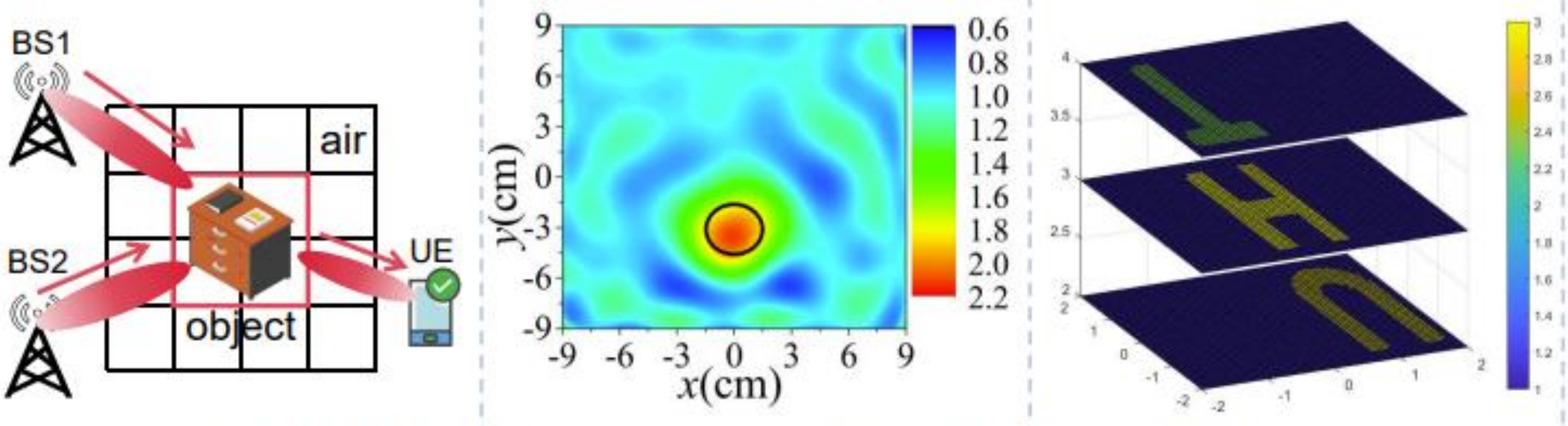
Electromagnetic Property Sensing: A New Paradigm of Integrated Sensing and Communication



Scene model of OMR | Electromagnetic scattering field | EC estimation

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Electromagnetic Property Sensing: A New Paradigm of Integrated Sensing and Communication

IF 10.7 SCIE JCR Q1 计算机科学1区 Top EI

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Yuhua Jiang ; Feifei Gao ; Shi Jin All Authors

Abstract

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Integrated sensing and communication (ISAC) has opened up numerous game-changing opportuni
systems. In this paper, we develop a novel scheme that utilizes orthogonal frequency division multi
in ISAC systems to sense the electromagnetic (EM) property of the target and thus also identify the
Specifically, we first establish an end-to-end EM propagation model by means of Maxwell equation
the target is captured by a closed-form expression of the ISAC channel, incorporating the Lippman
the method of moments (MOM) for discretization. We then model the relative permittivity and condu
within a specified detection region. Based on the sensing model, we introduce a multi-frequency-ba
method by which the RPCD can be reconstructed from compressive sensing techniques that exploi
of the EM property vector. To improve the sensing accuracy, we design a beamforming strategy from the communications transmitter based on the Born approximation that can minimize the mutual coherence of the sensing matrix. The optimization problem is cast in terms of the Gram matrix and is solved iteratively to obtain the optimal beamforming matrix. Simulation results demonstrate the efficacy of the proposed method in achieving high-quality RPCD reconstruction and accurate material classification. Furthermore, improvements in RPCD reconstruction quality and material classification accuracy are observed with increased signal-to-noise ratio (SNR) or reduced target-transmitter distance.

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Y Jiang, F Gao, S Jin

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Integrated sensing and communication (ISAC) has opened up numerous game-changing opportunities for future wireless systems. In this paper, we develop a novel scheme that utilizes orthogonal frequency division multiplexing (OFDM) pilot signals in ISAC systems to sense the electromagnetic (EM) property of the target and thus also identify the material of the target. Specifically, we first establish an end-to-end EM propagation model by means of Maxwell equations, where the EM property of the target is captured by a closed-form

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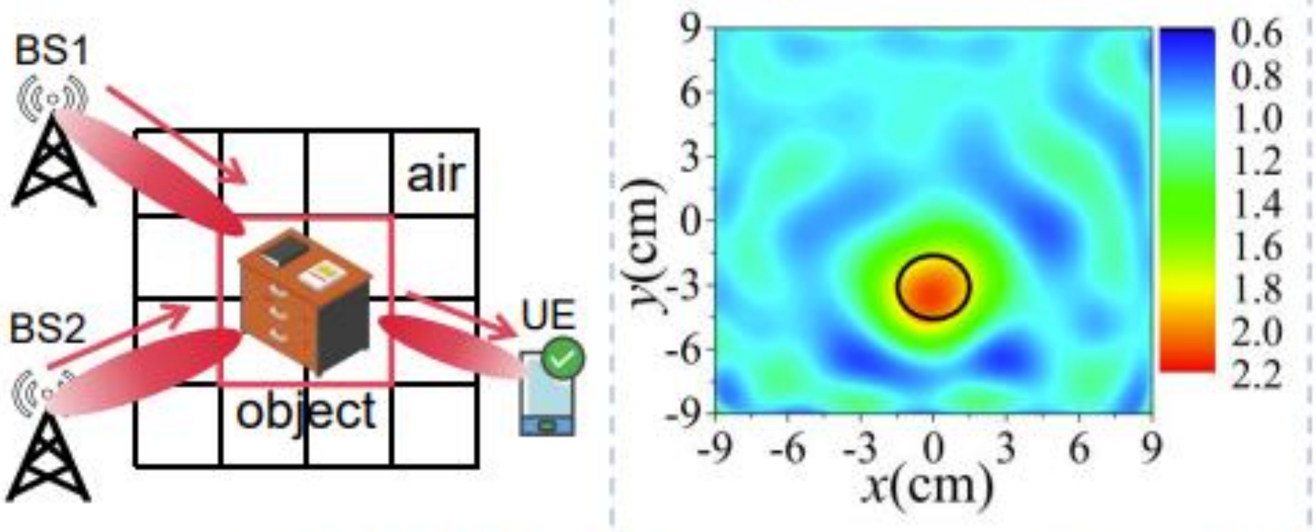
[1] Y. Jiang, F. Gao and S. Jin, "Electromagnetic Property Sensing: A New Paradigm of Integrated Sensing and Communication," in IEEE Transactions on Wireless Communications, vol. 23, no. 10, pp. 13471-13483, Oct. 2024, doi: 10.1109/TWC.2024.3401859

介绍框架

- 背景/简要介绍
- 研究方法
- 实验结果
- 总结



Scene model of OMR | Electromagnetic scattering field

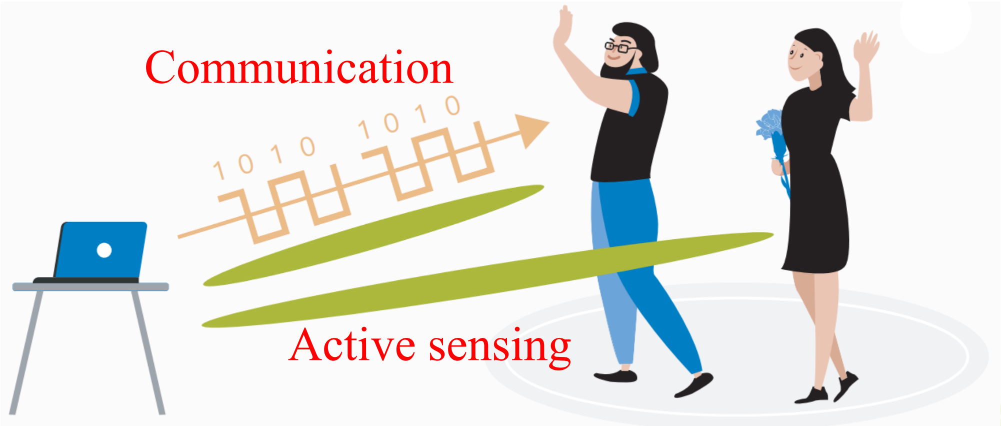
基于通感一体化的电磁特征感知

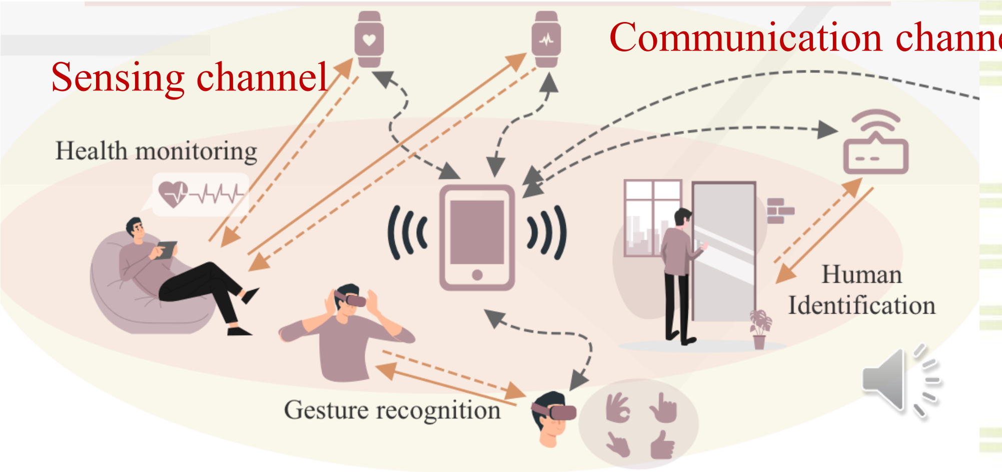
- 什么是通感一体化?
  - ISAC系统通过共用同一个硬件平台与无线资源来同时实现无线通信与感知的功能。

→ 为通信网络赋予新的感知功能
→ 感知信息可以提升通信功能

  - 如何从通信信号中恢复出感知信息?

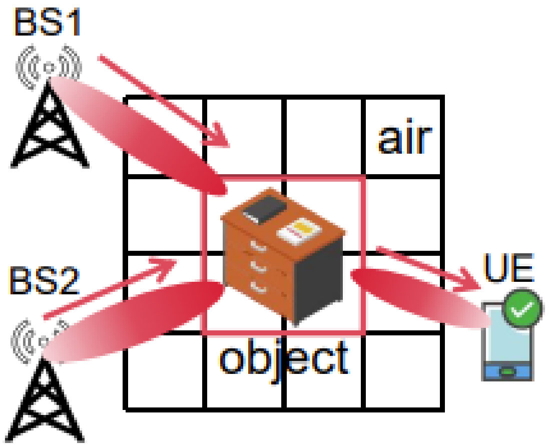
- ISAC有什么应用场景?
  - 车联网 / 无人机通信网络 /智能家居
  - 定位 (localization) / 电磁特性感知 (EM property)



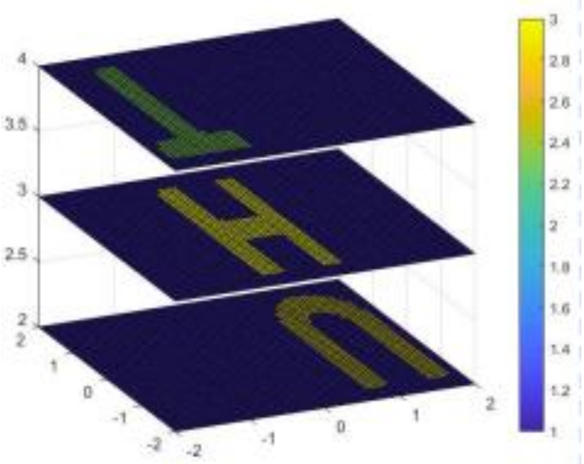


[2] J. Wang, N. Varshney, C. Gentile, S. Blandino, J. Chuang and N. Golmie, "Integrated Sensing and Communication: Enabling Techniques, Applications, Tools and Data Sets, Standardization, and Future Directions," in IEEE Internet of Things Journal, vol. 9, no. 23, pp. 23416-23440, 1 Dec.1, 2022.

基于通感一体化的电磁特征感知



Scene model of OMR



EC estimation

- ## 总体性能
  - 基于**OFMD, MIMO**通信系统的双基地的无设备感知系统 (bistatic, device-free)
  - 基于**麦克斯韦方程**建立了无线接收信号与空间内物体的电磁特征参数的关系式
  - 优化发射端的**波束设计**以最大化感知性能
  - 可以实现对2 × 2米内物体的**相对介电常数**与**电导率**的估计；基于估计的电磁特性，可以有效完成目标物体的**材质分类(material classification)**

基于通感一体化的电磁特征感知

- 信号模型

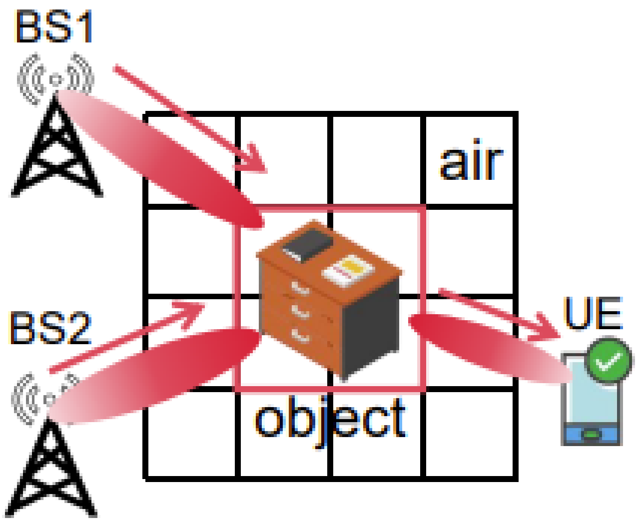
波束设计

$$\tilde{\mathbf{y}}_k = \mathbf{H}_{2,k}\underline{\mathrm{diag}\left(\chi_k\right)\left(\mathbf{I}-\mathbf{G}_k\mathrm{diag}\left(\chi_k\right)\right)^{-1}}\mathbf{H}_{1,k}\mathbf{w}_k+\tilde{\mathbf{n}}_k. \tag{12}$$

物体→接收端　　与物体的电磁特性相关　　发射端→物体

  - 单个子频点；后续会叠加不同时隙/频点的信号
  - 基于Lippmann–Schwinger物理模型，描述了物体带来的散射效应

- 电磁特征感知
  - 基于压缩感知的电磁特征感知
  - 最大化感知性能的波束设计优化



Scene model of OMR

基于通感一体化的电磁特征感知

- 基于压缩感知的电磁特征感知

$$\begin{bmatrix} \mathbf{z}_1 \\ \vdots \\ \mathbf{z}_K \end{bmatrix} = \begin{bmatrix} \mathbf{E}_1 \\ \vdots \\ \mathbf{E}_K \end{bmatrix} \mathbf{s} + \begin{bmatrix} \Re(\mathbf{n}_1) \\ \Im(\mathbf{n}_1) \\ \vdots \\ \Re(\mathbf{n}_K) \\ \Im(\mathbf{n}_K) \end{bmatrix}.$$

$$\begin{aligned} \min \ & \|\mathbf{s}\|_{1,2} \\ \text{s.t.} \ & \|\tilde{\mathbf{z}} - \tilde{\mathbf{E}}\mathbf{s}\|_2 \leqslant \varepsilon', \\ & \mathbf{s} \geqslant \mathbf{0}, \end{aligned}$$

  - 叠加了不同时隙/频点的信号
  - 物体在空间中所占体积很小→未知向量**s**具有稀疏性
  - 压缩感知：混合(ℓ1,ℓ2)范数的最优化问题
  - $\mathbf{E}_k$与**s**也相关，因此需要多次迭代以上的优化求解直到收敛

- 最大化感知性能的波束设计

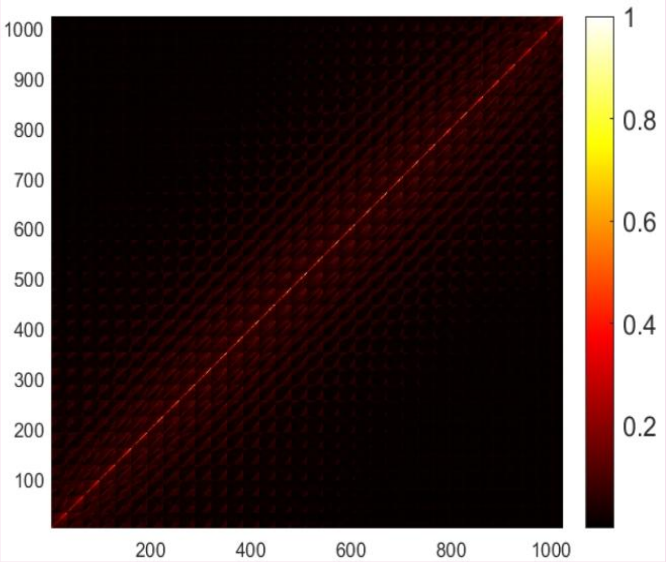
$$\mu_{ij}(\tilde{\mathbf{E}}) = \frac{\left|\tilde{\mathbf{E}}[:,i]^\top \tilde{\mathbf{E}}[:,j]\right|}{\left\|\tilde{\mathbf{E}}[:,i]\right\|_2 \left\|\tilde{\mathbf{E}}[:,j]\right\|_2} = \frac{|G_{ij}|}{\sqrt{|G_{ii}|\,|G_{jj}|}},$$

  - 最小化相干性测度 (mutual coherence)
  - 由于没有物体位置的先验信息，其实波束设计只与发射端到物体的信道相关

基于通感一体化的电磁特征感知

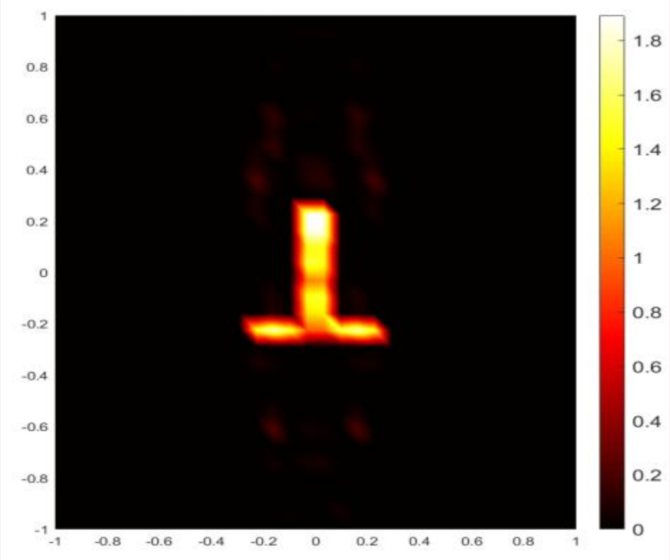
- 实验结果

1



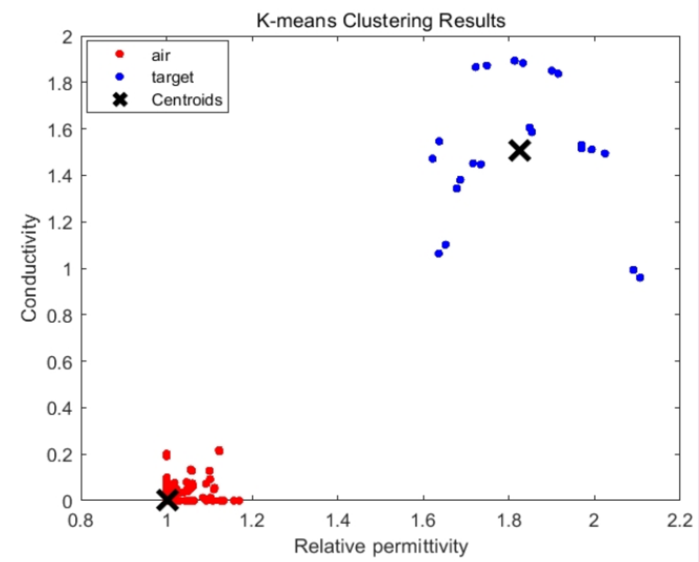
- 经过波束设计优化，不同频点，时隙下接收信号的相关性很低

2



- 对物体相对介电常数的估计在SNR较高的区域非常精准

3



- 用k-means方法做材质区分，可以大致判断物体的材质

基于通感一体化的电磁特征感知

- 总结
  - 很前沿的关于通感一体化领域电磁特征感知的工作，后续会有很多工作跟进
  - 基于逆散射/物理模型，感知的区域大小比较局限，并且计算复杂度较高

Electromagnetic Property Sensing Based on Diffusion Model in ISAC System IF 10.7 SCIE

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