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Stacked intelligent metasurface-aided multi-static sensing and cooperative communication

Key words: Stacked intelligent metasurface (SIM); Integrated sensing and communication (ISAC); Multi-static sensing; Cooperative communication; Wave-domain beamforming

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Motivation

- Future 6G networks are expected to support not only high-rate communications, but also sensing, localization, and environmental perception. ISAC enables communication and sensing to share spectrum, hardware, waveforms, and signal-processing resources.
- Multi-static/cooperative sensing can exploit spatial diversity from geographically distributed base stations, but most existing designs rely on **conventional active antenna arrays**, whose RF-chain, digital-precoding, and echo-processing costs increase with the number of nodes and aperture size.
- **Stacked intelligent metasurfaces** (SIMs) employ multiple cascaded metasurface layers to perform **beamforming and spatial filtering directly in the electromagnetic wave domain**, offering a promising low-power alternative to conventional fully active processing. Existing SIM-assisted ISAC studies focus mainly on single-transceiver or co-located systems. The potential of SIMs for cooperative multi-static ISAC with both transmit- and receive-side SIMs has not yet been fully characterized.

Main idea

1. SIM-aided multi-static ISAC architecture

Multiple geographically distributed base stations (BSs) are coordinated by a central processing unit (CPU). The BSs are divided into transmitting BSs (TBSs) and receiving BSs (RBSs), with SIMs deployed at both sides to realize wave-domain transmit beamforming and receive spatial filtering.

2. Joint optimization problem formulation

A joint design problem is formulated to maximize the communication sum rate while guaranteeing target-specific sensing SINR requirements. The optimization simultaneously accounts for transmit power allocation, SIM phase shifts, and centralized sensing receive beamformers, thereby capturing the strong coupling between communication and sensing introduced by cascaded SIM transformations.

3. Efficient algorithm design

To solve the resulting non-convex problem, an alternating optimization framework is developed by combining generalized Rayleigh quotient maximization for sensing receive beamforming, WMMSE-based optimization for transmit power allocation, and Riemannian manifold optimization for the unit-modulus SIM phase shifts.

Method

System model

A CPU coordinates N BSs, K single-antenna users, and S point targets. The BSs are partitioned into transmitting BSs and receiving BSs, enabling distributed target illumination and cooperative echo reception.

Each SIM contains L stacked metasurface layers with M meta-atoms per layer. Cascaded diffraction matrices $\mathbf{T}_{n,l}$ and phase-shift matrices $\Phi_{n,l}$ form the aggregate wave-domain beamformer as follows:

$$\mathbf{W}_n = \Phi_{n,L} \mathbf{T}_{n,L} \Phi_{n,L-1} \cdots \mathbf{T}_{n,2} \Phi_{n,1} \mathbf{T}_{n,1}. \quad (1)$$

ISAC signal transmission

The same downlink waveform supports communication and sensing. TBSs serve K UEs; RBSs collect target echoes, clutter, and inter-BS interference for centralized receive beamforming at the CPU.

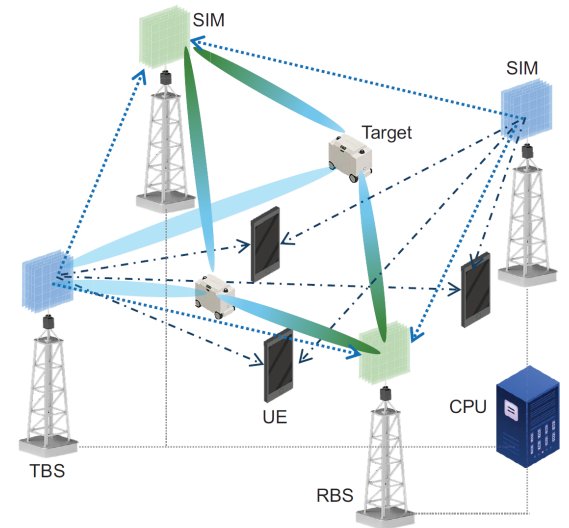


Fig. 1 SIM-aided multi-static ISAC system

Method (Cont'd)

Design objective

The joint design maximizes the downlink communication sum rate while enforcing target-specific sensing quality, transmit power limits, and passive SIM hardware constraints.

$$\begin{aligned} \max_{\mathbf{P}, \mathbf{\Phi}, \mathbf{U}} \quad & \sum_{k=1}^K \log_2(1 + \gamma_k^{\text{comm}}) \\ \text{s.t.} \quad & \gamma_s^{\text{sens}} \geq \Gamma_s^{\min}, \quad \forall s, \\ & \sum_{k=1}^K p_{n,k} \leq P_n^{\max}, \quad \forall n \in \mathcal{N}_T, \quad (2) \\ & p_{n,k} \geq 0, \quad \forall n, k, \\ & |[\mathbf{\Phi}_{n,l}]_{m,m}| = 1, \quad \forall n, l, m, \end{aligned}$$

Optimization variables

P: baseband transmit power allocation across users and TBSs

Φ: phase shifts of transmit- and receive-side SIM layers

U: centralized receive beamformers for cooperative target sensing

Challenge: The SINR expressions couple all variables, and SIM phase shifts have unit-modulus constraints, making the problem non-convex.

Method (Cont'd)

Core updates per iteration:

Sensing receive beamformers:

maximize sensing SINR using generalized Rayleigh quotient / eigenvector update.

Power allocation: convert sum-rate maximization to weighted minimum mean square error (WMMSE) minimization; handle sensing constraints with successive convex approximation (SCA) techniques and standard quadratic constrained quadratic programming (QCQP) solvers.

SIM phase shifts: optimize unit-modulus variables with Riemannian conjugate gradient and a squared hinge penalty for sensing constraints.

Alternating optimization framework

Algorithm 1 Joint design for SIM-aided multi-static sensing and cooperative communication

- 1: **Input:** CSI and target-response information, sensing SINR thresholds $\{\Gamma_s^{\min}\}$, transmit power budgets $\{P_n^{\max}\}$, penalty factor ρ , and tolerance ϵ .
 - 2: **Initialize:** SIM phase shifts $\Phi^{(0)}$, power allocation $P^{(0)}$, and iteration index $t = 0$.
 - 3: **repeat**
 - 4: Update $\{u_s^{(t+1)}\}$ for each target by computing the generalized eigenvector of (A_s, B_s) via Eq. (19).
 - 5: Update equalizers $\{q_k^{(t+1)}\}$ and weights $\{v_k^{(t+1)}\}$ based on fixed $\Phi^{(t)}$ and $P^{(t)}$ via Eqs. (21) and (22).
 - 6: Update $P^{(t+1)}$ by solving the convex QCQP subproblem using successive convex approximation (SCA) techniques.
 - 7: Update $\Phi^{(t+1)}$ via the RCG algorithm to minimize the penalized objective $\mathcal{J}$ in Eq. (26).
 - 8: Update $t \leftarrow t + 1$.
 - 9: **until** The relative change of the sum rate is below ϵ and the sensing constraints are satisfied.
 - 10: **Output:** P , U , and Φ .
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Major results

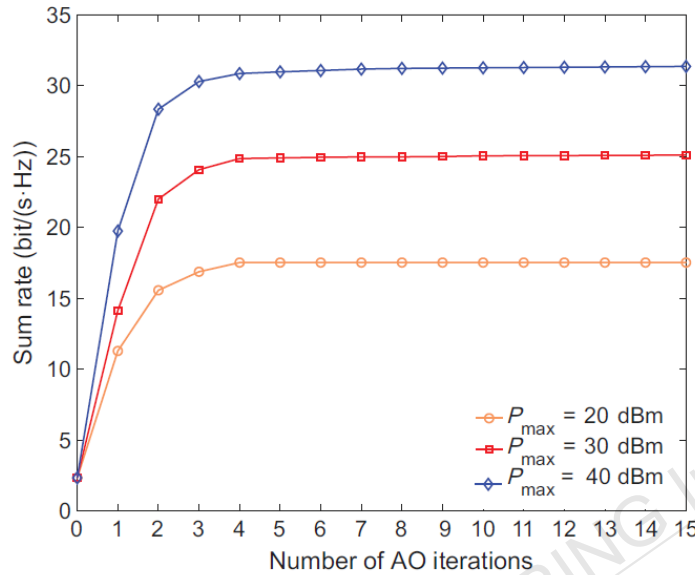


Table 1 Average running time for different numbers of SIM layers and meta-atom configurations

M	Average running time (s)					
	$L=3$	4	5	6	7	8
7×7	20.01	31.03	35.52	39.96	44.91	49.61
8×8	27.93	35.94	42.40	48.96	55.63	64.33
9×9	36.51	49.66	66.76	78.09	92.47	99.48

Table 2 Simulation parameters

Parameter	Value
Number of BSs	$N_T = 3, N_R = 3$
Number of antennas per BS	$U = 8$
Number of UEs and targets	$K = 4, S = 2$
SIM configuration	$M = 8 \times 8, L = 4$
Sensing SINR threshold	$\Gamma_s^{\min} = 0$ dB
Noise power	$\sigma_k^2 = \sigma_r^2 = -102$ dBm
Maximum transmit power	$P_n^{\max} = P_{\max} = 30$ dBm

Fig. 3 The AO algorithm converges within about six iterations

Key observation

The AO framework exhibits rapid monotonic improvement and stabilizes within about six iterations under different transmit power budgets. This supports offline or semi-static SIM configuration updates.

Major results (Cont'd)

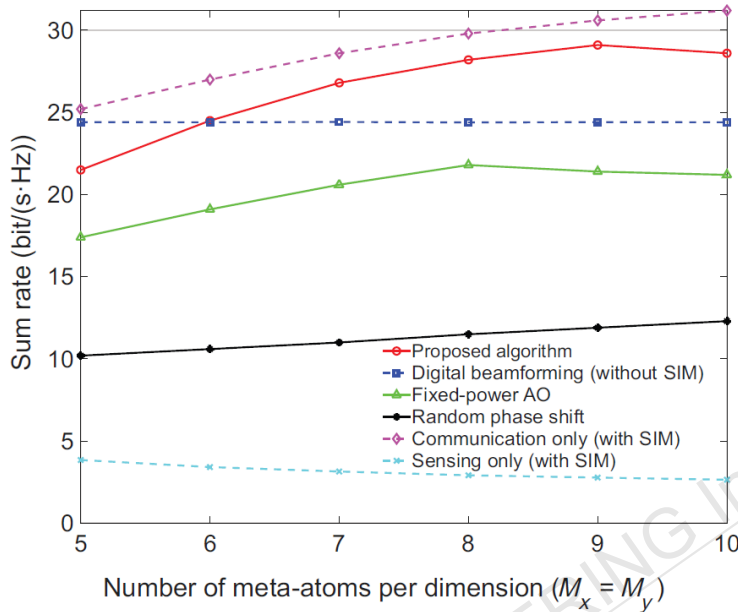


Fig. 4 Sum rate vs. number of meta-atoms

Table 3 Achieved sensing SINRs of the proposed algorithm under different numbers of meta-atoms per dimension with $L = 6$

Dimension ($M_x = M_y$)	SINR (dB)	
	Target 1	Target 2
5	6.25	6.12
6	6.82	6.65
7	7.35	7.18
8	7.92	7.78
9	8.35	8.12
10	8.33	8.05

Communication gain with sensing QoS

The proposed joint design outperforms fixed-power AO and random-phase benchmarks.

Sensing feasibility

Both targets remain above the 0 dB sensing SINR threshold across all tested SIM configurations.

Major results (Cont'd)

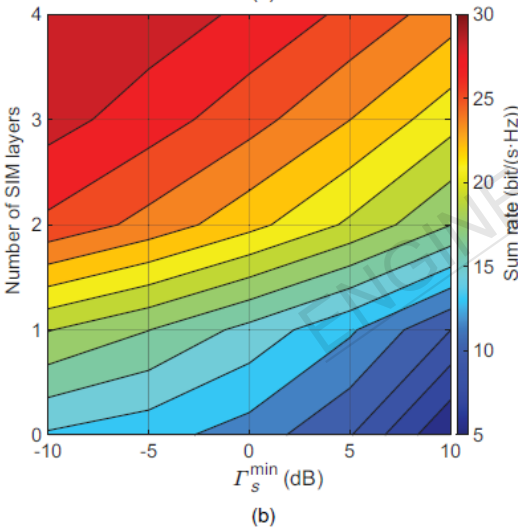
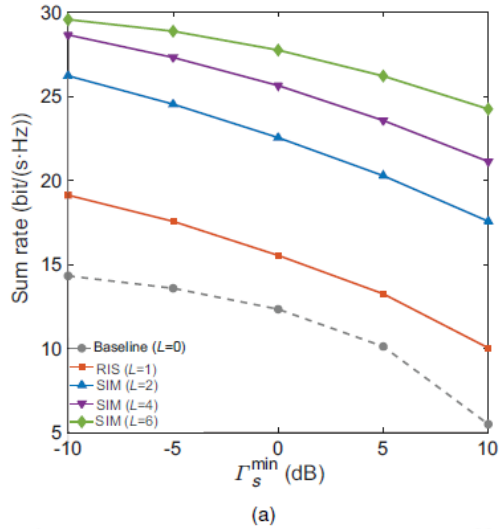


Fig. 5 Effects of the sensing SINR threshold and number of SIM layers

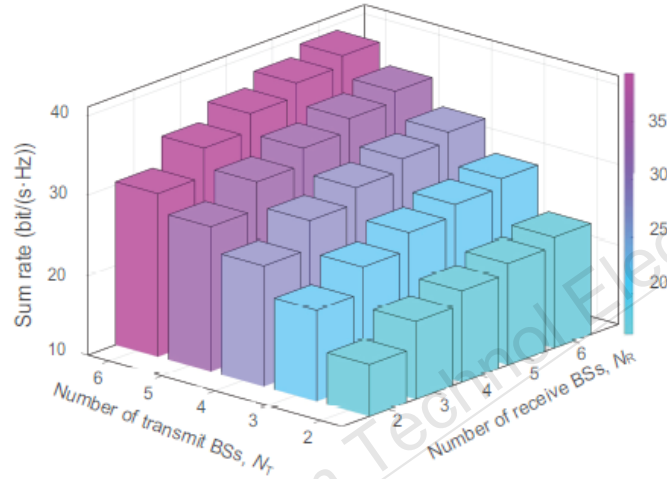


Fig. 6 More TBSs/RBSs improve sum rate

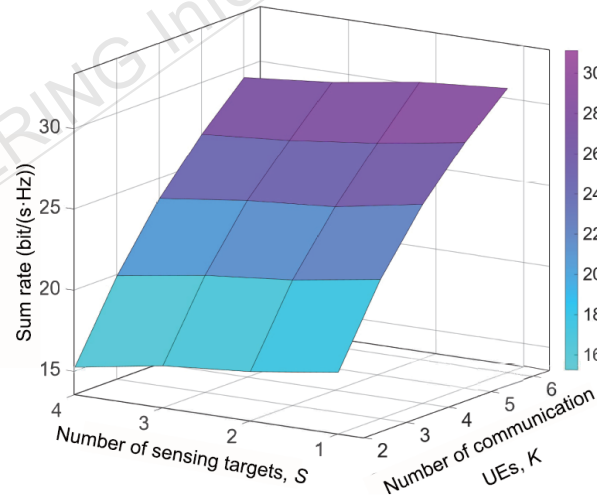


Fig. 7 UE/target scaling trade-off

Communication–sensing trade-off

A stricter sensing SINR threshold reduces the achievable sum rate because more system resources must be allocated to target sensing. Increasing the number of SIM layers alleviates this bottleneck by expanding wave-domain degrees of freedom.

Network-scale effects

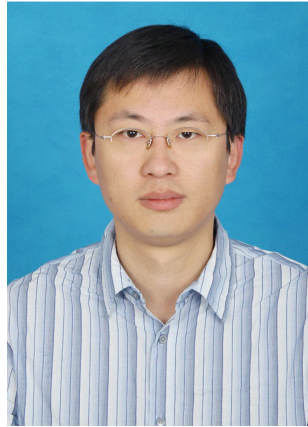
More TBSs provide stronger cooperative transmission gains, while more RBSs strengthen cooperative target detection. More users increase multiplexing gains, whereas more targets consume additional sensing resources.

Conclusions

- This work investigates an SIM-aided multi-static sensing and cooperative communication framework. By exploiting wave-domain signal processing, the architecture supports joint user communication and cooperative target sensing with reduced reliance on high-dimensional fully digital precoding and active-array scaling.
- The formulated sum-rate maximization problem jointly captures transmit power allocation, SIM phase shifts, and centralized sensing receive beamforming under sensing SINR constraints. The AO algorithm combines Rayleigh quotient maximization, WMMSE/SCA-based power optimization, and Riemannian manifold optimization.
- Future extensions include robust operation under CSI errors, target-location uncertainty, RCS fluctuations, BS synchronization mismatch, and SIM phase quantization/control errors, as well as fairness-aware and hardware-aware designs.



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