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Joint active user detection and channel estimation for massive machine-type communications: a difference-of-convex optimization perspective

Key words: Joint active user detection and channel estimation; Massive machine-type communications; Difference-of-convex function algorithm; Alternating direction multiplier method

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Motivation

- Sparsity-based joint active user detection and channel estimation (JADCE) algorithms are crucial in grant-free massive machine-type communication (mMTC) systems.
- The conventional compressed sensing algorithms are tailored for noncoherent communication systems, where the correlation between any two measurements is as minimal as possible. However, existing sparsity-based JADCE approaches may not achieve optimal performance in strongly coherent systems, especially with a small number of pilot subcarriers.

Main idea

- To tackle this challenge, we formulate JADCE as a joint sparse signal recovery problem, leveraging the block-type row-sparse structure of millimeter-wave (mmWave) channels in massive multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) systems.
- We propose an efficient difference-of-convex function algorithm (DCA)-based JADCE algorithm with multiple measurement vector (MMV) frameworks.
- To mitigate the computational complexity further, we introduce a fast DCA-based JADCE algorithm via a proximal operator, which allows a low-complexity alternating direction multiplier method (ADMM) to resolve the optimization problem directly.

System model

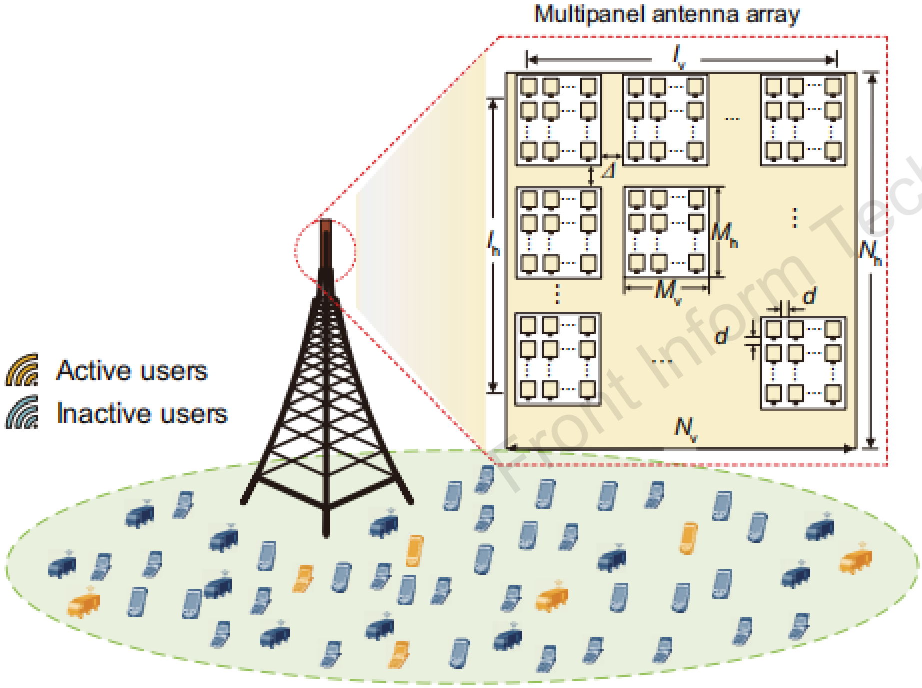


Fig. 1 In the mMTC scenarios, the massive multi-panel MIMO systems employ the mmWave channel model

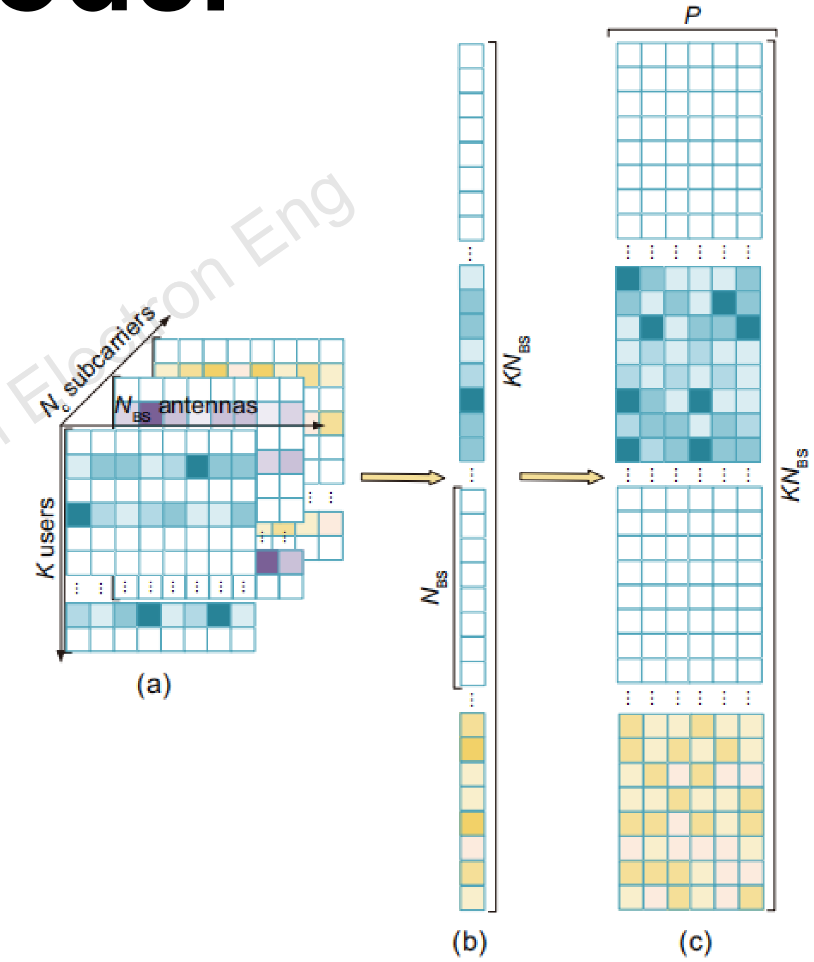
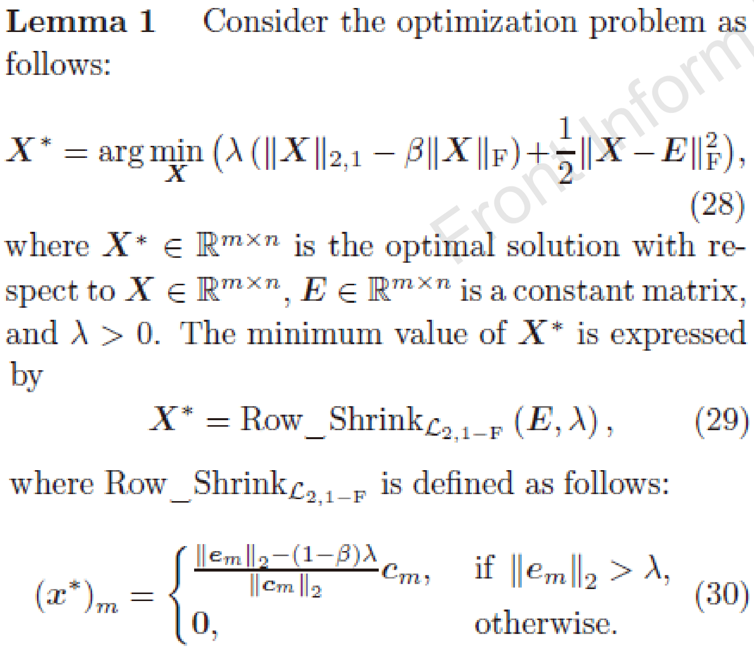


Fig. 2 Due to the spatial-frequency-domain structure, $\widetilde{H}_p$ exhibits a row-sparse structure in (a); by vectorization of $\widetilde{H}_p$, h_p^t shows a block-type sparse structure in (b); after aggregating P pilot subcarriers, $\widetilde{H}$ has the property of block-type row sparsity in (c)

Method

The existing sparsity-based JADCE methods do not perform well in the presence of strong coherence, resulting in performance degradation as the number of pilot subcarriers declines. We introduce a modified DCA based $\mathcal{L}_{\mathbf{2,1-F}}$ minimization algorithm for the JADCE problem in the MMV case. Moreover, we adopt a low-complexity ADMM solver to address the convex subproblems decomposed by DCA.



Lemma 1 Consider the optimization problem as follows:

$$\boldsymbol{X}^* = \arg\min_{\boldsymbol{X}} \left(\lambda\left(\|\boldsymbol{X}\|_{2,1} - \beta\|\boldsymbol{X}\|_{\mathrm{F}}\right) + \frac{1}{2}\|\boldsymbol{X}-\boldsymbol{E}\|_{\mathrm{F}}^2\right), \tag{28}$$

where $\boldsymbol{X}^* \in \mathbb{R}^{m\times n}$ is the optimal solution with respect to $\boldsymbol{X} \in \mathbb{R}^{m\times n}$, $\boldsymbol{E} \in \mathbb{R}^{m\times n}$ is a constant matrix, and $\lambda > 0$. The minimum value of $\boldsymbol{X}^*$ is expressed by

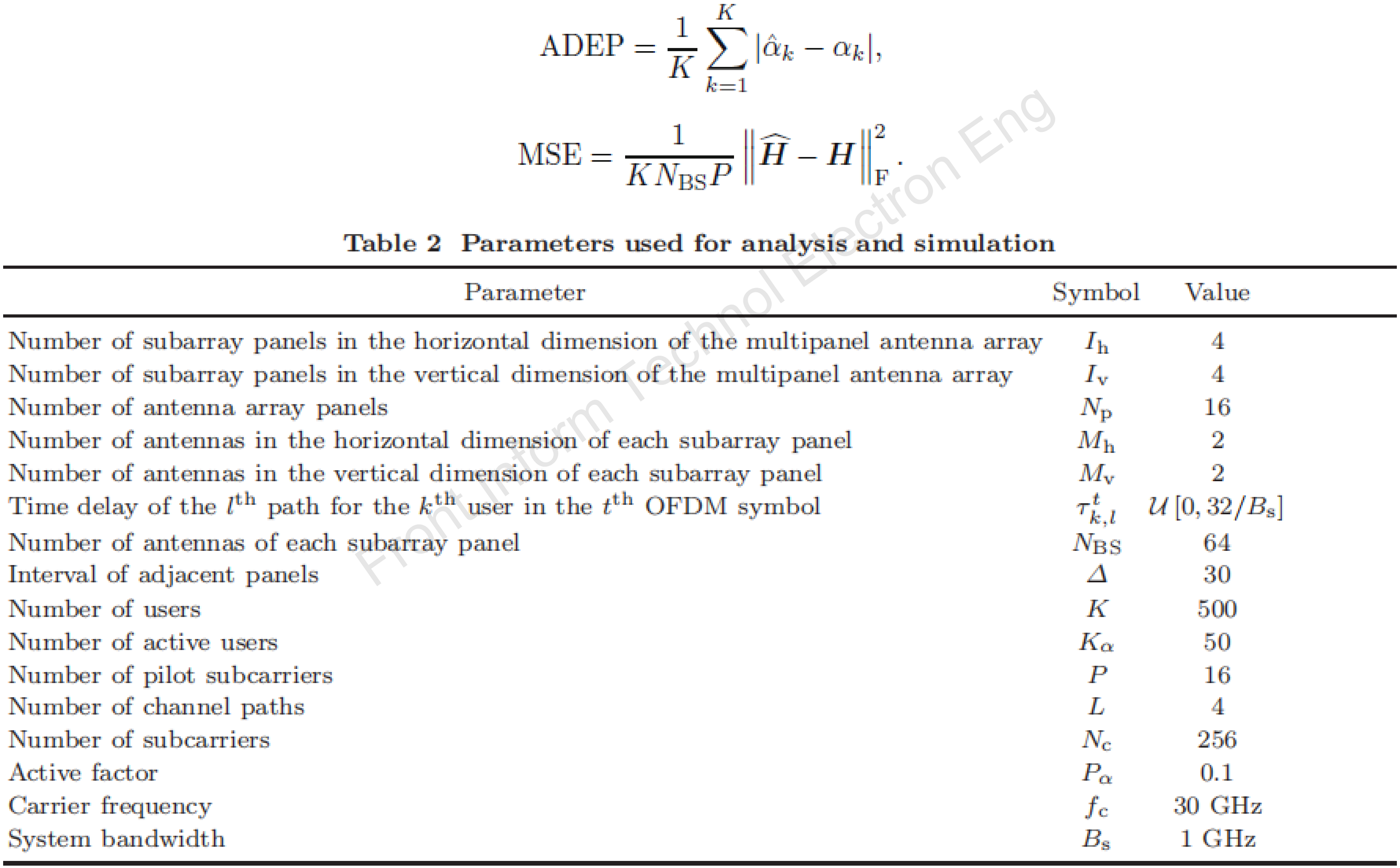
$$\boldsymbol{X}^* = \mathrm{Row\_Shrink}_{\mathcal{L}_{2,1-\mathrm{F}}}\left(\boldsymbol{E}, \lambda\right), \tag{29}$$

where $\mathrm{Row\_Shrink}_{\mathcal{L}_{2,1-\mathrm{F}}}$ is defined as follows:

$$(\boldsymbol{x}^*)_m = \begin{cases} \frac{\|\boldsymbol{e}_m\|_2-(1-\beta)\lambda}{\|\boldsymbol{c}_m\|_2}\boldsymbol{c}_m, & \text{if } \|\boldsymbol{e}_m\|_2 > \lambda, \\ 0, & \text{otherwise.} \end{cases} \tag{30}$$

To further reduce the computational complexity of the DCA-based JADCE algorithm, we derive the analytical solution of the $\mathcal{L}_{\mathbf{2,1-F}}$ metric proximal operator, enabling the ADMM algorithm to solve the optimization problem directly.

Metrics and parameters



$$\mathrm{ADEP} = \frac{1}{K}\sum_{k=1}^{K}|\hat{\alpha}_k - \alpha_k|,$$

$$\mathrm{MSE} = \frac{1}{KN_{\mathrm{BS}}P}\left\|\widehat{\boldsymbol{H}} - \boldsymbol{H}\right\|_{\mathrm{F}}^{2}.$$

Table 2 Parameters used for analysis and simulation

Parameter	Symbol	Value
Number of subarray panels in the horizontal dimension of the multipanel antenna array	I_{h}	4
Number of subarray panels in the vertical dimension of the multipanel antenna array	I_{v}	4
Number of antenna array panels	N_{p}	16
Number of antennas in the horizontal dimension of each subarray panel	M_{h}	2
Number of antennas in the vertical dimension of each subarray panel	M_{v}	2
Time delay of the l^{th} path for the k^{th} user in the t^{th} OFDM symbol	$\tau_{k,l}^{t}$	$\mathcal{U}[0, 32/B_{\mathrm{s}}]$
Number of antennas of each subarray panel	N_{BS}	64
Interval of adjacent panels	Δ	30
Number of users	K	500
Number of active users	K_{α}	50
Number of pilot subcarriers	P	16
Number of channel paths	L	4
Number of subcarriers	N_{c}	256
Active factor	P_{α}	0.1
Carrier frequency	f_{c}	30 GHz
System bandwidth	B_{s}	1 GHz

Results

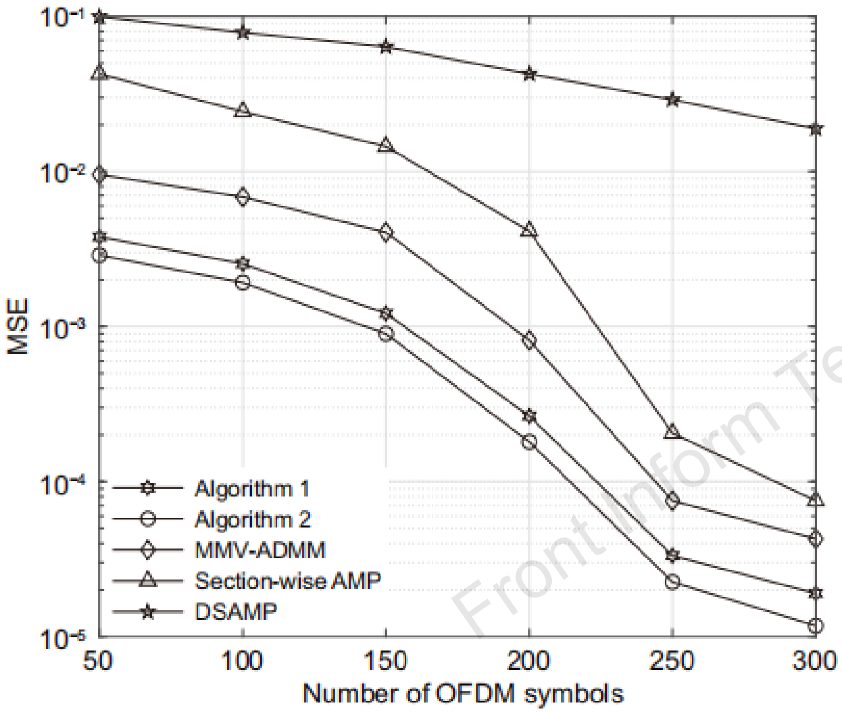


Fig. 3 Channel estimation performance of MSE versus the number of OFDM symbols. The parameter settings are $K = 500$, $K_\alpha = 50$, SNR=30 dB, and $P = 16$

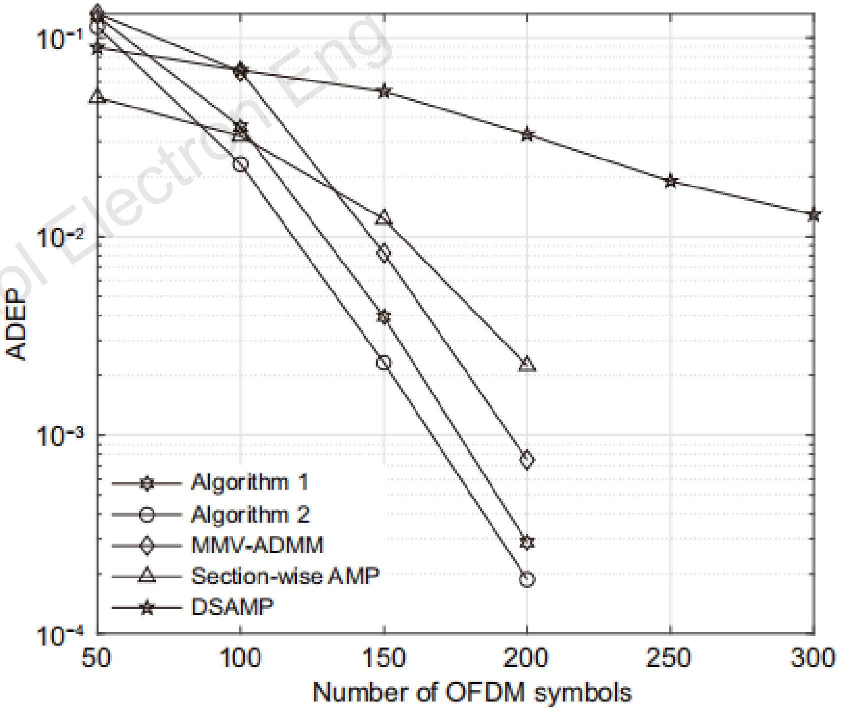


Fig. 4 Active user detection performance of ADEP versus the number of OFDM symbols. The parameter settings are $K = 500$, $K_\alpha = 50$, SNR=30 dB, and $P = 16$

Results

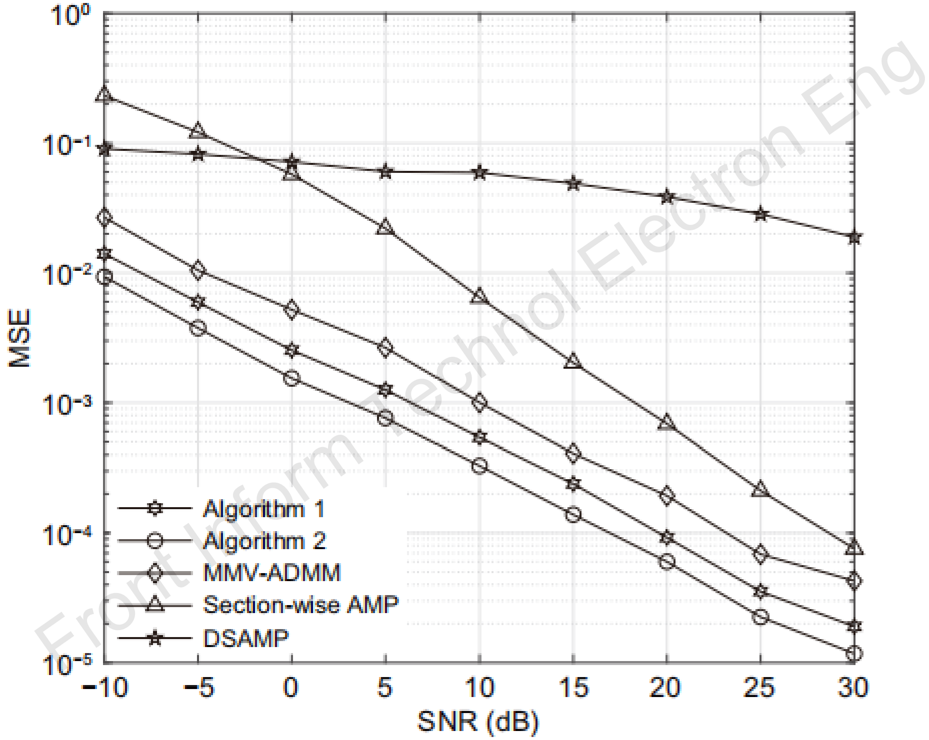
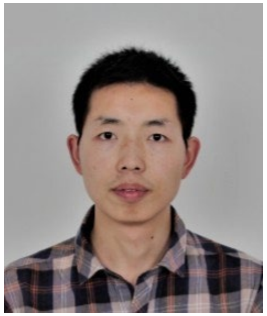


Fig. 5 Channel estimation performance of MSE versus SNR. The parameter settings are $K = 500$, $K_\alpha = 50$, $T = 300$, and $P = 16$

Conclusions

We have investigated the JADCE problem in strongly coherent mMTC scenarios based on the grant-free scenario. Due to the strongly coherent communication systems, the performance of existing compressed sensing algorithms degrades as the number of pilot subcarriers declines. Therefore, we introduced a novel DCA-based $\mathcal{L}_{\mathbf{2},\mathbf{1}-\mathbf{F}}$ algorithm with the MMV framework to solve the JADCE problem. To further reduce the computational complexity of the DCA-based JADCE algorithm, a fast DCA-based JADCE algorithm was provided, from which the analytical solution based on the $\mathcal{L}_{\mathbf{2},\mathbf{1}-\mathbf{F}}$ metric proximal operator was derived, and hence the ADMM solver can directly address the optimization problem.

Lijun ZHU is currently pursuing the PhD degree of engineering of telecommunication in Beijing University of Posts and Telecommunications, Beijing, China.



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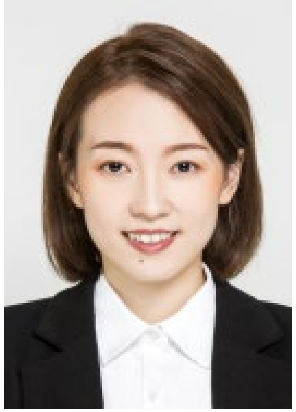

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