厦門大學
XIAMEN UNIVERSITY

基于多任务联邦学习的可见光通信定位一体化技术

Visible Light Integrated Positioning and Communication Based on Multi-Task Federated Learning

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汇报提纲

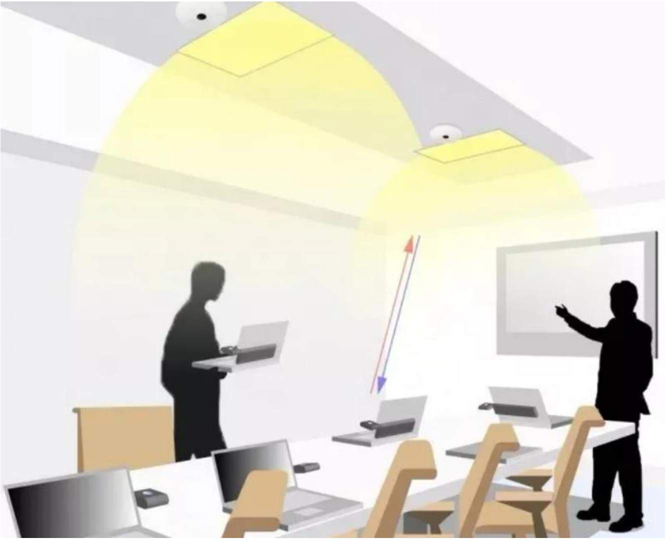
- 研究背景
- 可见光通信定位融合架构
- 基于稀疏感知多任务学习的可见光通信信道估计与可见光定位
- 面向多用户协作可见光定位通信一体化的联邦多任务学习框架
- 性能评估与理论分析
- 仿真结果与讨论
- 小结
- 关于AI+VLC的一些工作

研究背景

可见光通信

Visible Light Communication (VLC)

- Ultra-wide spectrum
- Cost-effective hardware
- Privacy protection ability
- No Electromagnetic interference



可见光定位

Visible Light Positioning (VLP)

- High positioning accuracy
- Unregulated spectrum

研究背景

室内可见光定位方法

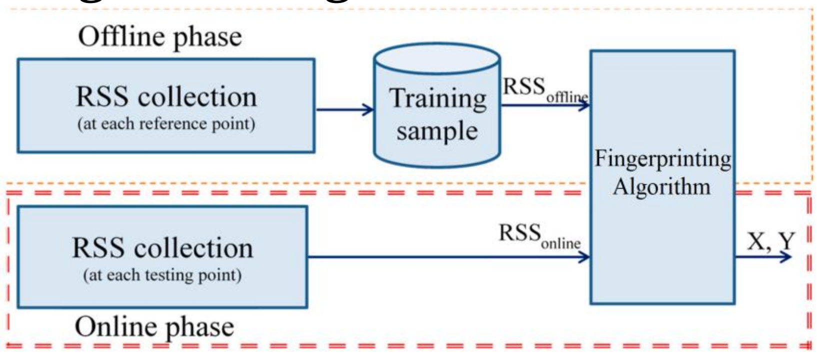
- 基于PD(光电二极管)的方法
  - Time of arrival (TOA)/time difference of arrival (TDOA) [1]
  - Received signal strength (RSS) [2]
  - Angle of arrival (AOA) [3]
- 基于传感器/传感辅助的方法
  - Image Sensor/Camera [4]
  - Light Sensor
  - Accelerometer

[1] K. Majeed and S. Hranilovic, "Passive Indoor Visible Light Positioning System Using Deep Learning," in IEEE Internet Things J., vol. 8, no. 19, pp. 14810-14821, Oct. 2021.
[2] M. F. Keskin, E. Gonendik, and S. Gezici, "Improved lower bounds for ranging in synchronous visible light positioning systems," J. Lightw. Technol., vol. 34, no. 23, pp. 5496–5504, Dec. 1, 2016.
[3] S.-H. Yang, H.-S. Kim, Y.-H. Son, and S.-K. Han, "Three-dimensional visible light indoor localization using AOA and RSS with multiple optical receivers," J. Lightw. Technol., vol. 32, no. 14, pp. 2480–2485, Jul. 15, 2014.
[4] H. Cheng, C. Xiao, Y. Ji, J. Ni and T. Wang, "A Single LED Visible Light Positioning System Based on Geometric Features and CMOS Camera," in IEEE Photon. Technol. Lett., vol. 32, no. 17, pp. 1097-1100, 1 Sept.1, 2020.

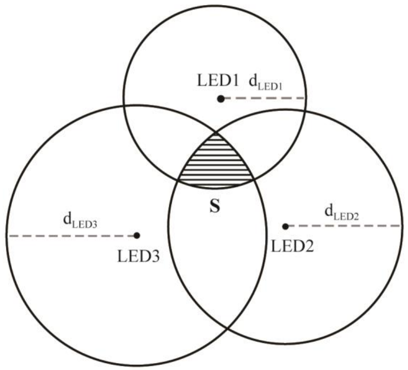
研究背景

基于PD的可见光定位算法

- Fingerprinting-based algorithms



- Trilateration/multilateration-based methods



$$\hat{d}_i = d_i + \varepsilon_i,\ i = 1, 2, 3$$

$$\begin{cases} (x - x_1)^2 + (y - y_1)^2 = d_1^2 \\ (x - x_2)^2 + (y - y_2)^2 = d_2^2 \\ (x - x_3)^2 + (y - y_3)^2 = d_3^2 \end{cases}$$

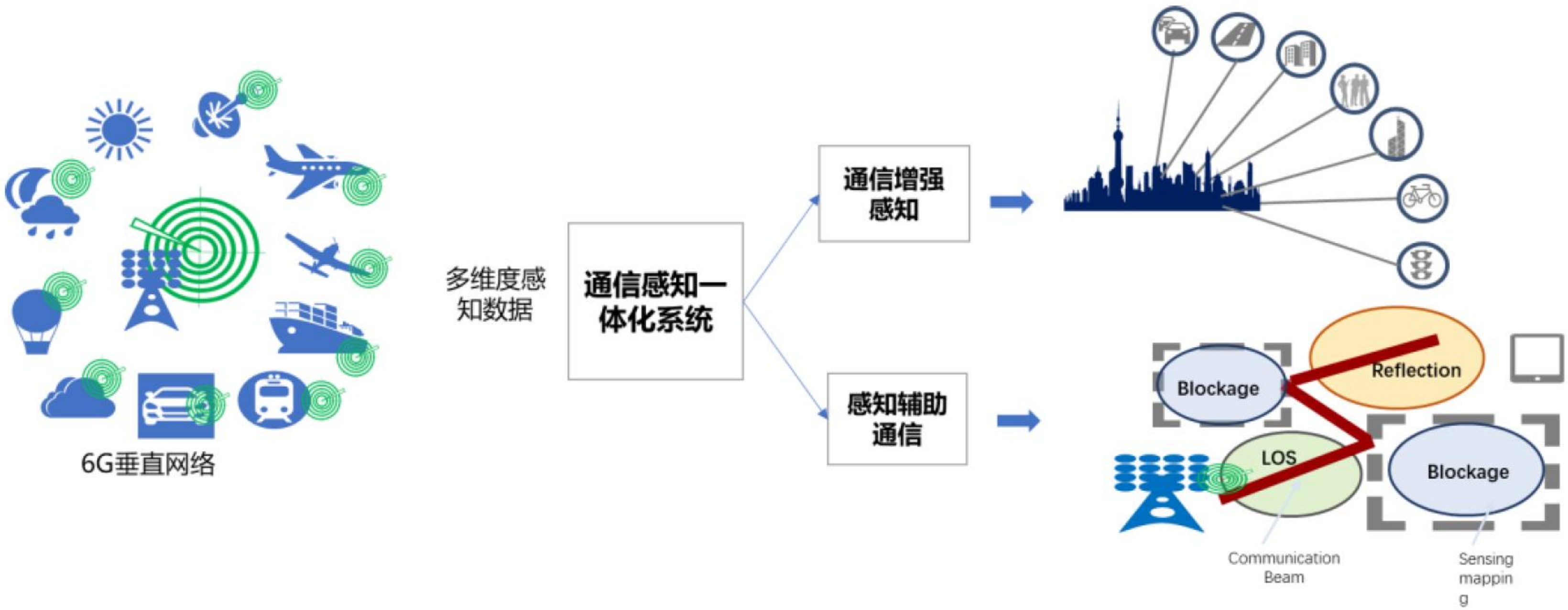
$$P_t = \underset{p}{\operatorname{argmin}} \sum_{i=1}^{N} \left(d_i - \hat{d}_i \right)^2$$

require

Specific signals for positioning or extra modules

研究背景

通信感知一体化 Integrated sensing and communication (ISAC)



Integrated sensing and communication will become a key technology in future wireless systems. [5, 6]

[5] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," IEEE J. Sel. Areas Commun., vol. 40, no. 6, pp. 1728–1767, Jun. 2022.
[6] Y. Cui, F. Liu, X. Jing, and J. Mu, "Integrating sensing and communications for ubiquitous IoT: Applications, trends, and challenges," IEEE Netw., vol. 35, no. 5, pp. 158–167, Sep./Oct. 2021.

研究背景

通感一体化 (ISAC) for 可见光通信 + 可见光定位

- Isolated design of positioning and communication

limit →

- Resource utilization efficiency
- Potential mutual benefits

↓ inspire

- Integrated positioning and communication

←

- Pilots for joint channel estimation and positioning

多任务学习

Multi-task Learning (MTL) framework can be considered [7-9]

[7] R. Caruana, "Multitask learning," Mach. Learn., vol. 28, no. 1, pp. 41–75, Jul. 1997.
[8] Y. Zhang and Q. Yang, "A survey on multi-task learning," IEEE Trans. Knowl. Data Eng., 2021.
[9] Y. Lu, P. Cheng, Z. Chen, W. H. Mow, Y. Li, and B. Vucetic, "Deep multi-task learning for cooperative NOMA: System design and principles," IEEE J. Sel. Areas Commun., vol. 39, no. 1, pp. 61–78, Jan. 2021.

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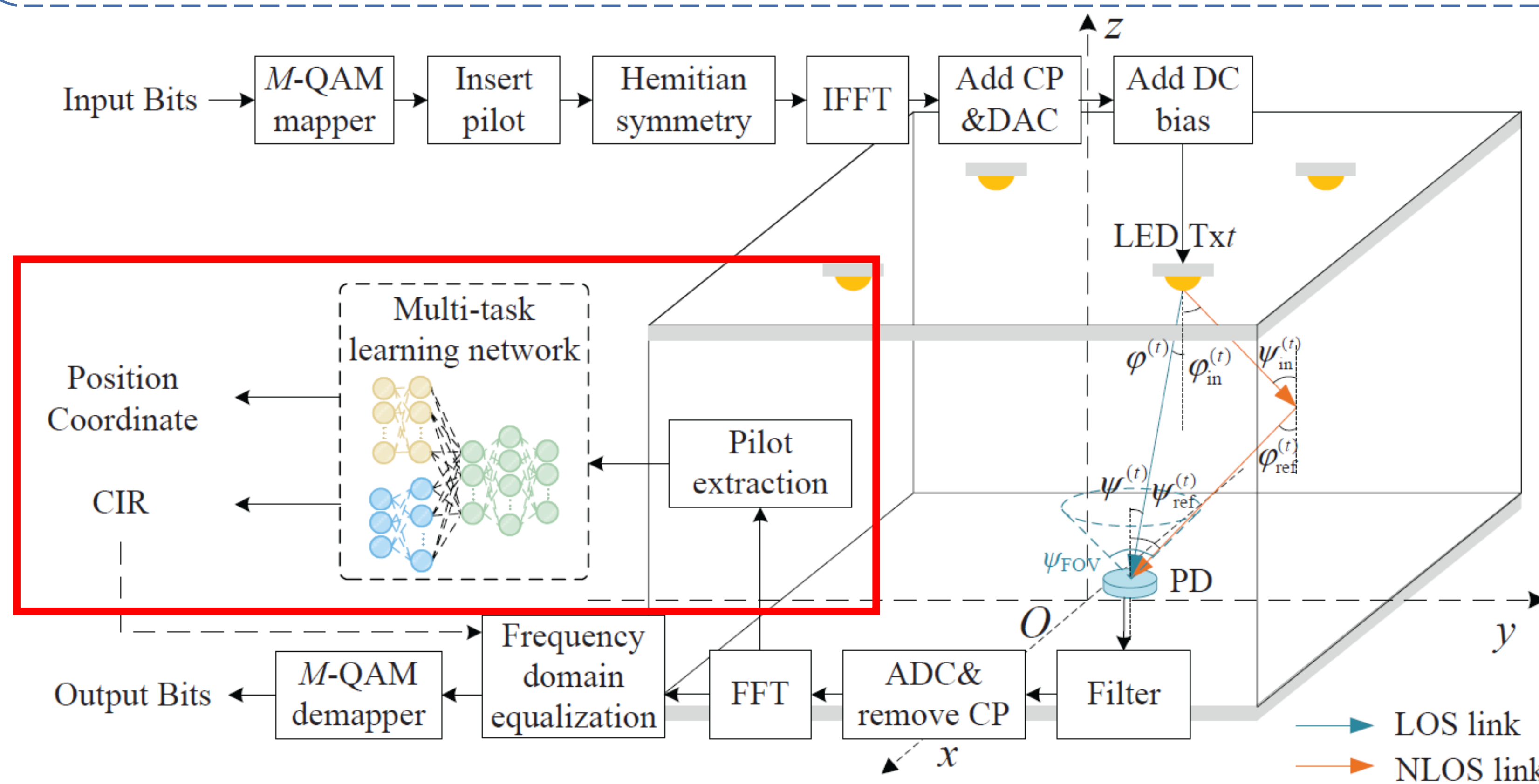
可见光通信定位融合架构 Visible Light Integrated Positioning and Communication (VIPAC)

- A typical multi-LED OFDM-based VLC system using intensity modulation/direct detection (IM/DD)
- The position coordinates and the CIR can be simultaneously obtained from the received pilot signal using the proposed MTL network



可见光通信定位融合 (VIPAC) 架构 —— 信道模型

- 信道CIR的直射line-of-sight (LOS)径分量

$$[\mathbf{h}_{\mathrm{LOS}}^{(t)}]_n = \frac{(m+1)A_{\mathrm{PD}}\cos^m(\varphi^{(t)})\cos(\psi^{(t)})gT_{\mathrm{s}}}{2\pi {d^{(t)}}^2} \mathrm{rect}(\frac{\psi^{(t)}}{\psi_{\mathrm{FOV}}})\delta(n\tau_{\mathrm{s}} - \frac{d^{(t)}}{\mathrm{c}}),$$

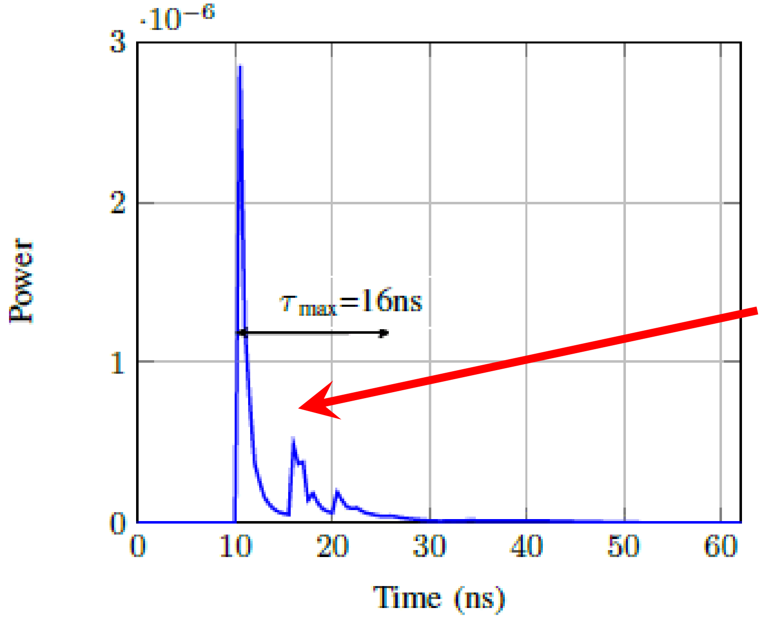
- 信道CIR的非直射non-line-of-sight (NLOS)径分量

$$[\mathbf{h}_{\mathrm{NLOS}}^{(t)}]_n = \int_{\mathrm{walls}} \frac{(m+1)A_{\mathrm{PD}}gT_{\mathrm{s}}\bar{\rho}}{4\pi^2 {d_{\mathrm{in}}^{(t)}}^2 {d_{\mathrm{ref}}^{(t)}}^2}\cos^m(\varphi_{\mathrm{in}}^{(t)})\cos(\psi_{\mathrm{in}}^{(t)}) \cos(\varphi_{\mathrm{ref}}^{(t)})\cos(\psi_{\mathrm{ref}}^{(t)})\mathrm{rect}(\frac{\psi_{\mathrm{ref}}^{(t)}}{\psi_{\mathrm{FOV}}})\delta(n\tau_{\mathrm{s}} - \frac{d_{\mathrm{in}}^{(t)} + d_{\mathrm{ref}}^{(t)}}{\mathrm{c}})dA_{\mathrm{walls}},$$

The CIR is dependent on lots of position-related parameters.

可见光通信定位融合 (VIPAC) 架构 —— 信道模型

可见光信道的稀疏特性 (Sparse nature)

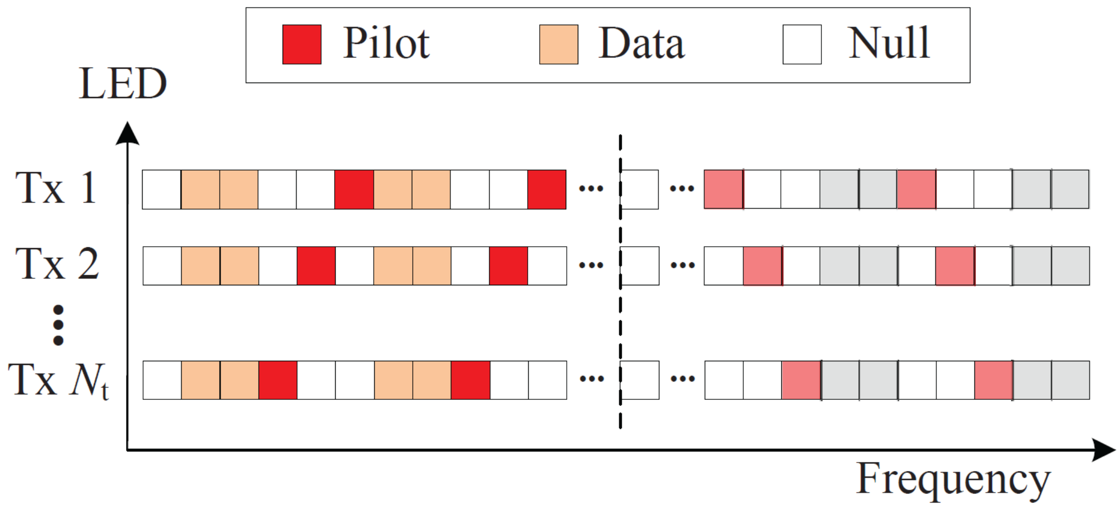


Channel impulse response (CIR) of visible light channel

- Energy is concentrated on only a few dominant taps [10, 11]

[10] J. C. Estrada-Jiménez, B. G. Guzmán, M. J. Fernández-Getino García and V. P. G. Jiménez, "Superimposed Training-Based Channel Estimation for MISO Optical-OFDM VLC," in IEEE Trans. Veh. Technol., vol. 68, no. 6, pp. 6161-6166, June 2019.
[11] Xiaolin Shi, Shu-Hung Leung, Jie Min, "Adaptive least squares channel estimation for visible light communications based on tap detection", Opt. Commun., vol. 467, pp.125712, 2020.

可见光通信定位融合 (VIPAC) 架构 ——信号模型



导频图样

- The received frequency-domain OFDM data block

$$\tilde{\mathbf{y}} = \alpha R_{\mathrm{p}} \sum_{t=1}^{N_{\mathrm{t}}} \mathrm{diag}(\tilde{\mathbf{x}}^{(t)}) \mathbf{F}_L \mathbf{h}^{(t)} + \tilde{\mathbf{w}}$$

- The received pilot subcarriers from the t-th LED

$$\mathbf{u}^{(t)} = \mathbf{F}_{\mathrm{p}}^{(t)} \mathbf{h}^{(t)} + \tilde{\mathbf{w}}^{(t)}$$

- The stacked channel measurement vector

$$\mathbf{u} = \mathbf{F}_{\Lambda} \mathbf{h} + \tilde{\mathbf{w}}_{\Lambda}$$

可见光通信定位融合 (VIPAC) 架构 ——信道估计

传统信道估计方法

- 经典信号处理算法
  - Least squares (LS) [12]
- 基于压缩感知(compressed sensing)的算法
  - Orthogonal Matching Pursuit (OMP) [13]
  - Subspace Pursuit (SP) [14]

Sparse-learning-based framework (稀疏学习) can improve the estimation accuracy.

[12] X. Shi, S.-H. Leung, and J. Min, "Adaptive least squares channel estimation for visible light communications based on tap detection," Opt. Commun., vol. 467, p. 125712, Jul. 2020.
[13] J. Wen, Z. Zhou, J. Wang, X. Tang, and Q. Mo, "A sharp condition for exact support recovery with orthogonal matching pursuit," IEEE Trans. Signal Process., vol. 65, no. 6, pp. 1370–1382, Mar. 2017.
[14] D. Park, "Improved sufficient condition for performance guarantee in generalized orthogonal matching pursuit," IEEE Signal Process. Lett., vol. 24, no. 9, pp. 1308–1312, Sep. 2017.

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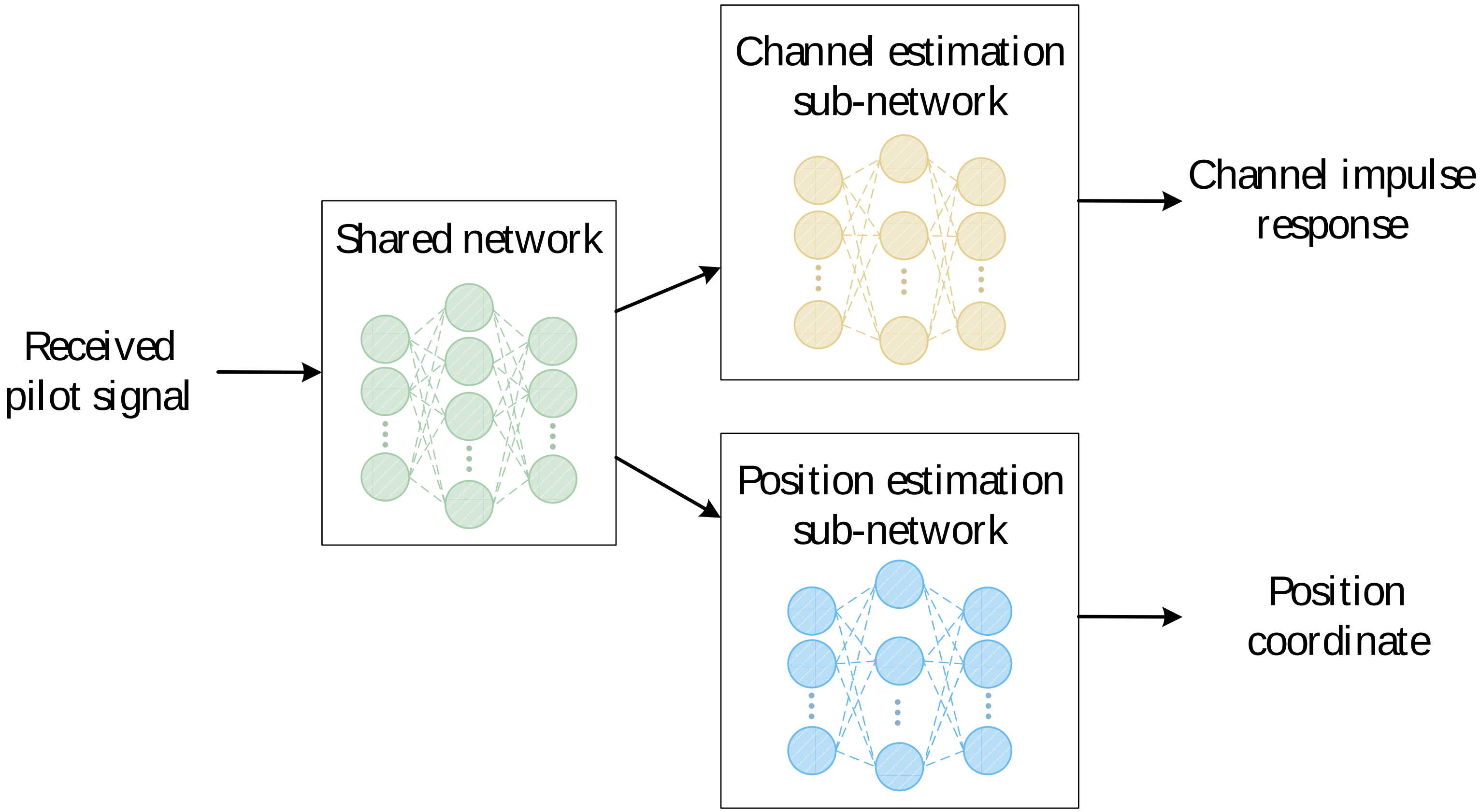
基于多任务学习的神经网络架构

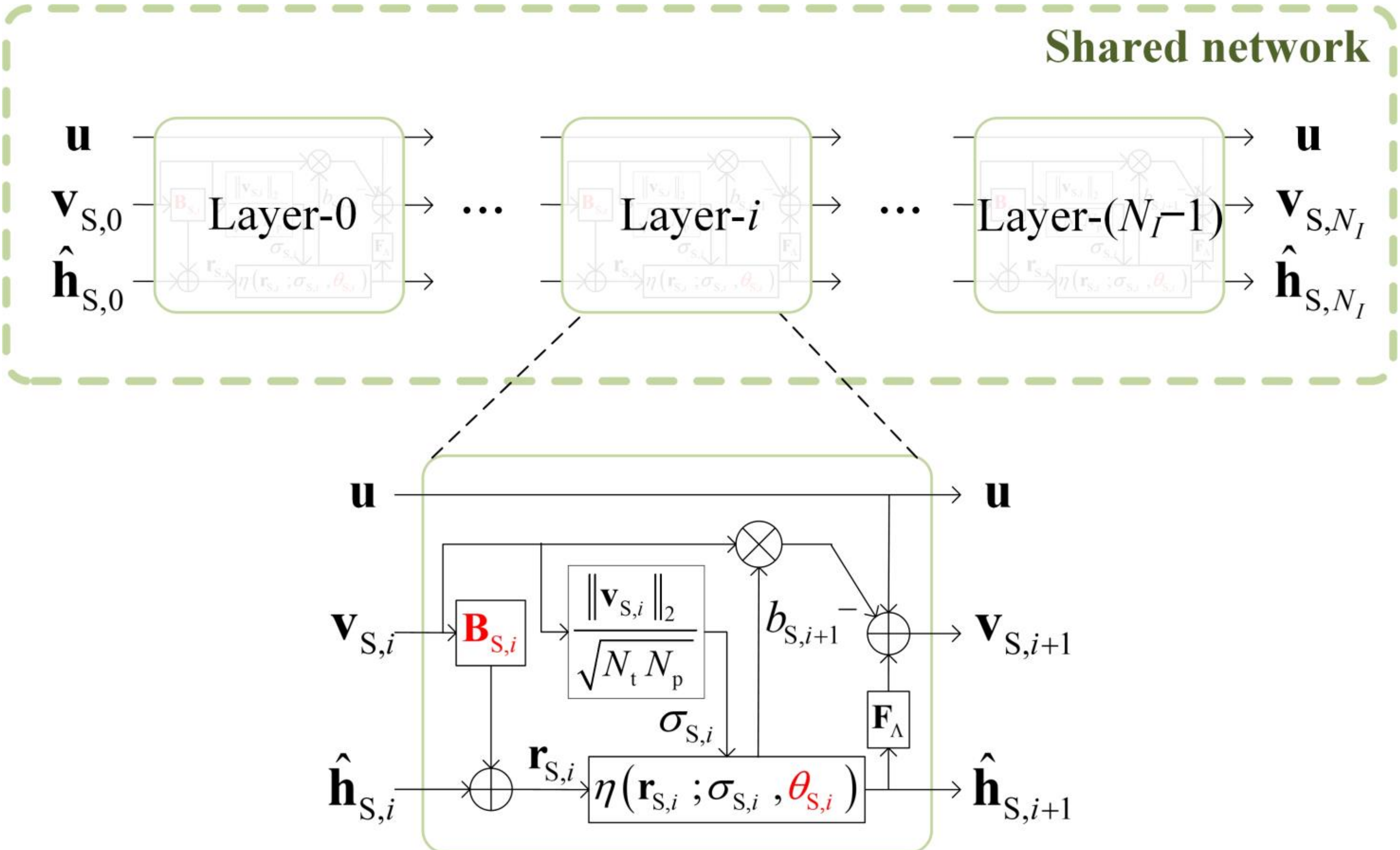


Shared network → Extract shared sparse features

Domain-specific knowledge

Channel estimation sub-network ↔ Position estimation sub-network

共享网络 (Shared Network)：稀疏感知、深度自适应

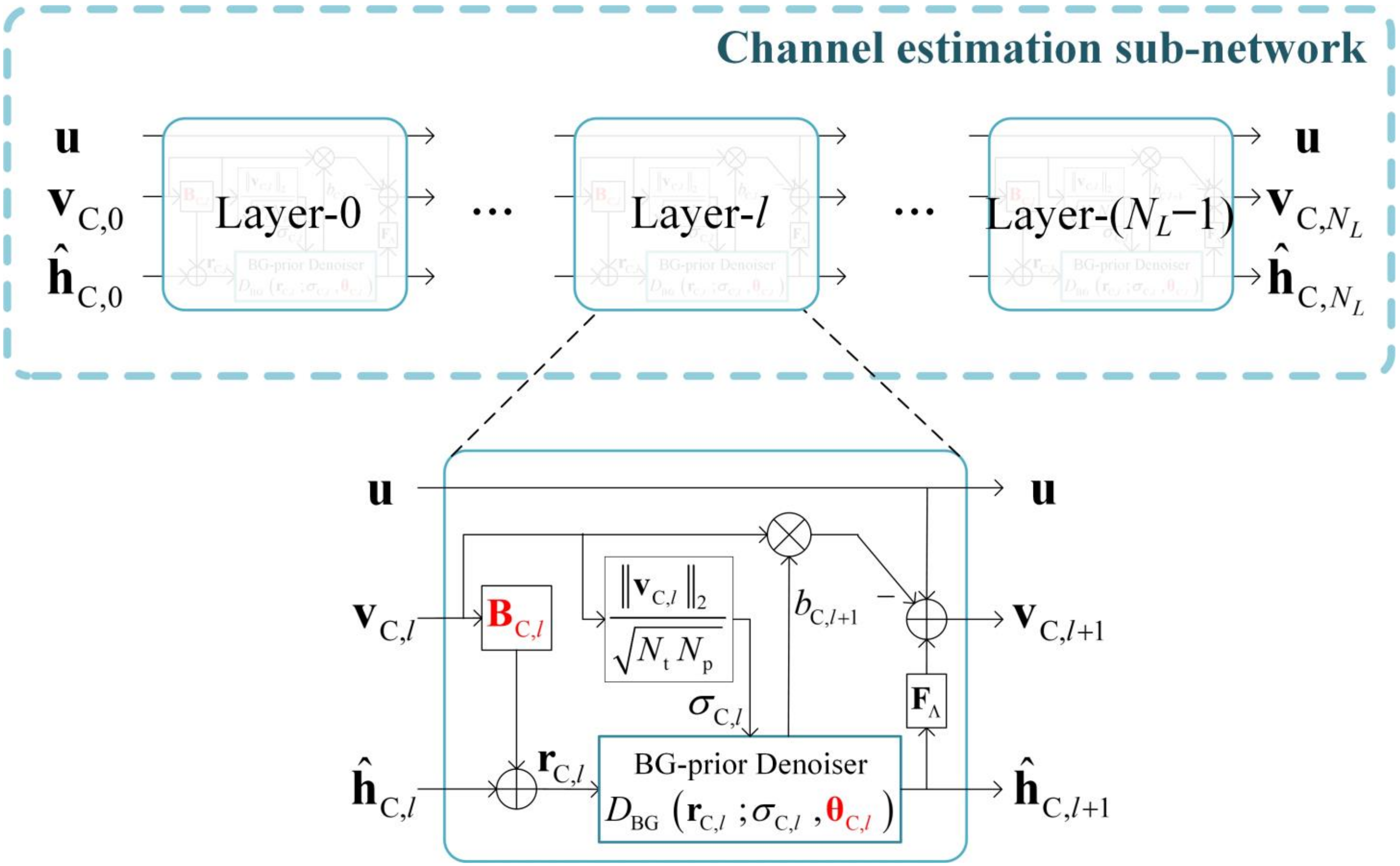


Unfolded by the traditional approximate message passing (AMP) algorithm

Each iteration → Each layer

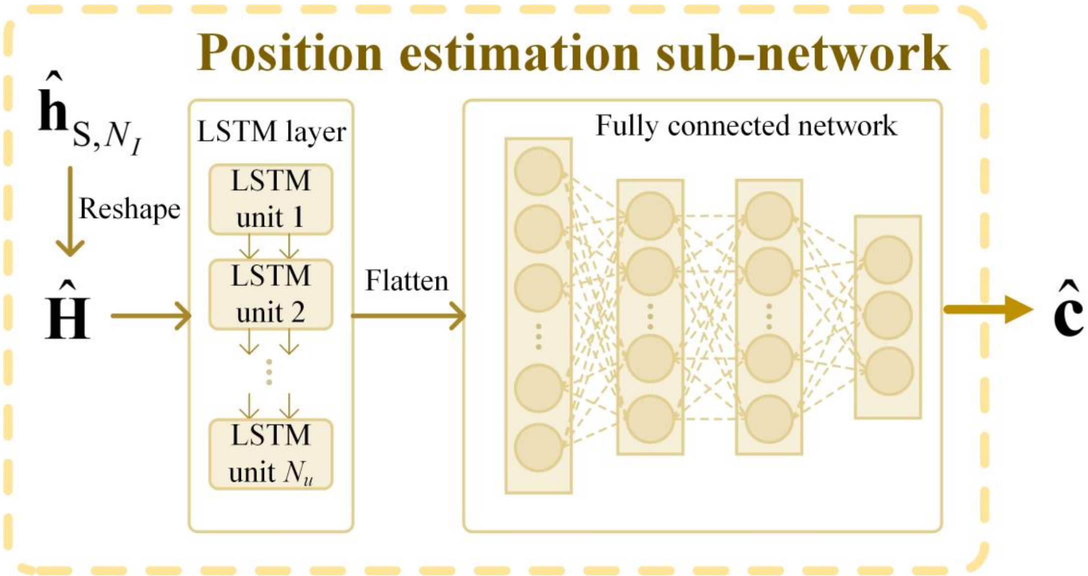
Adaptive network depth (optimized in training process)

信道估计子网络



Soft threshold shrinkage function → Replaced → MSE-optimal denoiser with Bernoulli-Gaussian prior

定位子网络



Long short-term memory (LSTM) → Extract the position-related features

Fully connected network → Generate the estimated position coordinate

深度自适应的多任务学习网络：联合训练

损失函数

The normalized mean squared error (NMSE) of both the position coordinate estimate and the CIR estimate

Tradeoff factor

$$\mathcal{L}(\boldsymbol{\Theta},\boldsymbol{\Omega}) = \boxed{\lambda}\mathcal{L}_{\mathrm{CE}}(\boldsymbol{\Theta},\boldsymbol{\Omega}) + (1-\lambda)\mathcal{L}_{\mathrm{PE}}(\boldsymbol{\Theta},\boldsymbol{\Omega})$$
$$= \frac{\lambda}{D}\sum_{d=1}^{D}\frac{\left\|\hat{\mathbf{h}}^d(\mathbf{u}^d;\boldsymbol{\Theta})-\mathbf{h}^d\right\|_2^2}{\|\mathbf{h}^d\|_2^2} + \frac{1-\lambda}{D}\sum_{d=1}^{D}\frac{\left\|\hat{\mathbf{c}}^d(\mathbf{u}^d;\boldsymbol{\Theta})-\mathbf{c}^d\right\|_2^2}{\|\mathbf{c}^d\|_2^2}$$

逐层训练

Update the parameters $\{\mathbf{B}_{\mathrm{S},i},\theta_{\mathrm{S},i}\}$, $\{\mathbf{B}_{\mathrm{C},l},\theta_{\mathrm{C},l}\}$ and $\boldsymbol{\Theta}_{\mathrm{P}}$ by minimizing $\mathcal{L}(\boldsymbol{\Theta}_{[i,l]},\boldsymbol{\Omega}) = \mathcal{L}\left(\left\{\{\mathbf{B}_{\mathrm{S},k},\theta_{\mathrm{S},k}\}_{k=1}^{i},\{\mathbf{B}_{\mathrm{C},n},\theta_{\mathrm{C},n}\}_{n=1}^{l},\boldsymbol{\Theta}_{\mathrm{P}}\right\},\boldsymbol{\Omega}\right)$

until the loss function does NOT decrease with the increase of the network depths; $\boldsymbol{\Omega}$ represents training dataset.

Optimal total layer numbers are set as N_I and N_L, respectively

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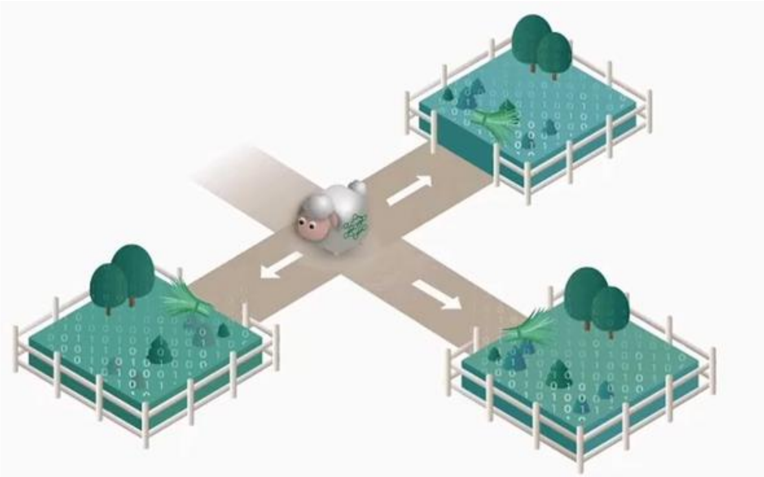
基于联邦多任务学习的多用户协作可见光定位通信融合

- Spatiotemporal nonstationary property of the visible light channel

cause →

- Performance degradation of positioning and channel estimation

联邦学习 (Federated Learning, FL) framework can be considered [15].

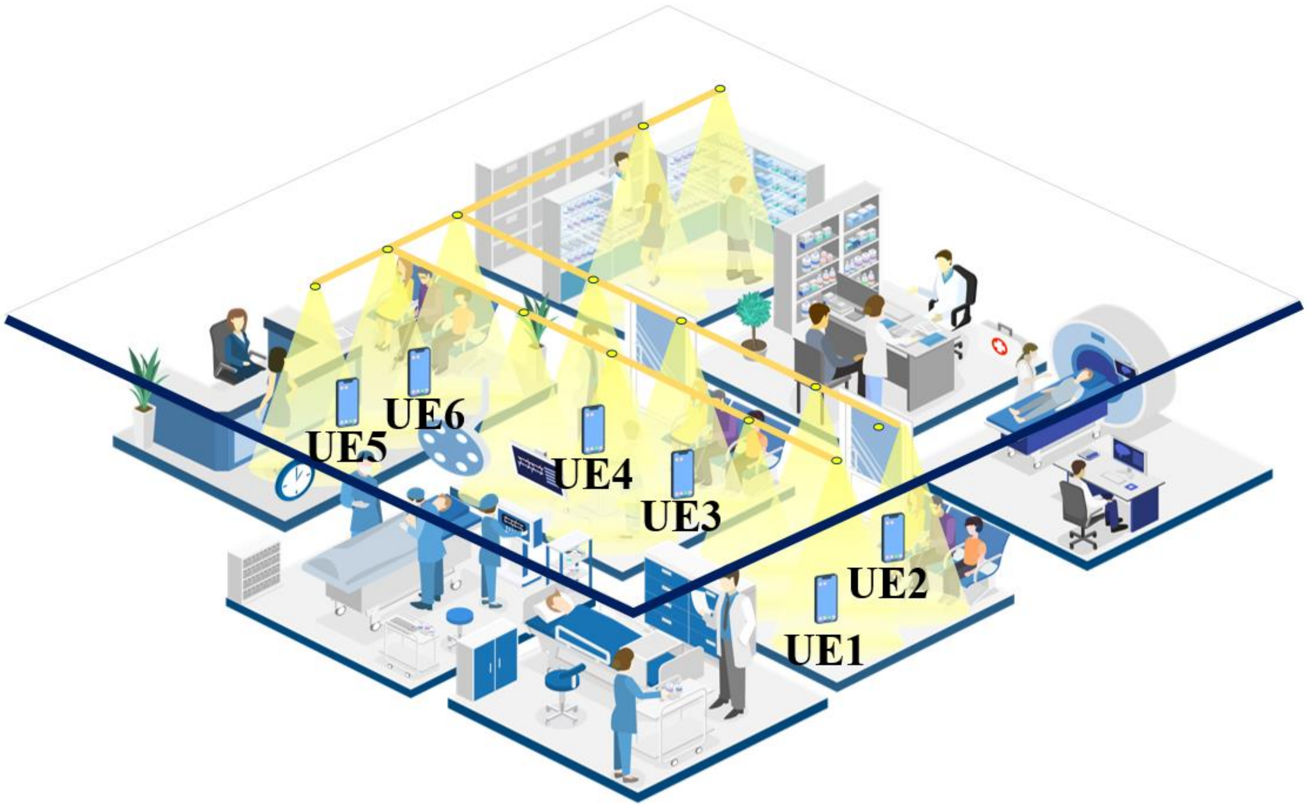


Federated Learning

- Train a global network model without transmitting training data

[15] Q. Yang, Y. Liu, T. Chen, and Y. Tong, "Federated machine learning: Concept and applications," ACM Trans. Intell. Syst. Technol., vol. 10, no. 2, pp. 1–19, Mar. 2019.

多用户协作可见光定位通信融合



协作数据收集

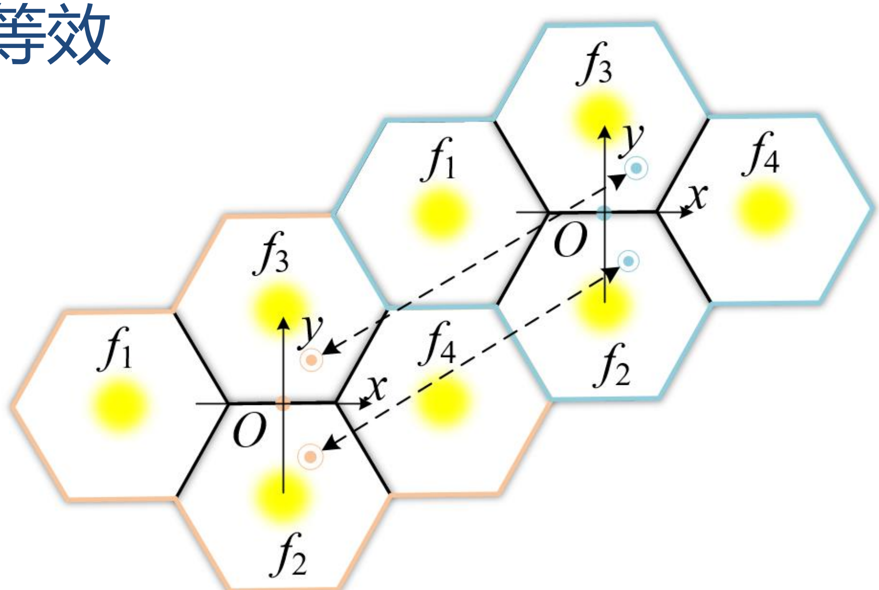
UE agents update the training samples over time

协作模型训练

UE agents participate in network training (federated learning)

多灯蜂窝簇(cellular cluster)结构设计

近似空间等效



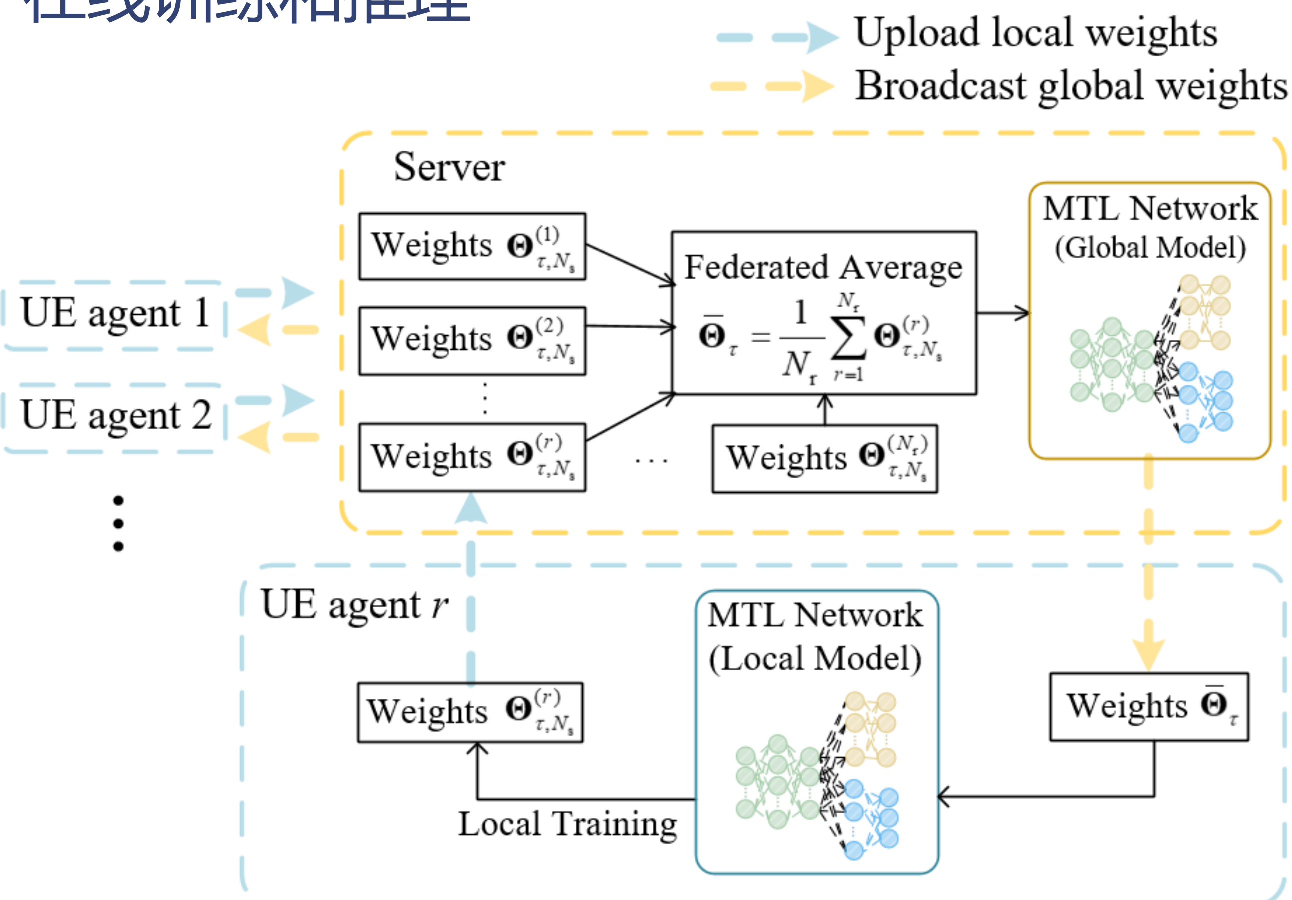
位置坐标标准化
(Standardization)

Absolute coordinates → Relative coordinate

$$\mathbf{c}^d = \left(\mathbf{c}^d_{\text{abs}} - \mathbf{c}^d_{\text{ref}}\right) \mathbf{\Phi}$$

基于联邦多任务学习的多用户协作可见光定位通信融合

在线训练和推理



1. Local Training
2. Upload local weights
3. Global Model aggregation
4. Broadcast global weights

- Spatiotemporally generalization performance
- Privacy preservation

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性能评估与理论分析

定位精度、信道估计精度的性能界

Cramér-Rao lower bound (CRLB), a widely adopted theoretical lower bound for an unbiased estimator

The asymptotical CRLB of the CIR vector for channel estimation

$$\mathbb{E}\left[\left\|\hat{\mathbf{h}}^{(t)}-\mathbf{h}^{(t)}\right\|_2^2\right]\geq\frac{L}{N_{\mathrm{p}}}\sigma_{\mathrm{w}}^2$$

The CRLB of the estimated distance in the positioning sub-task

$$\mathbb{E}\left[\|\hat{\mathbf{d}}-\mathbf{d}\|_2^2\right]\geq\frac{1}{N_{\mathrm{p}}}\left(\frac{2\pi\sigma_{\mathrm{w}}}{(m+1)(m+3)A_{\mathrm{PD}}gT_{\mathrm{s}}z^{m+1}}\right)^2\sum_{t=1}^{N_{\mathrm{t}}}\left(d^{(t)}\right)^{2m+8}$$

性能评估与理论分析

联邦多任务学习算法的收敛性分析

The average of the expected squared gradient norm of the loss function is widely adopted to characterize the convergence rate.

If the learning rate is $\zeta = \sqrt{\frac{N_{\mathrm{r}}}{N_{\mathrm{s}} T}} \leq \frac{1}{C}$, the average of the expected squared gradient norm is bounded by

$$\frac{1}{T N_{\mathrm{s}}} \sum_{\tau=1}^{T} \sum_{s=1}^{N_{\mathrm{s}}} \mathbb{E}\left[\left\|\nabla \mathcal{L}\left(\bar{\mathbf{\Theta}}_{\tau, s-1}\right)\right\|_2^2\right]$$

$$\leq \mathcal{O}\left(\frac{2}{\sqrt{N_{\mathrm{r}} N_{\mathrm{s}} T}}\right)+\mathcal{O}\left(\frac{4 G^2 C^2 N_{\mathrm{r}} N_{\mathrm{s}}}{T}\right)+\mathcal{O}\left(\frac{C \sigma_{\mathrm{g}}^2}{\sqrt{N_{\mathrm{r}} N_{\mathrm{s}} T}}\right)$$

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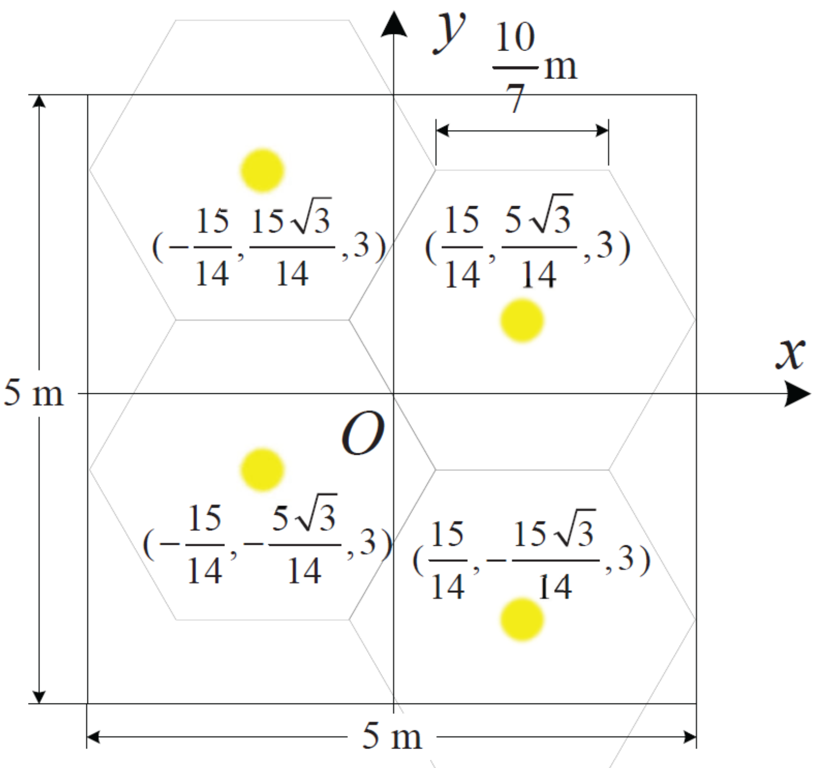
仿真环境与参数设置

A room with size of $L \times W \times H = 5 \times 5 \times 3\text{m}^3$ is considered. The simulation parameters of the VIPAC system are listed as follows.

Parameter	Symbol	Value
Half-power angle of LEDs	$\varphi_{1/2}$	60°
Electro-optical conversion efficiency	α	1 W/A
Average reflectance of walls	$\bar{\rho}$	0.7
FOV angle of PDs	ψ_{FOV}	90°
PD effective area	A_{PD}	1 cm^2
Optical filter gain	T_{s}	1
Optical concentrator gain	g	1
PD responsivity	R_{p}	0.6 A/W

Parameter	Symbol	Value
Number of LEDs	N_{t}	4
Length of the OFDM data block	N	1024
Length of the cyclic prefix	N_{CP}	64
Number of pilot subcarriers	N_{p}	16
OFDM bandwidth		20 MHz
Maximum channel length	L	64

(1) 考察基于**多任务学习**的VIPAC:仿真设置



室内环境中的LED灯部署方式

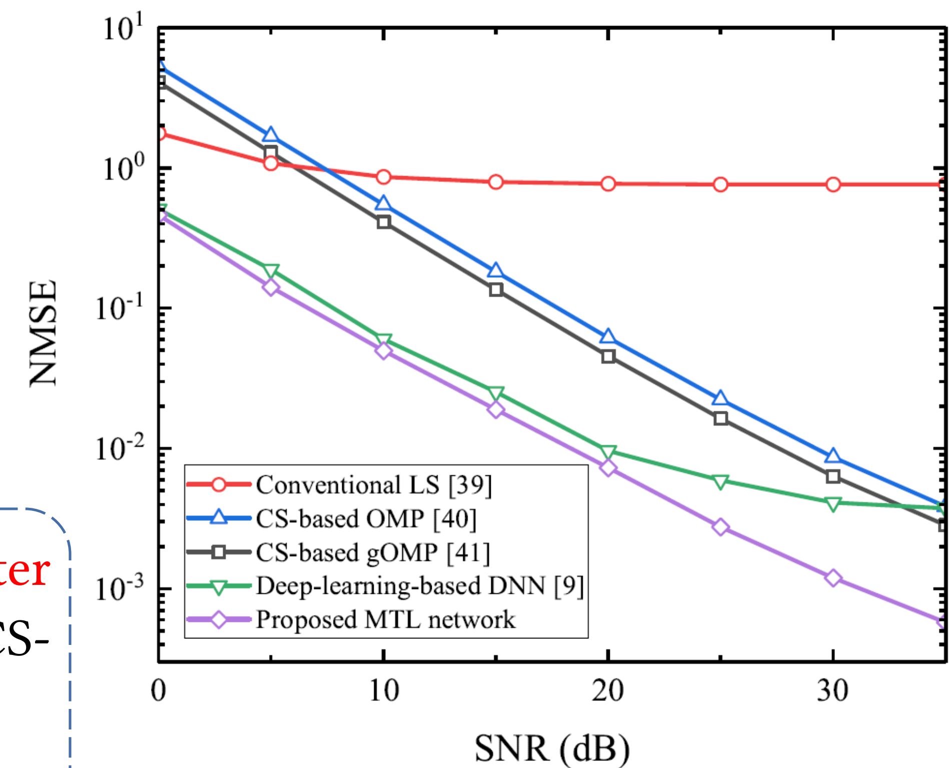
Tradeoff factor between two sub-tasks $\lambda = 0.9$

Size of training set $D = 9000$

Adam optimizer with the learning rate 10^{-3}

(1) 仿真结果：基于多任务学习的VIPAC

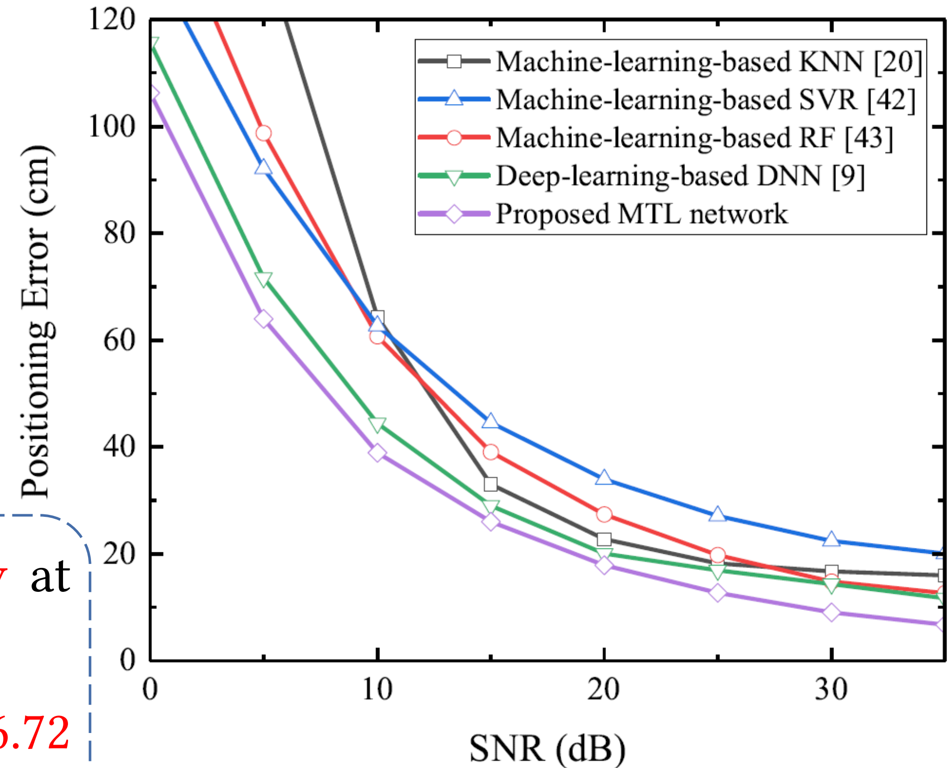
信道估计子任务：NMSE性能



- Achieve the SNR gain of greater that 10 dB compared with the CS-based methods (NMSE = 7×10^{-3})
- Achieve higher accuracy than deep-learning-based method using DNN

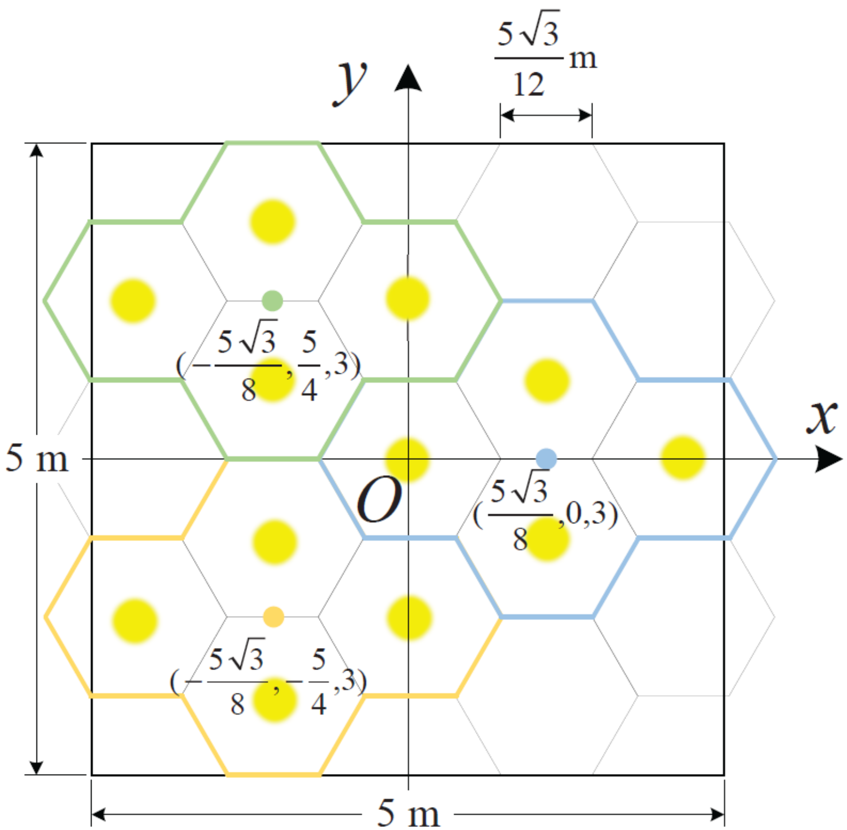
(1)仿真结果：基于多任务学习的VIPAC

定位子任务：定位误差



- Achieve centimeter-level accuracy at an SNR greater than 25 dB
- Reach the positioning error of 6.72 cm at the SNR of 35 dB
- Significantly outperform benchmarks

(2) 考察基于联邦多任务学习的VIPAC:仿真设置



Number of UE agents $N_r = 10$

Size of local datasets $D_r = 900$

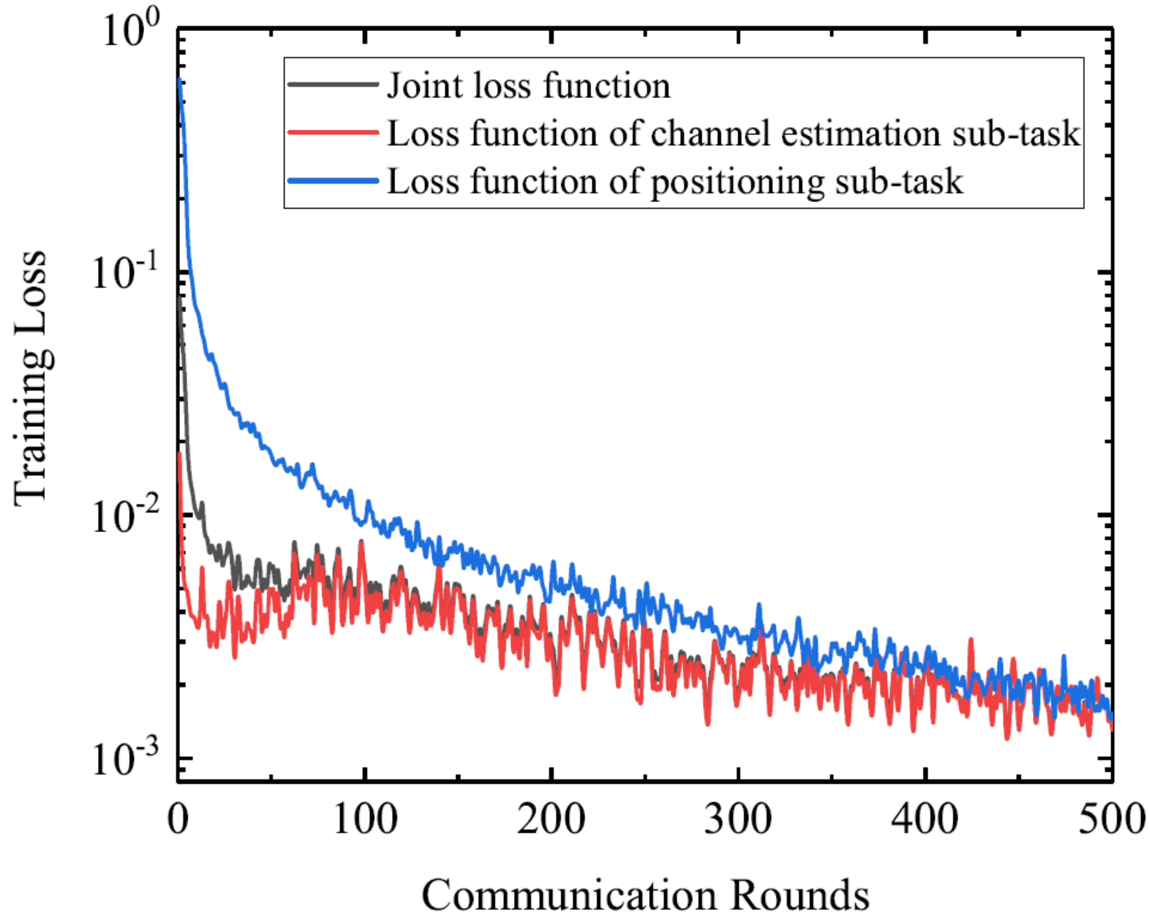
Batch size $B = 128$

Number of local steps $N_s = 5$

LED灯的部署：多灯蜂窝簇结构

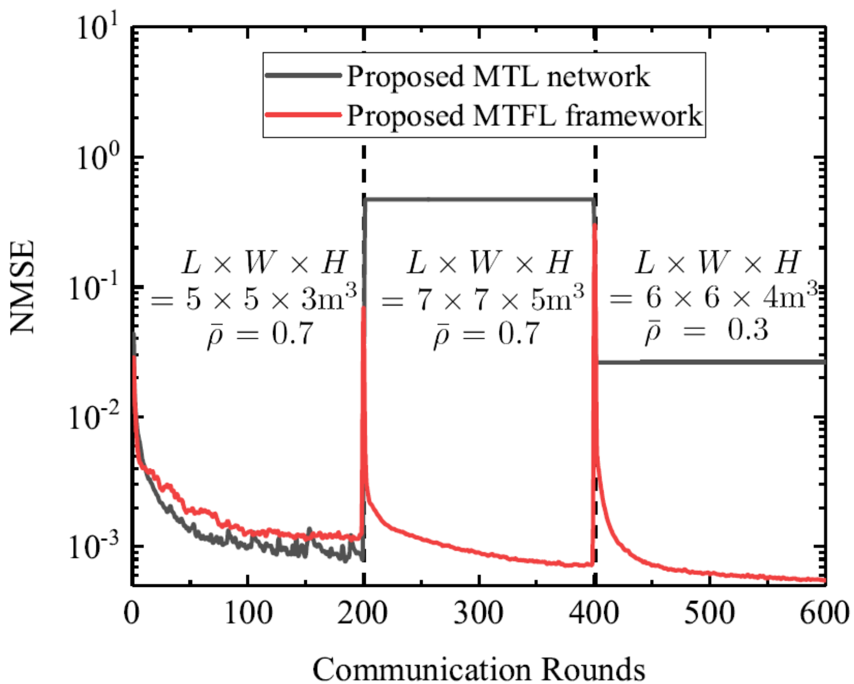
(2) 仿真结果：基于联邦多任务学习的VIPAC

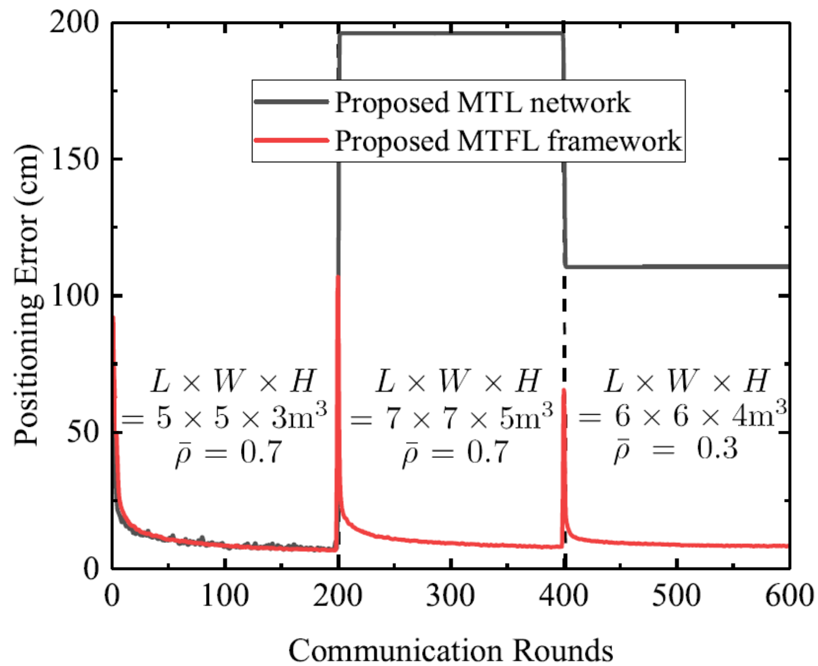
Training loss of the MTFL framework for VIPAC with respect to communication rounds



(2) 仿真结果：基于联邦多任务学习的VIPAC

Performance in spatiotemporally variant environments (the environment changes every 200 communication rounds)





NMSE performance of channel estimation

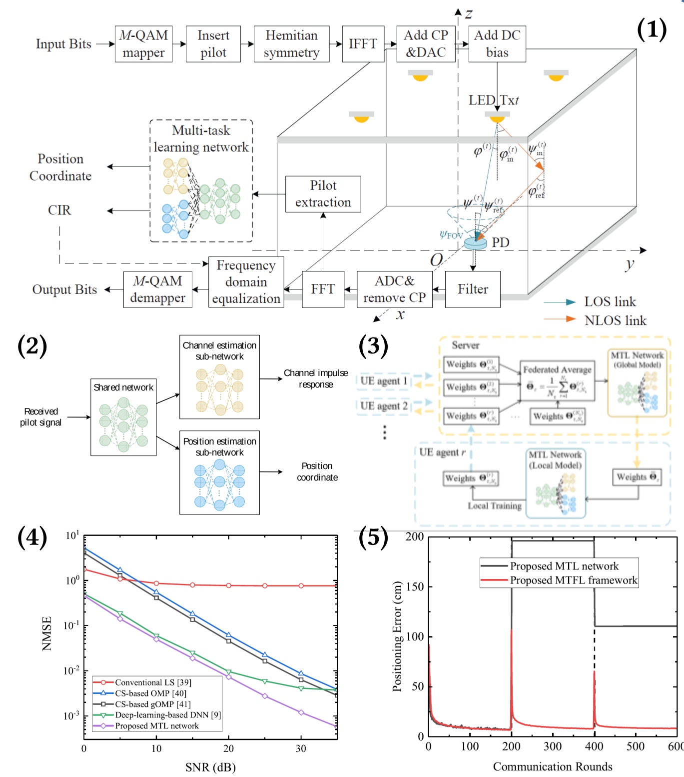
Positioning error

- The estimation error of the proposed MTFL scheme can reduce rapidly again to a satisfactory level

小结

Main work

- 可见光定位通信融合(VIPAC)架构
- 信道估计与定位多任务联合
- 稀疏感知的多任务学习(MTL)网络
- 多个子任务之间互惠(Mutual benefits)
- 联邦多任务学习(MTFL)框架
- 空时非平稳的泛化能力



Future issues

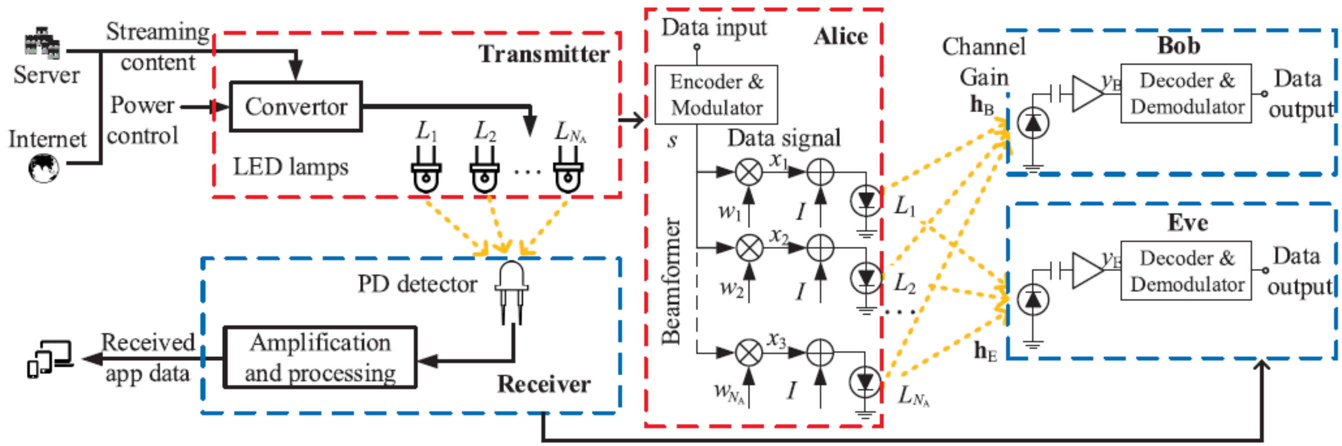
- 在下一代移动通信与无线通信的应用
- 估计精度性能与泛化适应能力的提升

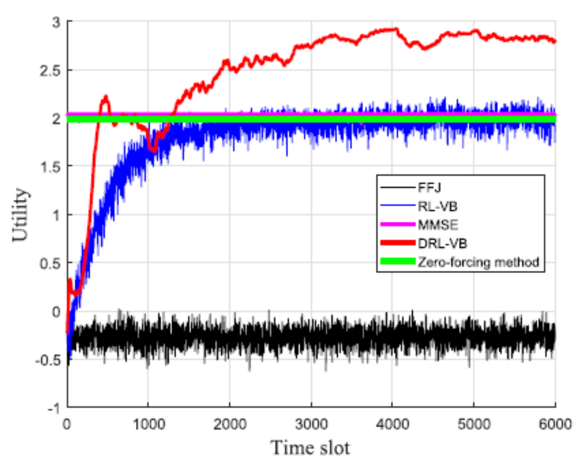
汇报提纲

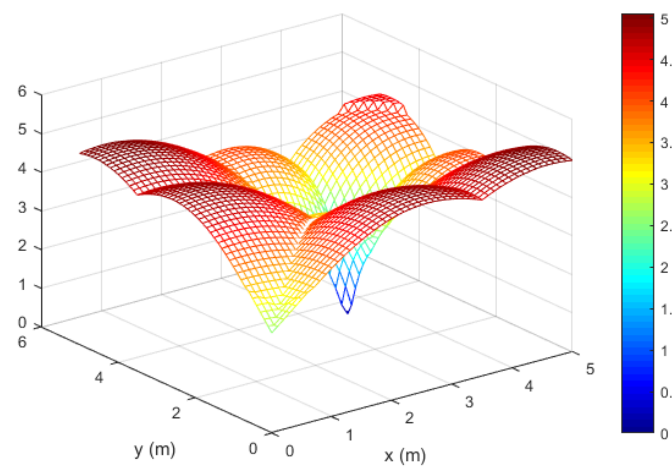
- 研究背景
- 可见光通信定位融合架构
- 基于稀疏感知多任务学习的可见光通信信道估计与可见光定位
- 面向多用户协作可见光定位通信一体化的联邦多任务学习框架
- 性能评估与理论分析
- 仿真结果与讨论
- 小结
- 关于AI+VLC的一些工作

(1) 基于强化学习的可见光通信反窃听技术

- 采用多灯协作的可见光MISO波束成型实现反窃听
- 基于深度强化学习的波束动态智能控制策略

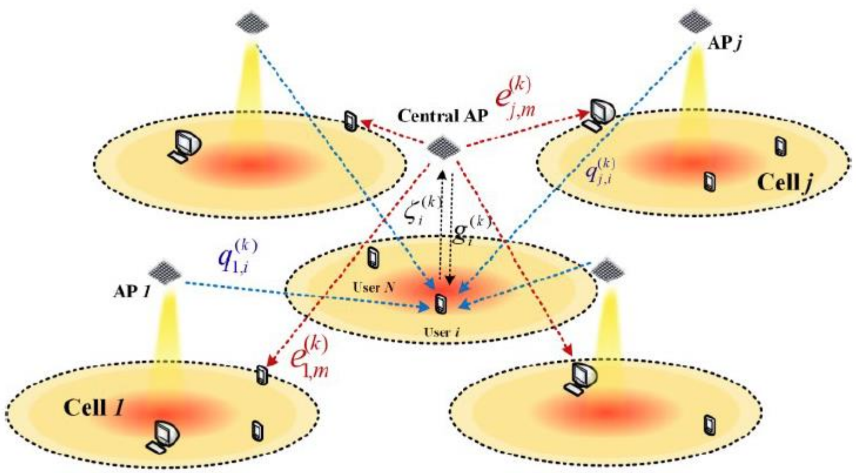


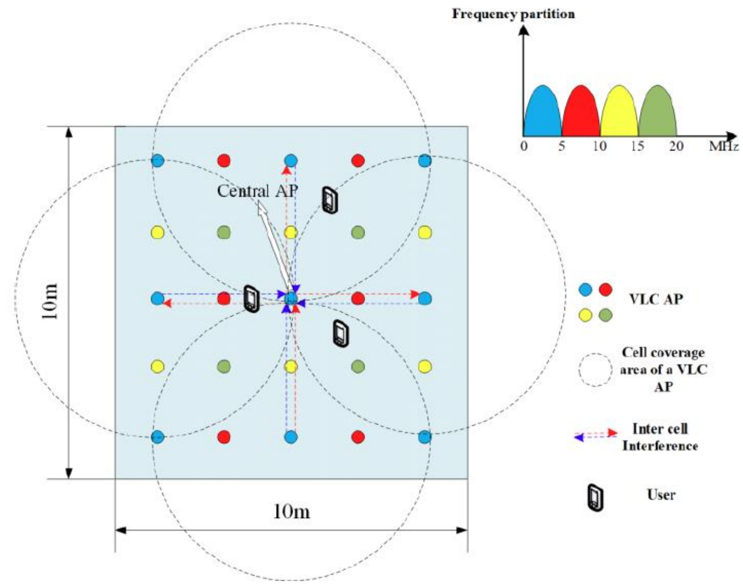


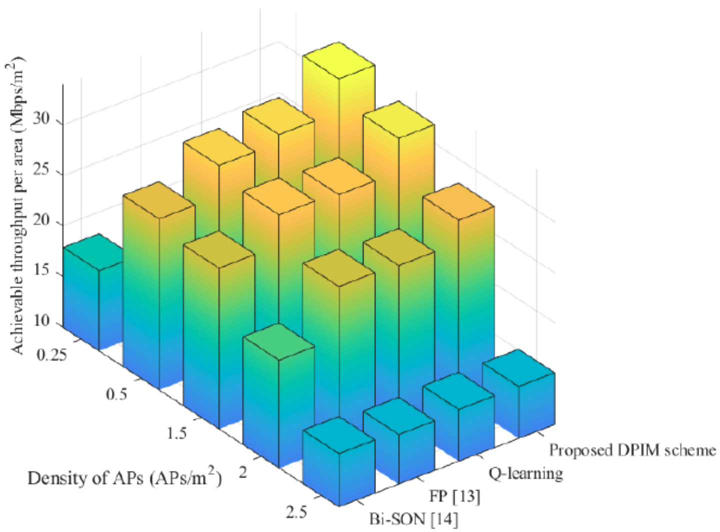


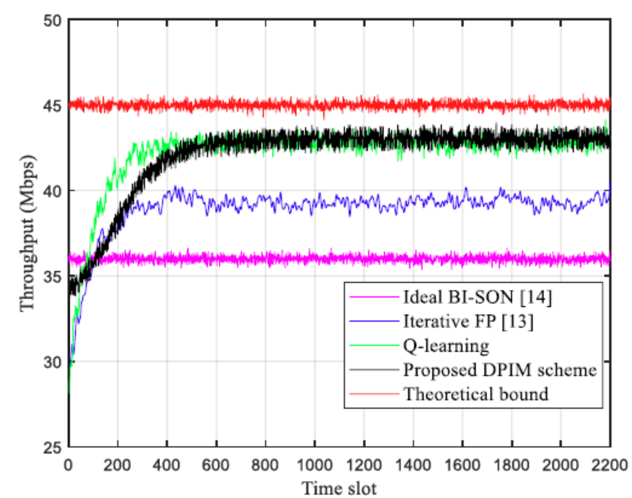
(2) 基于强化学习的可见光超密集组网干扰管理

- 可见光超密集蜂窝网络结构及频率复用设计
- 基于深度强化学习的功率控制和干扰抑制策略









谢谢！

基于多任务联邦学习的可见光通信定位一体化技术

Visible Light Integrated Positioning and Communication Based on Multi-Task Federated Learning

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