Energy-Efficient Beamforming and Time Allocation in Wireless Powered Communication Networks

Miaomiao Fu

College of Information Engineering

University of Shenzhen

fumiaomiaos@163.com

IEEE Vehicle Techology communication

Acknowledgment to co-authors

Professor:

- Chongtao Guo
- Shnegli Zhang
- Gongbin Qian

outline

- Background
- System model
- Optimization algorithm
- Simulation result

Background

Traditional wireless communication powered by

- Batteries :

- Costly, inconvenient
- Inapplicable in some scenarios

  e.g., implanted medical devices,

Background

Traditional wireless communication powered by

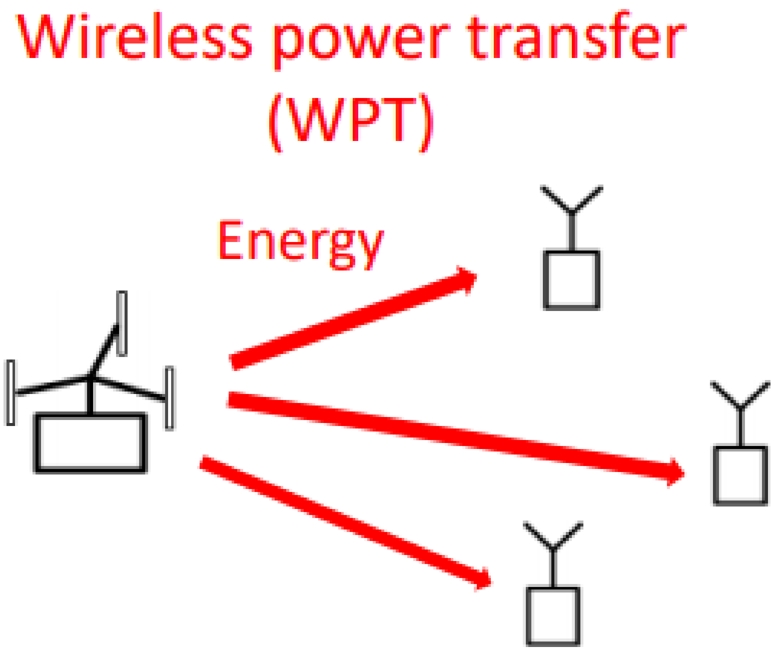
- Energy harvesting

  (from solar, wind, ambient radio power, etc.)

- Costly/Bulky
- Intermittent and uncontrollable
- Highly depend on dynamic natural enviorments

Background

- Wireless power transfer (WPT):



Advantages over traditional energy supply methods:

 Convenient: without the hassle of connecting wires and replacing batteries

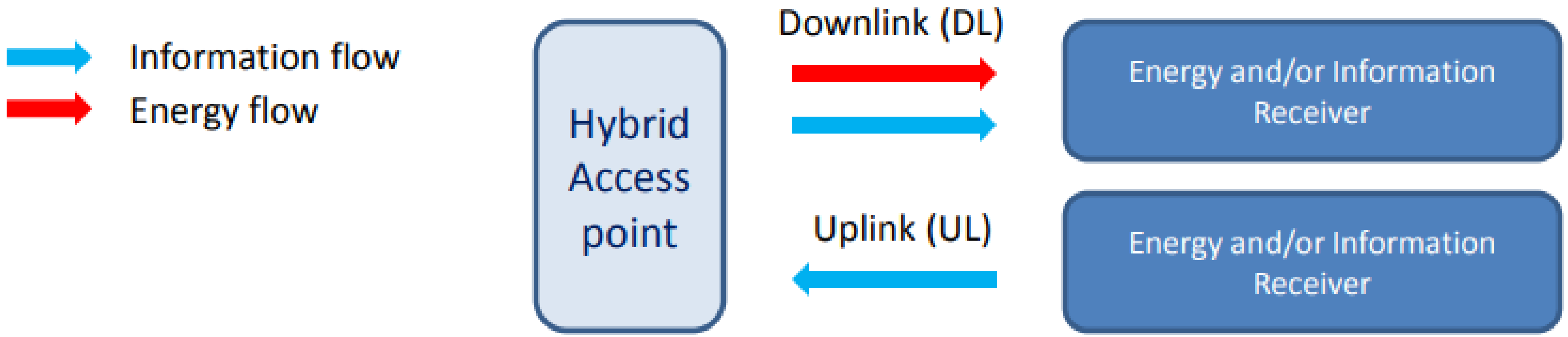
 Cost-effective: on-demand power

supply with uninterrupted operations

 Environmental friendly: avoid battery disposal

Background

- Wireless information and power transfer



- Wireless Powered Communication Network (WPCN): DL WPT and UL wireless information transmission (WIT) .
- Simultaneous wireless information and power transfer (SWIPT): DL WPT and WIT at the same time .

Background

- Main challenges
  - the rising energy costs and the tremendous carbon footprints in information communication .
  - low efficiency of wireless power transfer, wireless information and power transfer joint design .

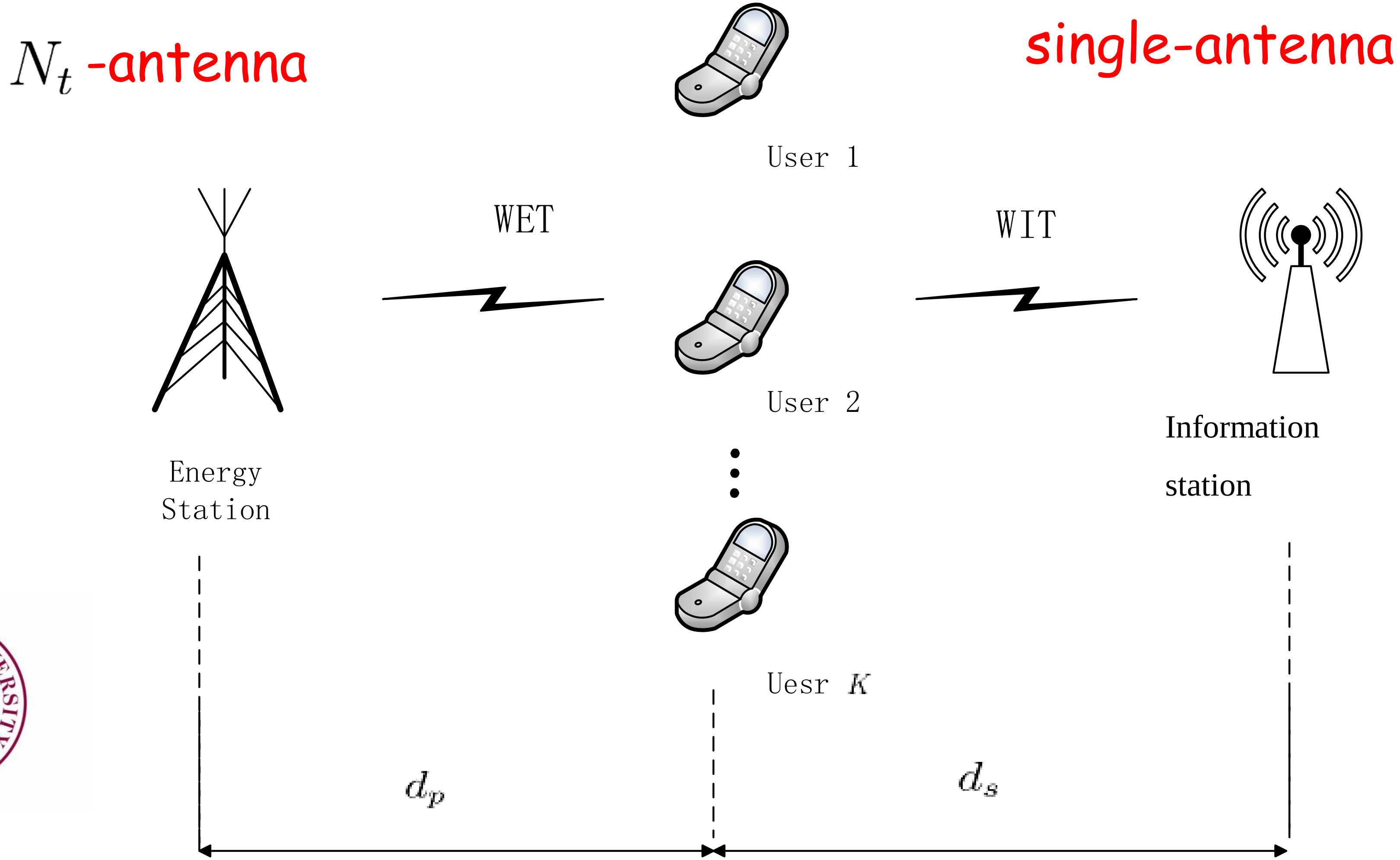
- Our work

– Trade off multi-antenna beamforming and time allocation.

– Maximize the network-side energy efficiency (EE) in a WPCN.

System model

The system operates in the harvest-then-transmit protocol



System model

- One time frame with unit length is divided into two stages is denoted by $\tau_0, \dots \tau_k$

τ_0 : all user harvesting energy

τ_k : user k transfer their information by time division multiple access (TDMA) moudel

- Broadcasting signal from ES is denoted by $\mathbf{x} \in \mathbb{C}^{N_t}$ and $\mathbf{X} = \mathbb{E}\left(\mathbf{x}\mathbf{x}^H\right)$.

System model

- suppose that users do not have initial energy and use up all the harvested energy .

- transmit power P_k can be figured out as :

$$P_k = \frac{E_k}{\tau_k} = \frac{\tau_0 \xi_k \mathbf{h}_k \mathbf{X} \mathbf{h}_k^H}{\tau_k} - a_k \qquad \forall k$$

- The DL and the UL are quasi-static flat-fading channel and power gain is denoted by $\mathbf{h}_k \in \mathbb{C}^{N_t}$ and $g_k \in \mathbb{C}$ respectively.

System model

- The achievable rate of user k :

$$R(\tau, \mathbf{X}) = \sum_{k=1}^{K} \tau_k \log_2 \left(1 + \gamma_k \left(\frac{\tau_0 \mathbf{h}_k \mathbf{X} \mathbf{h}_k^H}{\tau_k} - \frac{a_k}{\xi_k}\right)\right)$$

where $\gamma_k = \frac{\xi_k |g_k|^2}{\Gamma \delta_k^2}$.

- The total energy consumption:

$$E(\tau, \mathbf{X}) = \tau_0 \left(\mathrm{Tr}(\mathbf{X}) + b_0\right)$$

System model

- The system EE is defined as : $\dfrac{\text{sum-throughput}}{\text{total energy consumption}}$
- EE optimization problem can be formulated as :

$$\max_{\tau,\mathbf{X}} \quad \frac{\sum_{k=1}^{K} \tau_k \log_2\left(1+\gamma_k\left(\frac{\tau_0 \mathbf{h}_k \mathbf{X} \mathbf{h}_k^H}{\tau_k} - \frac{a_k}{\xi_k}\right)\right)}{\tau_0\left(\mathrm{Tr}\left(\mathbf{X}\right)+b_0\right)} \tag{1}$$

$$\text{s.t.} \quad \tau_k \geq 0, k=0,\ldots,K, \tag{1a}$$

$$\sum_{k=0}^{K} \tau_k \leq 1, \tag{1b}$$

$$\mathbf{X} \succeq \mathbf{0}, \tag{1c}$$

$$\mathrm{Tr}\left(\mathbf{X}\right) \leq P_{\max}, \tag{1d}$$

$$\tau_0 \mathbf{h}_k^H \mathbf{X} \mathbf{h}_k \geq \tau_k \frac{a_0}{\xi_k}, k=1,\ldots,K, \tag{1e}$$

Optimization algorithm

This problem is a highly non-convex problem

- τ and X are the optimization variables

- fractional form

Optimization algorithm

Non-convex

- the fractional form can be transformed as a function in subtractive form base for the Dinkelbach method

- introduce auxiliary variables V with $V = \tau_0 * X$

Convex

- objective function : perspective functions of the concave function plus the linear function
- inequality constraints : convex.

Optimization algorithm

Accordingly, the optimization problem becomes:

$$
\begin{aligned}
\max_{\tau,\mathbf{V}} \quad & \sum_{k=1}^{K} \tau_k \log_2 \left(1 + \gamma_k \left(\frac{\mathrm{Tr}(\mathbf{h}_k \mathbf{h}_k^H \mathbf{V})}{\tau_k} - \frac{a_k}{\xi_k}\right)\right) && (3)\\
& - e\Big(Tr(\mathbf{V}) + \tau_0 b_0\Big) && (3a)\\
\text{s.t.} \quad & \tau_k \geq 0, k = 0, \ldots, K, && (3b)\\
& \sum_{k=0}^{K} \tau_k \leq 1, && (3c)\\
& \mathbf{V} \succeq \mathbf{0}, && (3b)\\
& \mathrm{Tr}(\mathbf{V}) \leq \tau_0 P_{\max}, && (3d)\\
& \mathrm{Tr}\left(\mathbf{h}_k^H \mathbf{h}_k \mathbf{V}\right) \geq \tau_k \frac{a_0}{\xi_k}, k = 1, \ldots, K, && (3e)
\end{aligned}
$$

Ps: e is a given value

Optimization algorithm

Two iterative algorithm for locating the maximum EE e.

- *Algorithm 1*

– Iterate the initial vaule to converge to the optimal vaule.

- *Algorithm 2*

– shrink a region which contains the maximum EE constantly by solving a convex feasibility problem.

Algorithm 1

- The iterative parameter e^{n+1} is computed by

$$e^{n+1} = \frac{R(\tau^n, \mathbf{X}^n)}{E\left(\tau^n, \mathbf{X}^n\right)}$$

to converge to the optimal vaule.

Optimization algorithm

- *Algorithm 1*

Algorithm 1

Initialization:

Set EE e with a small value.
Set iteration index $n = 0$.
Set tolerance ϵ.

repeat
  Solve the problem in (12) for a given e and obtain the optimal solution $\boldsymbol{\tau}^n, \mathbf{V}^n$.
  if $|F(e^n)| = |R(\boldsymbol{\tau}^n, \mathbf{V}^n) - e^n E_{ps}(\boldsymbol{\tau}^n, \mathbf{V}^n)| > \epsilon$, **then**
    set $e^{n+1} = \frac{R(\boldsymbol{\tau}^n, \mathbf{V}^n)}{E_{ps}(\boldsymbol{\tau}^n, \mathbf{V}^n)}$ and $n = n + 1$.
  end if
until $|F(e^n)| = |R(\boldsymbol{\tau}^n, \mathbf{V}^n) - e^n E_{ps}(\boldsymbol{\tau}^n, \mathbf{V}^n)| \le \epsilon$.

Algorithm 2

- Transformed as a feasibility problem

$$
\begin{aligned}
\text{find} \quad & \tau, \mathbf{V} \\
\text{s.t.} \quad & \sum_{k=1}^{K} \tau_k \log_2 \left(1 + \gamma_k \Big(\frac{\mathrm{Tr}\left(\mathbf{h}_k \mathbf{h}_k^H \mathbf{V}\right)}{\tau_k} - \frac{a_k}{\xi_k}\Big)\right) \\
& \geq e\Big(Tr(\mathbf{V}) + \tau_0 b_0\Big) && (4) \\
& \tau_k \geq 0, k = 0, \ldots, K, && (4a) \\
& \sum_{k=0}^{K} \tau_k \leq 1, && (4b) \\
& \mathbf{V} \succeq \mathbf{0}, && (4c) \\
& \mathrm{Tr}\big(\mathbf{V}\big) \leq \tau_0 P_{\max}, && (4d) \\
& \mathrm{Tr}\big(\mathbf{h}_k^H \mathbf{h}_k \mathbf{V}\big) \geq \tau_k \frac{a_0}{\xi_k}, k = 1, \ldots, K. && (4e)
\end{aligned}
$$

Optimization algorithm

- *Algorithm 2*

Algorithm 2

Initialization:

Set $\eta_{\min} < e^*, \eta_{\max} > e^*$.

Set tolerance ϵ.

1: **repeat**

2: $e = \frac{\eta_{\min}+\eta_{\max}}{2}$.

3: Solve the convex feasibility problem in (14).

4: **if** The problem is feasible, **then**

5: $\eta_{\min} = e$.

6: **else**

7: $\eta_{\max} = e$.

8: **end if**

9: **until** $\eta_{\max} - \eta_{\min} \leq \epsilon$.

Simulation result

$N_t = 4$

$d_s = 5 \quad m$

$K_R = 3$

$\alpha = 2$

$\epsilon = -10^6$

$\delta^2 = -110 \quad dBm$

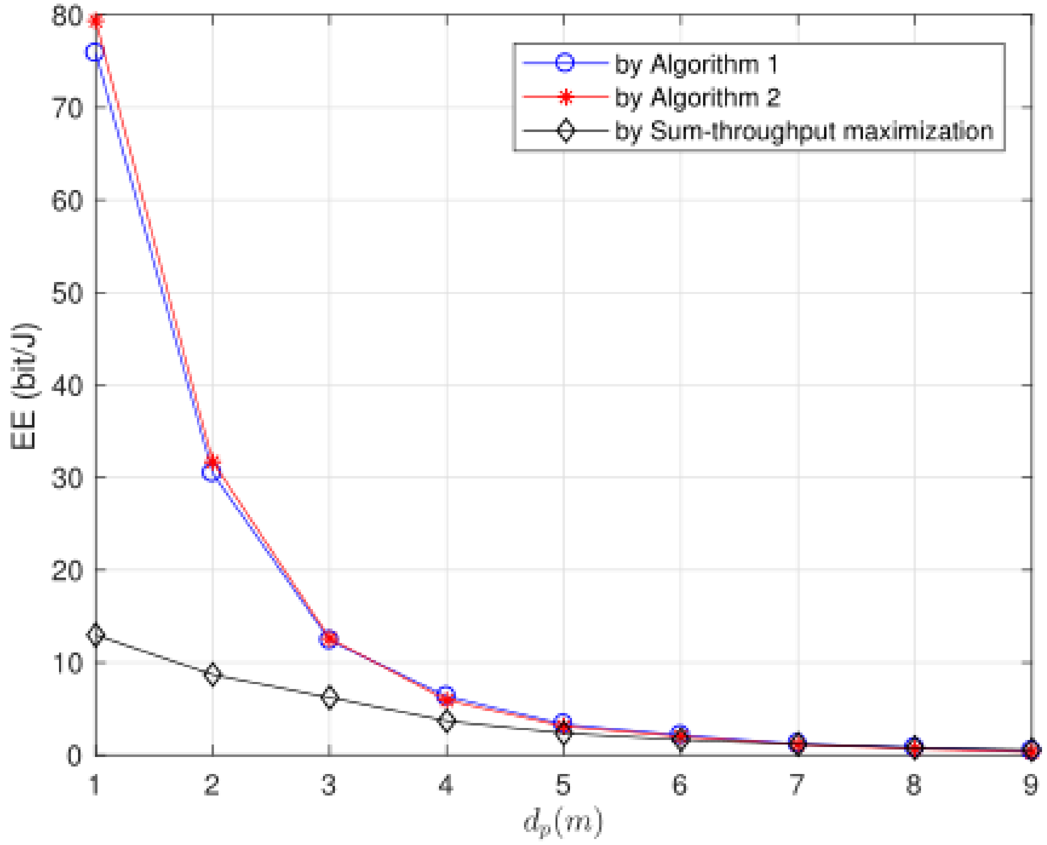


Fig. 2: EE versus the distance d_p in different methods, where the number of user K set as 4.

Simulation result

- Algorithm 1 and 2 in this paper have better performance than the maximization of sum-throughput only in terms of EE value.

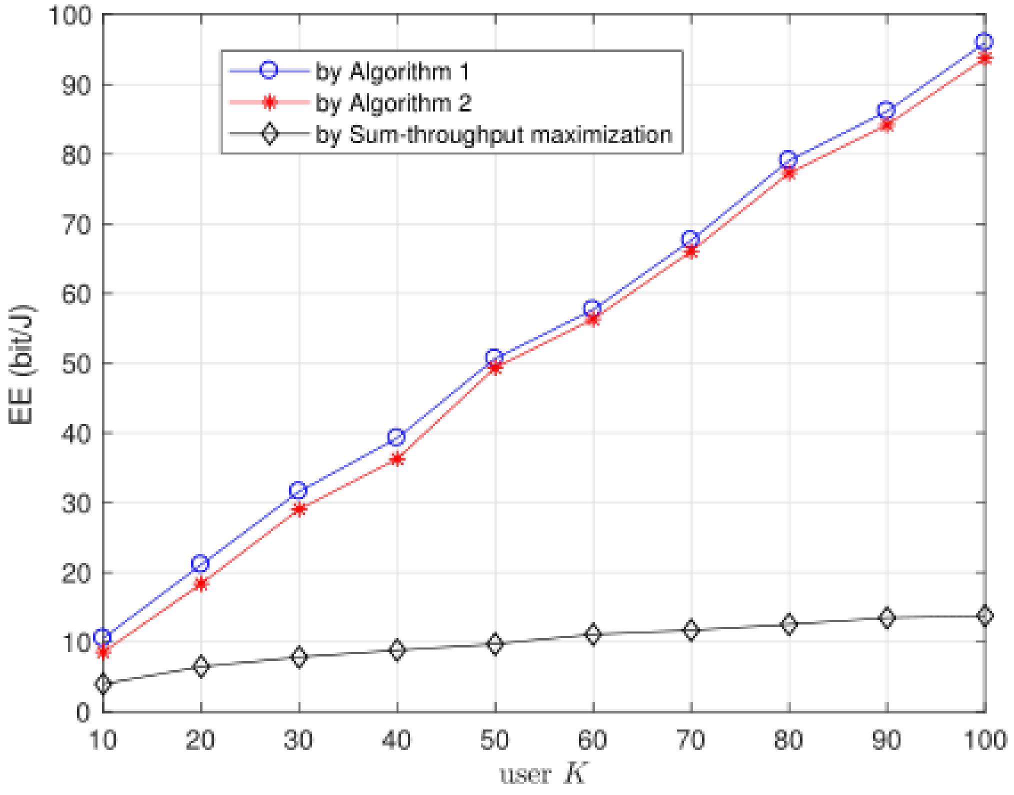


Fig. 3: EE versus the amount of user K in different methods, where the distance d_p set as 5 meters.

Simulation result

- In Algorithm 1, the convergence rate is greatly related to the initialization value
- In Algorithm 2 ,iteration times is fixed at 20 times, due to the length of initial interval and the tolerance fixed

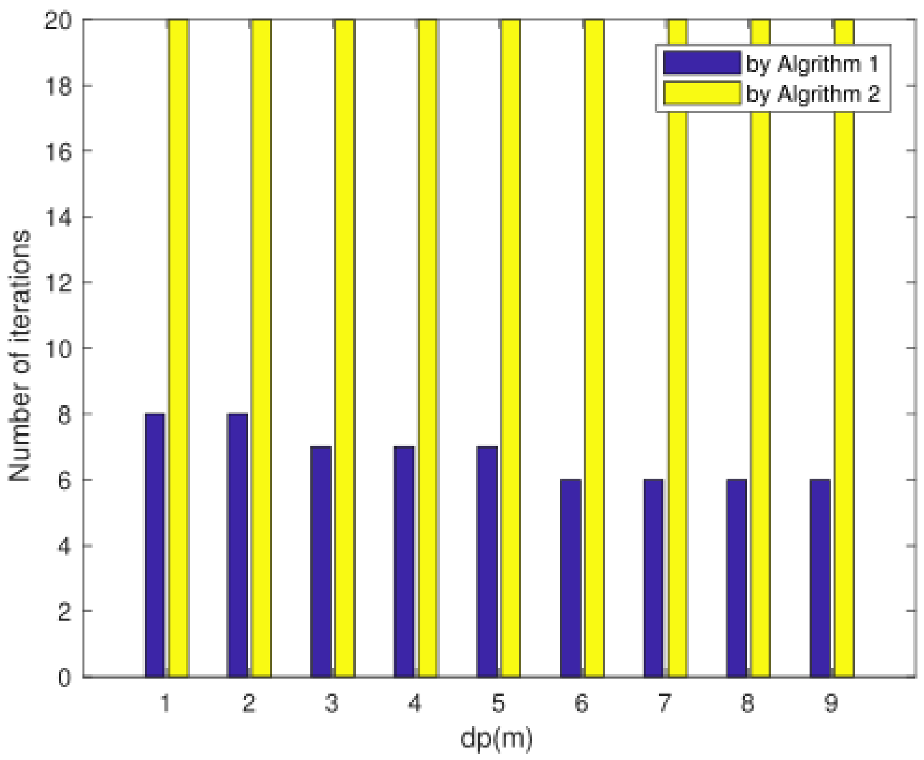


Fig. 4: This figure shows the iteration times of Algorithm 1 and Algorithm 2 versus the distance d_p.

Thank you for listening