Connectivity Maximizing of Network Slicing Enabled Industrial Internet-of-Things

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IoT and IIoT

Internet of Things (IoT)

- **Physical objects** (or groups of such objects), that are embedded with **sensors**, **processing ability**, **software**, and other technologies.
- **Connect and exchange data** with other devices and systems over the Internet or other communications networks[1].

Industrial Internet of Things (IIoT) (Industry 4.0)

- Interconnected **sensors**, **instruments**, and other devices networked together with computers' industrial applications, including **manufacturing** and **energy management**[2].
- Other Characteristics[3]:
  - Connected devices that can sense, communicate and store information about themselves;
  - Public and/or private data communications infrastructure;
  - Storage for the data that is generated by the IIoT devices;
  - People, etc.

Relationship

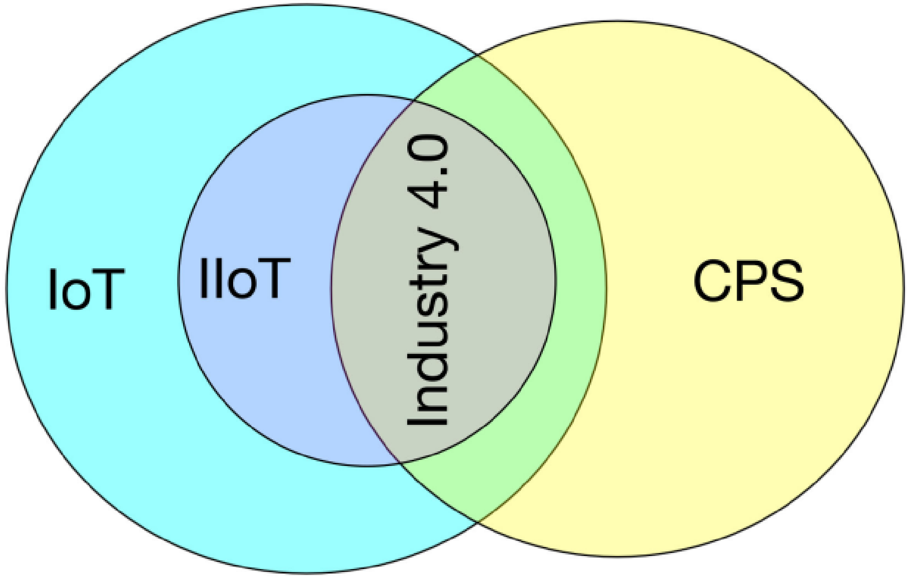

Fig. 1. IoT, CPS, IIoT, and Industry 4.0 in Venn diagram [4].

	Consumer IoT	Industrial IoT
Impact	Revolution	Evolution
Service Model	Human-centered	Machine-oriented
Current Status	New devices and standards	Existing devices and standards
Connectivity	Ad-Hoc (infrastructure is not tolerated; nodes can be mobile)	Structured (nodes are fixed; centralized network management)
Criticality	Not stringent (excluding medical applications)	Mission critical (timing, reliability, security, privacy)
Data Volume	Medium to High	High to Very High

Fig. 2. Compare CIoT and IIoT [4].

Background

ZigBee
Bluetooth Low Energy (BLE)
WIFI and Low-Power WIFI (LP-WIFI)
Low Power Wide Area (LPWA)
…

5G plays the role of a unified interconnection framework.

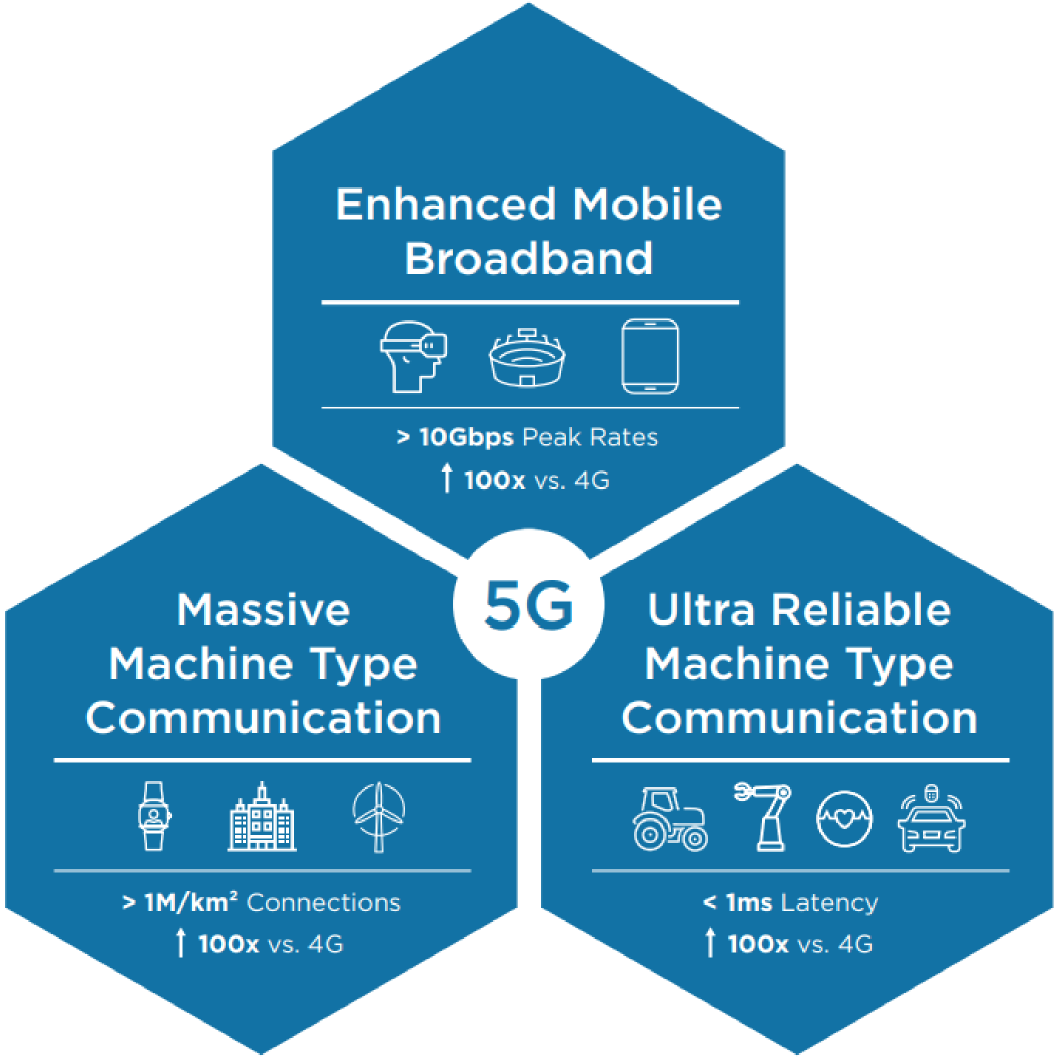

Fig. 3. Three 5G use categories [5].

Outline

1. Introduction

2. Motivation

3. System Model & Methods

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5. Conclusion

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Motivation

IIoT Requirements

- **Massive Connectivity**
- **Coexistence and Interoperability**
- **Energy Efficiency**
- **Real-Time Performance**
- **Security and Privacy**

Motivation

- **To improve connectivity density:**

  Non-orthogonal Multiple Access (**NOMA**)

  - The number of supportable users/devices is not strictly limited by the number of orthogonal resources available compared to Orthogonal Multiple Access (**OMA**).

- **To enrich service diversity:**

  Network Slicing

  - By facilitating multiple logical networks on top of a common physical network, it enables various service types for IIoT.

System Model

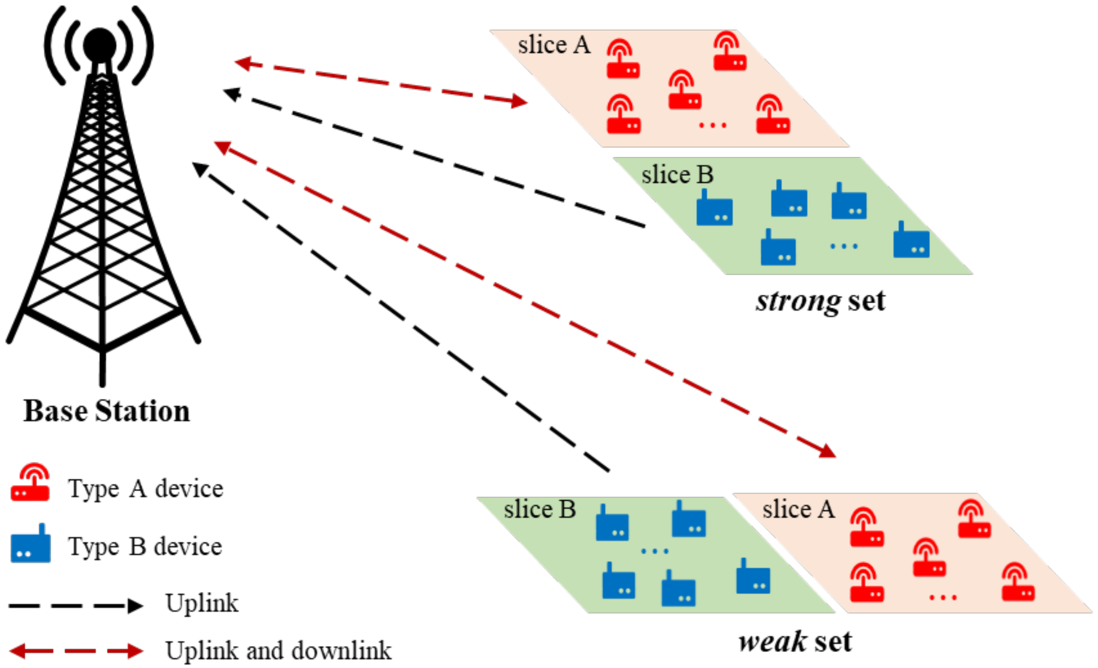


Fig. 4. System framework with two distinct services.

Devices:

- ***Strong set,*** denoted as $\mathcal{C}_{\mathscr{S}}$
- ***Weak set,*** denoted as $\mathcal{C}_{\mathscr{W}}$

In each set:

- ***Type A service***: uploading collected data to the BS and also acquiring data from the BS. e.g., the automated guided vehicle (AGV).
- ***Type B service***: uploading collected data only. e.g., the sensors.

- **OMA** for downlink, to guarantee the download rate for each of the type A devices.
- **NOMA** for uplink, to collet data from different MTCDs (either type A or type B devices) as much as possible.

Assumptions

- **A.1.** *Each sub-carrier can be accessed by at most one strong device and one weak device.*

$$0 \leq \sum_{k \in \mathcal{C}_{\mathcal{S}}} \alpha_{k,s} \leq 1, \forall s \in \mathcal{S}, \ 0 \leq \sum_{k \in \mathcal{C}_{\mathcal{W}}} \alpha_{k,s} \leq 1, \forall s \in \mathcal{S}, \ 0 \leq \sum_{k \in \mathcal{C}^{A}} \beta_{k,s} \leq 1, \forall s \in \mathcal{S}$$

- **A.2.** *each device can only occupy at most one sub-carrier for transmission.*

$$0 \leq \sum_{s \in \mathcal{S}} \alpha_{k,s} \leq 1, \ \forall k \in \mathcal{C}, \ 0 \leq \sum_{s \in \mathcal{S}} \beta_{k,s} \leq 1, \ \forall k \in \mathcal{C}^{A}$$

- **A.3.** *each sub-carrier can be only assigned to either downlink or uplink.*

$$0 \leq \frac{1}{2} \sum_{k \in \mathcal{C}} \alpha_{k,s} + \sum_{k \in \mathcal{C}^{A}} \beta_{k,s} \leq 1, \quad \forall s \in \mathcal{S}$$

Primal Problem Formulation

Type A **Type B**

$$\mathcal{P}1: \quad \underset{p^u_{k,s},\, p^d_{k,s},\, \alpha_{k,s},\, \beta_{k,s}}{\text{maximize}} \boxed{\xi \sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}} \alpha_{k,s}} + \boxed{(1-\xi)\sum_{k\in\mathcal{C}^B}\sum_{s\in\mathcal{S}} \alpha_{k,s}}$$

$$r^u_k \ge \left(\sum_{s\in\mathcal{S}} \alpha_{k,s}\right)\lambda_u,\ \forall k\in\mathcal{C}, \quad r^d_k \ge \left(\sum_{s\in\mathcal{S}} \beta_{k,s}\right)\bar{\lambda}_d, \quad \forall k\in\mathcal{C}^A,$$

QoS

$$0\le \sum_{k\in\mathcal{C}_{\mathscr{W}}} \alpha_{k,s} \le 1,\ 0\le \sum_{k\in\mathcal{C}^A} \beta_{k,s} \le 1,\ 0\le \sum_{k\in\mathcal{C}_{\mathscr{G}}} \alpha_{k,s} \le 1,\ 0\le \frac{1}{2}\sum_{k\in\mathcal{C}} \alpha_{k,s} + \sum_{k\in\mathcal{C}^A} \beta_{k,s} \le 1, \quad \forall s\in\mathcal{S},$$

$$0\le \sum_{s\in\mathcal{S}} \beta_{k,s} \le 1,\ \sum_{s\in\mathcal{S}} \alpha_{k,s} = \sum_{s\in\mathcal{S}} \beta_{k,s}, \quad \forall k\in\mathcal{C}^A, \qquad 0\le \sum_{s\in\mathcal{S}} \alpha_{k,s} \le 1, \quad \forall k\in\mathcal{C},$$

Device

$$\frac{1}{2}\sum_{k\in\mathcal{C}}\sum_{s\in\mathcal{S}} \alpha_{k,s} + \sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}} \beta_{k,s} \le \mathcal{S}_{tol},$$

Sub-carrier

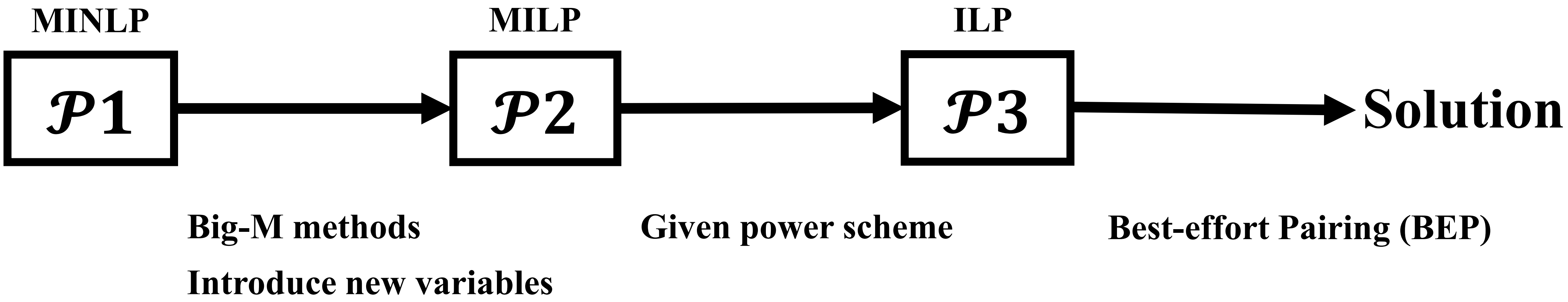
$$0\le \sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}} p^d_{k,s} \le P_B,$$

Power

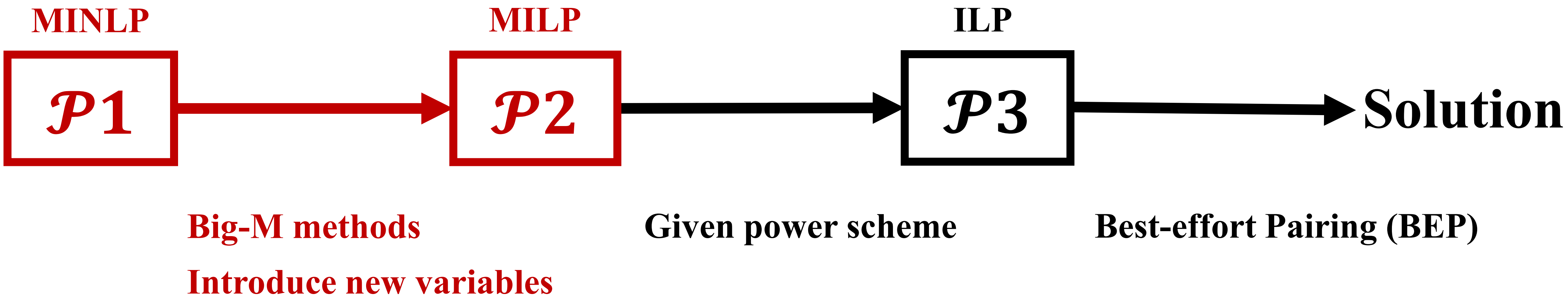
$$0\le p^d_{k,s} \le \beta_{k,s} P_B, \quad \forall k\in\mathcal{C}^A, s\in\mathcal{S}, \qquad 0\le p^u_{k,s} \le \alpha_{k,s} P_D, \quad \forall k\in\mathcal{C}, s\in\mathcal{S},$$

$$\alpha_{k,s}\in\{0,1\}, \quad \beta_{k,s}\in\{0,1\}, \quad \forall k\in\mathcal{C}, s\in\mathcal{S}.$$

Logical Flow



Logical Flow



MINLP to MILP?

■ $\mathcal{P}1$ is a mixed-integer nonlinear programming (MINLP).

$$r_i^u = \sum_{s\in\mathcal{S}} B\log_2\left(1+\frac{\alpha_{i,s}|h_i^u|^2 p_{i,s}^u}{I_{i,s}+N_0B}\right), \quad \forall i\in\mathcal{C}_{\mathscr{S}}$$

➡

$$|h_k^u|^2 p_{k,s}^u \geq \alpha_{k,s}(I_{k,s}+N_0B)\left(2^{\frac{\bar{\lambda}_u}{B}}-1\right), \quad \forall s\in\mathcal{S}$$

$$r_j^u = \sum_{s\in\mathcal{S}} B\log_2\left(1+\frac{\alpha_{j,s}|h_j^u|^2 p_{j,s}^u}{N_0B}\right), \quad \forall j\in\mathcal{C}_{\mathscr{W}}$$

➡

$$|h_k^d|^2 p_{k,s}^d \geq \beta_{k,s}N_0B\left(2^{\frac{\lambda_d}{B}}-1\right), \quad \forall s\in\mathcal{S}$$

Introduce new variables $\hat{\alpha}_{k,s}=\alpha_{k,s}I_{k,s}$, and use Big-M methods:

$$0\leq\hat{\alpha}_{k,s}\leq\sum_{i\in\mathcal{C}_{\mathscr{W}}}|h_i^u|^2 p_{i,s}^u,$$

$$\hat{\alpha}_{k,s}\leq\alpha_{k,s}\sum_{i\in\mathcal{C}_{\mathscr{W}}}|h_i^u|^2 P_D,$$

$$\hat{\alpha}_{k,s}\geq(\alpha_{k,s}-1)\sum_{i\in\mathcal{C}_{\mathscr{W}}}|h_i^u|^2 P_D+\sum_{i\in\mathcal{C}_{\mathscr{W}}}|h_i^u|^2 p_{i,s}^u$$

Then, we can get $\boldsymbol{\mathcal{P}2}$ here.

Complete $\mathcal{P}2$

$\mathcal{P}2$:

$$\underset{p^u_{k,s},\, p^d_{k,s},\, \alpha_{k,s},\, \beta_{k,s},\, \hat{\alpha}_{k,s}}{\text{maximize}} \quad \xi \sum_{k\in\mathcal{C}^A} \sum_{s\in\mathcal{S}} \alpha_{k,s} + (1-\xi) \sum_{k\in\mathcal{C}^B} \sum_{s\in\mathcal{S}} \alpha_{k,s}$$

$$|h^u_k|^2 p^u_{k,s} \geq \alpha_{k,s}(I_{k,s} + N_0 B)\left(2^{\frac{\bar{\lambda}_u}{B}} - 1\right), \quad \forall s \in \mathcal{S},$$

$$|h^d_k|^2 p^d_{k,s} \geq \beta_{k,s} N_0 B\left(2^{\frac{\lambda_d}{B}} - 1\right), \quad \forall s \in \mathcal{S},$$

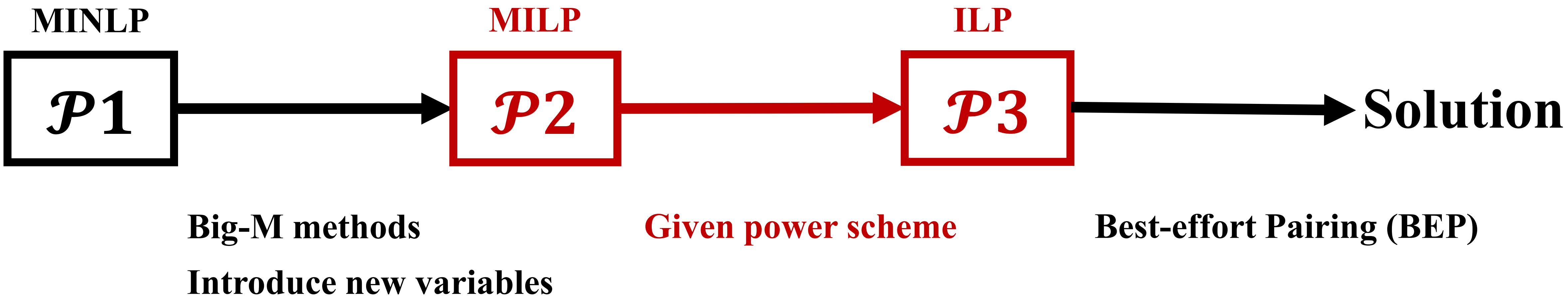
$$0 \leq \hat{\alpha}_{k,s} \leq \sum_{i\in\mathcal{C}_{\mathcal{W}}} |h^u_i|^2 p^u_{i,s}, \qquad \hat{\alpha}_{k,s} \leq \alpha_{k,s} \sum_{i\in\mathcal{C}_{\mathcal{W}}} |h^u_i|^2 P_D,$$

$$\hat{\alpha}_{k,s} \geq (\alpha_{k,s} - 1) \sum_{i\in\mathcal{C}_{\mathcal{W}}} |h^u_i|^2 P_D + \sum_{i\in\mathcal{C}_{\mathcal{W}}} |h^u_i|^2 p^u_{i,s},$$

And other linear constraints

- **$\mathcal{P}2$ is a mixed-integer linear programming (MILP).**

Logical Flow



Given Power Scheme

- **Since our objective is to maximize the connectivity, and the power from both BS and MTCDs are not our main concern.**

Power pre-allocation:

$$p_{k,s}^{u*} = \frac{N_0 B\left(2^{\frac{\bar{\lambda}_u}{B}} - 1\right)}{|h_k^u|^2}, \quad \forall k \in \mathcal{C}, s \in \mathcal{S},$$

$$p_{k,s}^{d*} = \frac{N_0 B\left(2^{\frac{\bar{\lambda}_d}{B}} - 1\right)}{|h_k^d|^2}, \quad \forall k \in \mathcal{C}^A, s \in \mathcal{S}$$

The pairing principle:

$$\Lambda_{k,s} = \frac{|h_k^u|^2 P_D}{\left(2^{\frac{\lambda_u}{B}} - 1\right)} - N_0 B, \quad \forall k \in \mathcal{C}_{\mathscr{S}}, s \in \mathcal{S},$$

$$\Omega_{k,s} = \left(2^{\frac{\lambda}{B}} - 1\right) N_0 B, \quad \forall k \in \mathcal{C}_{\mathscr{W}}, s \in \mathcal{S}$$

$$\sum_{k \in \mathcal{C}_W} \alpha_{k,s} \Omega_{k,s} \le \sum_{k \in \mathcal{C}_{\mathscr{S}}} \alpha_{k,s} \Lambda_{k,s} + M\left(1 - \sum_{k \in \mathcal{C}_{\mathscr{S}}} \alpha_{k,s}\right)$$

Then, we can get $\boldsymbol{\mathcal{P}3}$ here.

Complete $\mathcal{P}3$

$\mathcal{P}3$:

$$\underset{\alpha_{k,s},\,\beta_{k,s}}{\text{maximize}}\ \xi \sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}} \alpha_{k,s} + (1-\xi)\sum_{k\in\mathcal{C}^B}\sum_{s\in\mathcal{S}} \alpha_{k,s}$$

$$\sum_{k\in\mathcal{C}_W} \alpha_{k,s}\Omega_{k,s} \le \sum_{k\in\mathcal{C}_{\mathcal{G}}} \alpha_{k,s}\Lambda_{k,s} + M\left(1-\sum_{k\in\mathcal{C}_{\mathcal{G}}}\alpha_{k,s}\right)$$

$$\alpha_{k,s} \le P_D/p_{k,s}^{u*},\quad \forall k\in\mathcal{C}, s\in\mathcal{S},$$

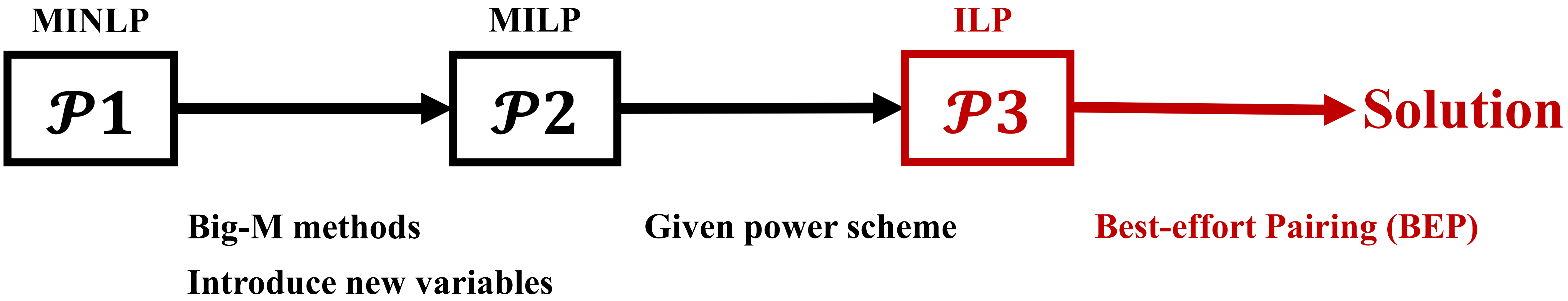
$$\beta_{k,s} \le P_B/p_{k,s}^{d*},\quad \forall k\in\mathcal{C}^A, s\in\mathcal{S},$$

$$\sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}} \beta_{k,s}\, p_{k,s}^{d*} \le P_B$$

And other linear constraints

- **$\mathcal{P}3$ is a integer linear programming (ILP).**

Logical Flow



Philosophy of BEP

■ **The core idea of BEP is to set pairings as our main subjective.**

Two principles of BEP algorithm:

- ***Interference accommodation principle***

  For any sub-carrier, a device (in strong set) has large $\Lambda_{k,s}$ should also accommodate a device (in weak set) has large $\Omega_{k,s}$.

- ***Priority principle***

  With the limited downlink transmit power, devices with smaller $p_{k,s}^{d*}$ should be paired and accessed with higher priority.

Define two sets as

$$\boldsymbol{\mu} = \left[\Lambda_k / p_k^{d*} \,\middle|_{\Lambda_k/p_k^{d*} \geq \Lambda_{k+1}/p_{k+1}^{d*}}\right] \in \mathbb{R}^{1\times|\mathcal{C}_{\mathscr{S}}|},$$

$$\boldsymbol{\nu} = \left[p_k^{d*} / \Omega_k \,\middle|_{p_k^{d*}/\Omega_k \leq p_{k+1}^{d*}/\Omega_{k+1}}\right] \in \mathbb{R}^{1\times|\mathcal{C}_{\mathscr{W}}|}$$

BEP

First,

Calculate p_k^{u*}, p_k^{d*}, $\tilde{p}_k^d$, $\Lambda_{k,s}$, $\Omega_{k,s}$ to determine $\boldsymbol{\mu}$ and $\boldsymbol{\nu}$.

Next,

Look for devices in $\boldsymbol{\mu}$ and $\boldsymbol{\nu}$ that meet the pairing requirements.

Finally,

Access the remaining devices in order until the total power or total sub-carrier is exceeded.

The time complexity of BEP is $\mathcal{O}\left(|\mathcal{C}_{\mathscr{S}}| \cdot |\mathcal{C}_{\mathscr{W}}|\right)$

Algorithm 1 Best-effort Pairing Algorithm for $\mathscr{P}3$

Input: P_D, P_B, B, S_{tol}, $\bar{\lambda}_u$, $\bar{\lambda}_d$, ξ, and $\forall k \in \mathcal{C}$, h_k^u, h_k^d.
Output: pairings, par, and accessed devices, tol.

Initialization: p, s, par, $tol \leftarrow 0$, $\mathcal{C}^{'} \leftarrow \emptyset$.
Calculate p_k^{u*}, p_k^{d*}, and $\tilde{p}_k^d$, $k \in \mathcal{C}$ by (21) and (25).
if $p_k^{u*} > P_D$ **or** $p_k^{d*} > P_B$ **then** $\mathcal{C} \leftarrow \mathcal{C} \setminus \{k\}$
end if
Calculate Λ_k and Ω_k, $k \in \mathcal{C}$ by (22).
Calculate the order of pairing $\boldsymbol{\mu}$ and $\boldsymbol{\nu}$, $k \in \mathcal{C}$ by (24).
for $i \in \boldsymbol{\mu}$, $j \in \boldsymbol{\nu}$ **do**
  if $\Lambda_i \geq \Omega_j$ **then** $p \leftarrow p + p_i^{d*} + p_j^{d*}$,
    $s \leftarrow s + \left(p_i^{d*} > 0\right) + \left(p_j^{d*} > 0\right) + 1$.
    if $p \leq P_B$ **and** $s \leq S_{tol}$ **then** $par \leftarrow par + 1$,
      $\boldsymbol{\nu} \leftarrow \boldsymbol{\nu} \setminus \{j\}$, $\mathcal{C}^{'} \leftarrow \mathcal{C}^{'} \cup \{i, j\}$, **break**
    else $p \leftarrow p - p_i^{d*} - p_j^{d*}$,
      $s \leftarrow s - \left(p_i^{d*} > 0\right) - \left(p_j^{d*} > 0\right) - 1$,
      continue
    end if
  end if
end for
Access m ($m \in \mathcal{C} \setminus \mathcal{C}^{'}$) devices in order, s.t. $p + \sum_{k=1}^{m} p_k^{d*} \leq P_B$ **and** $s + \sum_{k=1}^{m}\left(\left(p_k^{d*} > 0\right) + 1\right) \leq S_{tol}$.
$tol \leftarrow 2 * par + m$.

Fig. 5. The complete flow of BEP algorithm.

Simulation Results

- ***Optimal***: The result from solving **MILP $\mathcal{P}2$** by toolbox.

- ***Given-power***: It is from solving **MILP $\mathcal{P}3$** by toolbox.

- ***Near-far Pairing (NFP)***: It is a conventional **NOMA** pair scheme with respect to the distance of devices.

- ***Refined Near-far Pairing (R-NFP)***: It is a scheme that refines the pairs from **NFP** with respect to the downlink transmit power.

Simulation Results

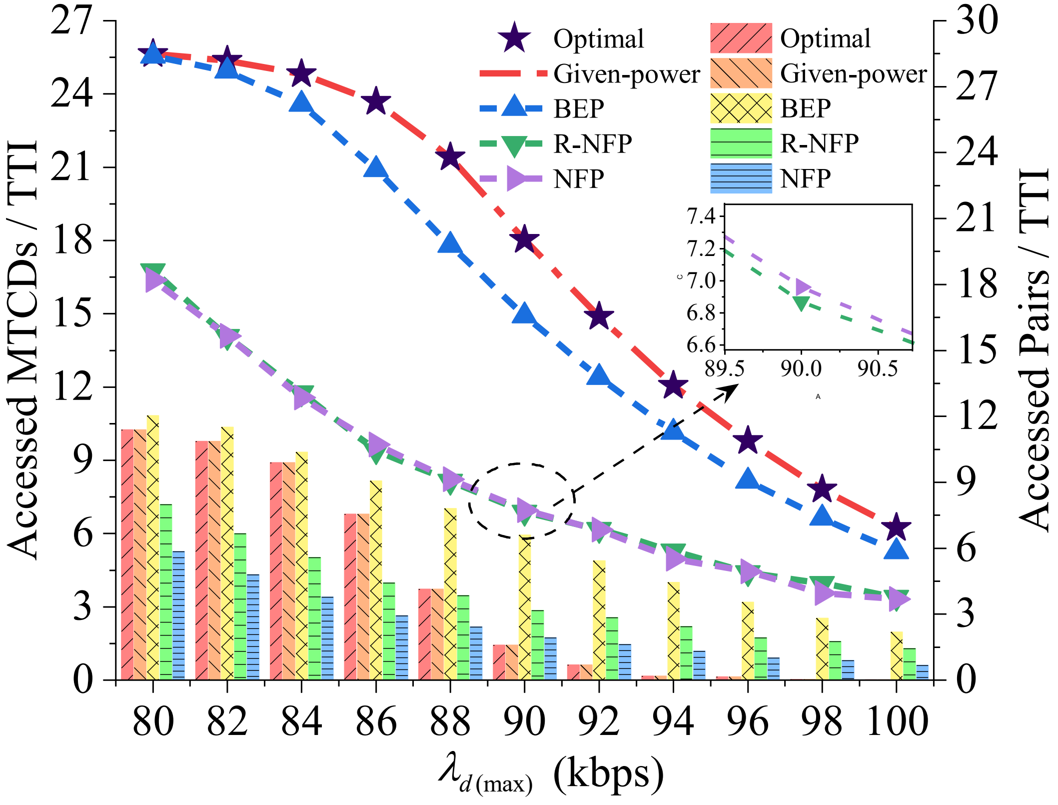


Fig. 6. Number of accessed devices and pairs versus downlink data rate $\lambda_{d(max)}$. ξ is set to 1.

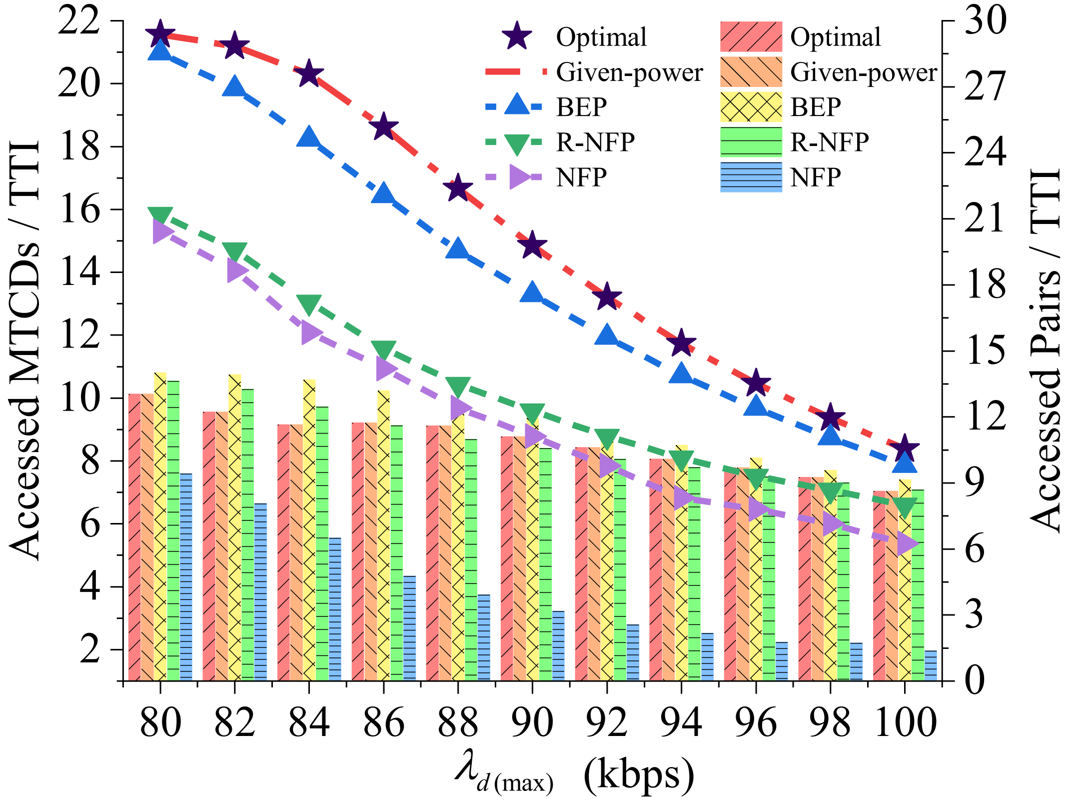


Fig. 7. Number of accessed devices and pairs versus downlink data rate $\lambda_{d(max)}$. ξ is set to 0.9.

Simulation Results

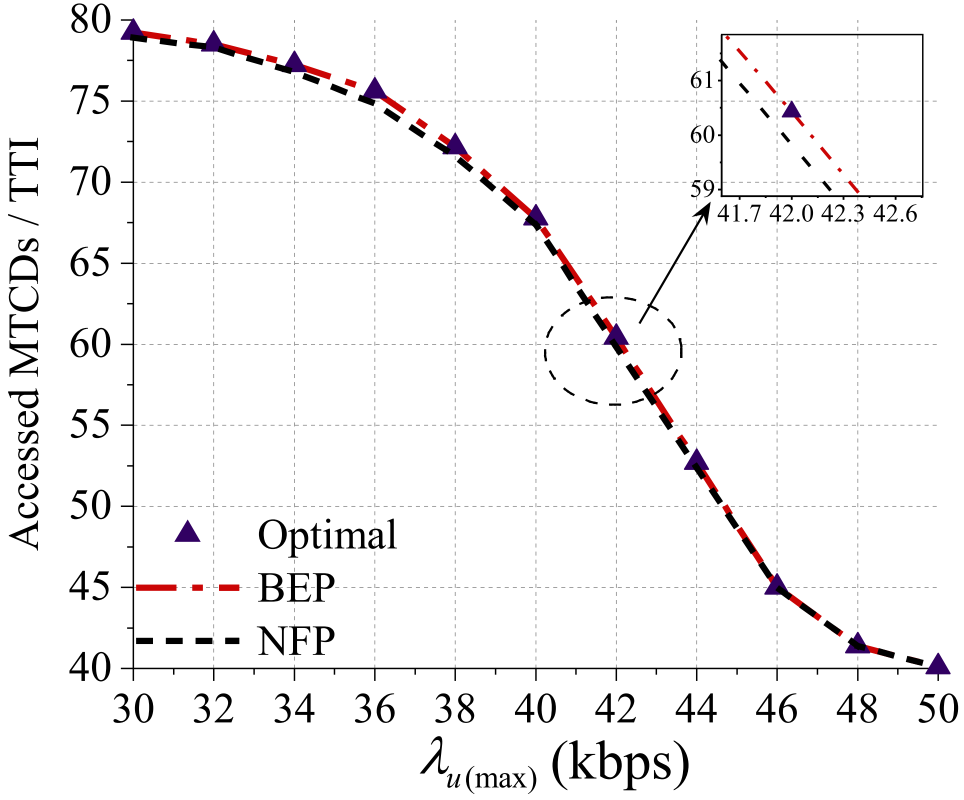


Fig. 8. Number of accessed devices versus uplink data rate $\lambda_{u(max)}$. ξ is set to 0.

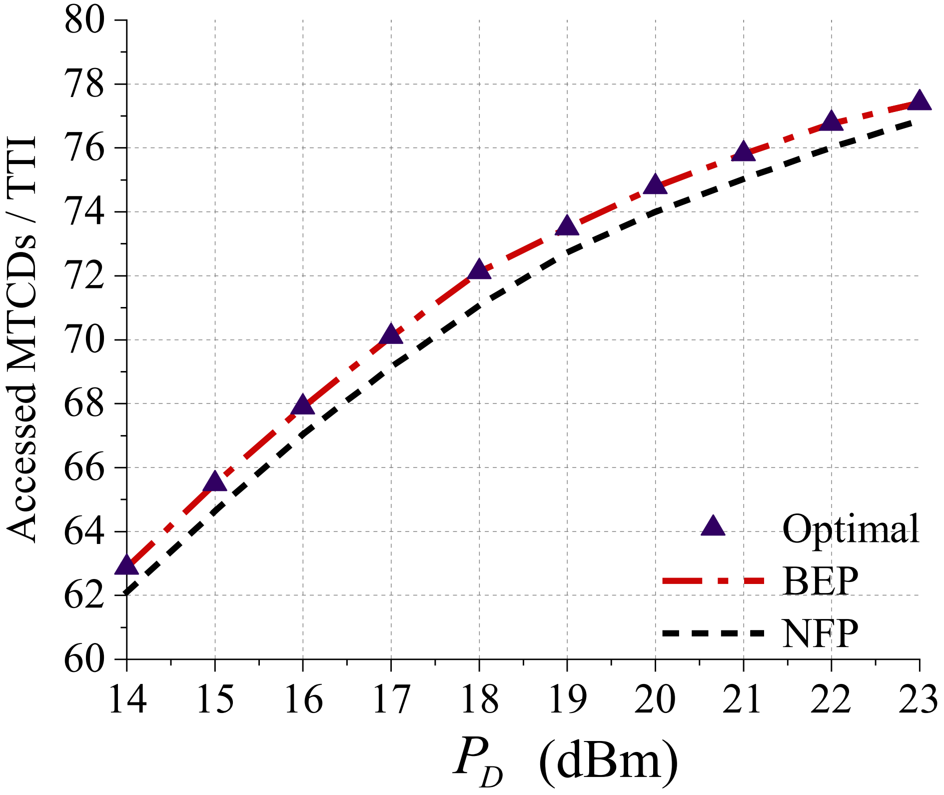


Fig. 9. Number of accessed devices versus power of devices P_{D}. ξ is set to 0.

Conclusion

- Build up the system with the coexistence of **NOMA** and **OMA** to provide two distinct services.
- Transform the optimization problem into a mixed-integer linear programming and then further reduce the **MILP** by finding out the optimal transmit power.
- Propose low-complexity **BEP** algorithm to solve system problem, which reduces the complexity and has a good performance.

Thank you for your attention!

Bo YIN

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Reference list

[1] *https://en.wikipedia.org/wiki/Internet_of_things*

[2] *https://en.wikipedia.org/wiki/Industrial_internet_of_things*

[3] *https://internetofthingsagenda.techtarget.com/definition/Industrial-Internet-of-Things-IIoT*

[4] *E. Sisinni, A. Saifullah, S. Han, U. Jennehag and M. Gidlund, "Industrial Internet of Things: Challenges, Opportunities, and Directions," in IEEE Transactions on Industrial Informatics, vol. 14, no. 11, pp. 4724-4734, Nov. 2018.*

[5] *data and devices mass connectivity in the 5G era.*