



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

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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

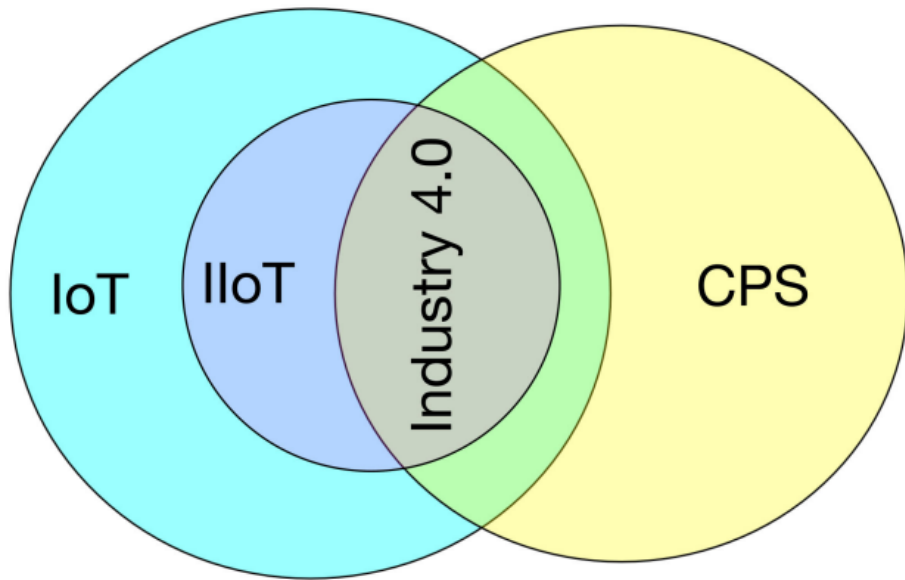


Fig. 1. IoT, CPS, IIoT, and Industry 4.0 in Venn diagram [4].

	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 CIIoT 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.**

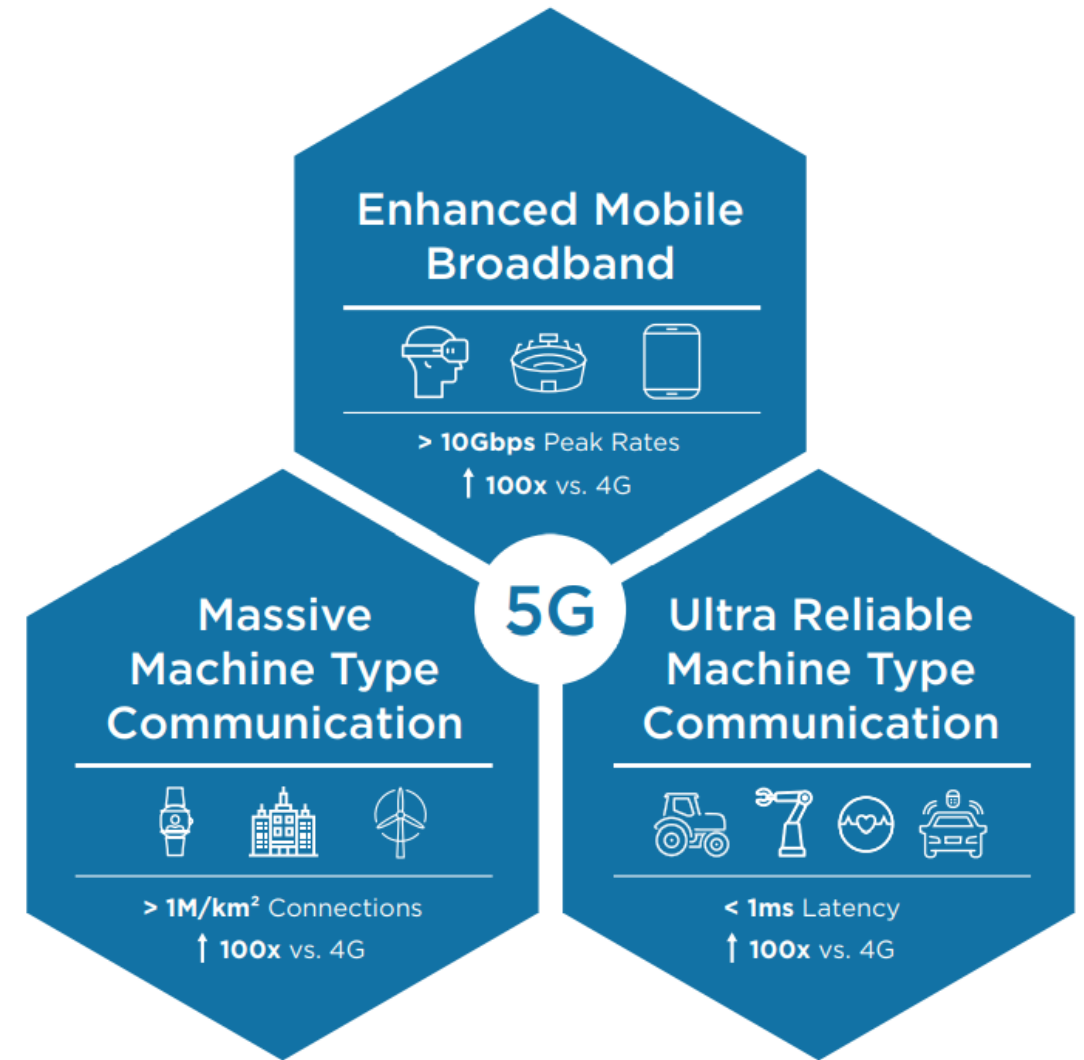


Fig. 3. Three 5G use categories [5].



1. Introduction

2. Motivation

3. System Model & Methods

4. Simulation Results

5. Conclusion

Reference List



IIoT Requirements

Massive Connectivity

Coexistence and Interoperability

Energy Efficiency

Real-Time Performance

Security and Privacy



- **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

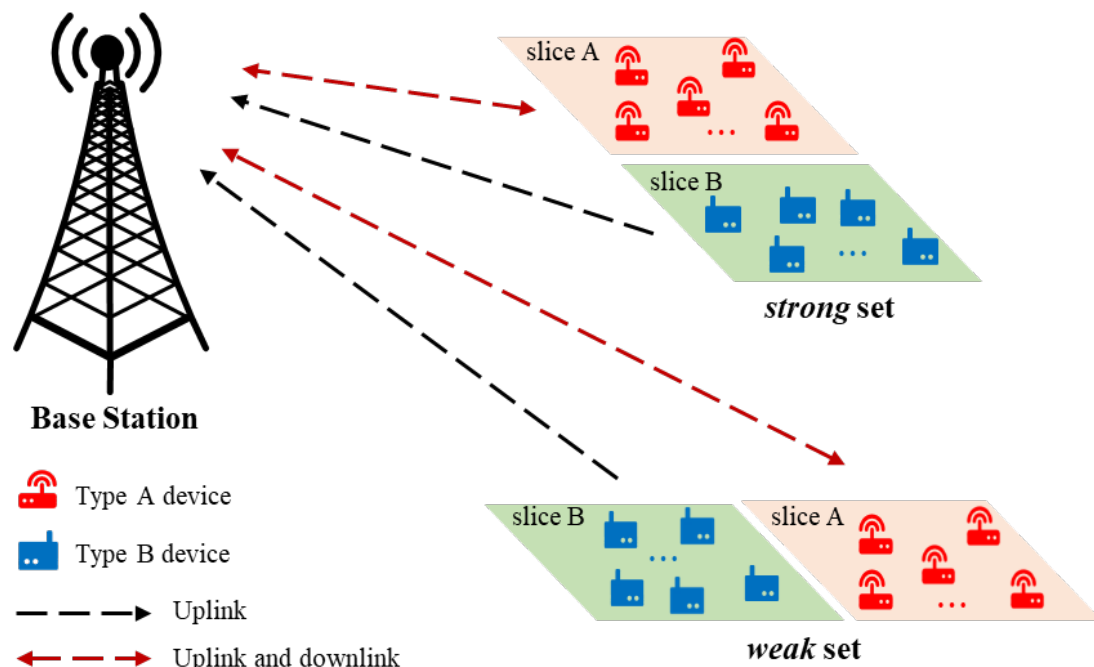


Fig. 4. System framework with two distinct services.

Devices:

- **Strong set**, denoted as \mathcal{C}_S
- **Weak set**, denoted as \mathcal{C}_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 collect 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.*

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

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

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

- **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

P1:

Type A

Type B

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

$$r_k^u \geq \left(\sum_{s \in \mathcal{S}} \alpha_{k,s} \right) \lambda_u, \quad \forall k \in \mathcal{C}, \quad r_k^d \geq \left(\sum_{s \in \mathcal{S}} \beta_{k,s} \right) \bar{\lambda}_d, \quad \forall k \in \mathcal{C}^A, \quad \text{QoS}$$

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

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

$$\frac{1}{2} \sum_{k \in \mathcal{C}} \sum_{s \in \mathcal{S}} \alpha_{k,s} + \sum_{k \in \mathcal{C}^A} \sum_{s \in \mathcal{S}} \beta_{k,s} \leq \mathcal{S}_{tol}, \quad \text{Sub-carrier}$$

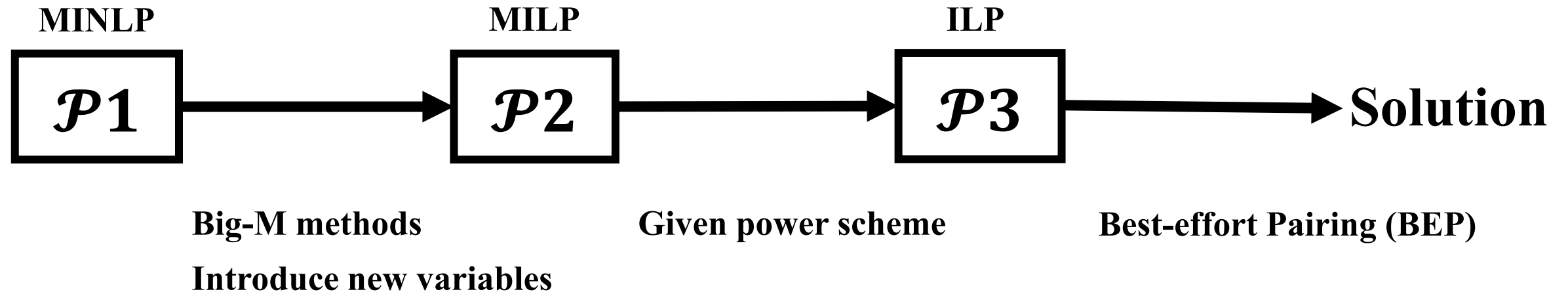
$$0 \leq \sum_{k \in \mathcal{C}^A} \sum_{s \in \mathcal{S}} p_{k,s}^d \leq P_B, \quad \text{Power}$$

$$0 \leq p_{k,s}^d \leq \beta_{k,s} P_B, \quad \forall k \in \mathcal{C}^A, s \in \mathcal{S}, \quad 0 \leq p_{k,s}^u \leq \alpha_{k,s} P_D, \quad \forall k \in \mathcal{C}, s \in \mathcal{S},$$

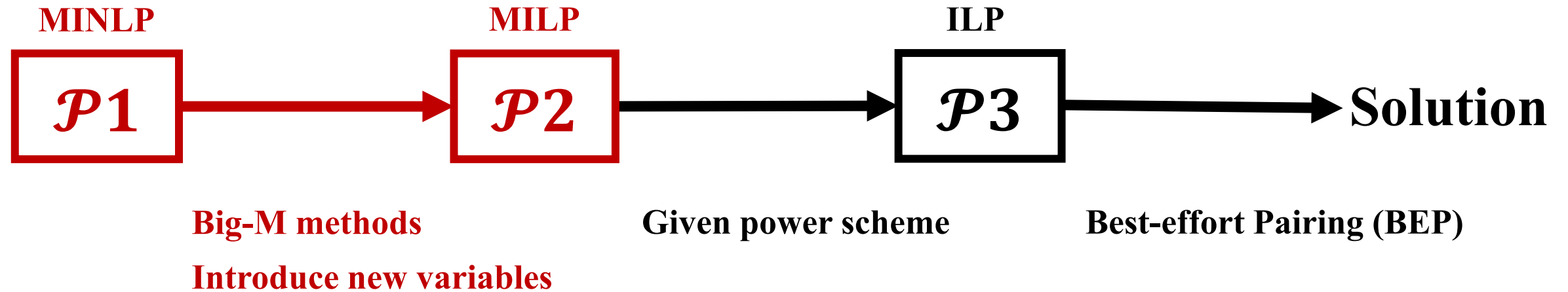
$$\alpha_{k,s} \in \{0, 1\}, \quad \beta_{k,s} \in \{0, 1\}, \quad \forall k \in \mathcal{C}, s \in \mathcal{S}.$$



Logical Flow



Logical Flow



MINLP to MILP?

■ **$\mathcal{P1}$ is a mixed-integer nonlinear programming (MINLP).**

$$\begin{aligned} r_i^u &= \sum_{s \in \mathcal{S}} B \log_2 \left(1 + \frac{\alpha_{i,s} |h_i^u|^2 p_{i,s}^u}{I_{i,s} + N_0 B} \right), \quad \forall i \in \mathcal{C}_{\mathcal{S}} \quad \Rightarrow \quad |h_k^u|^2 p_{k,s}^u \geq \alpha_{k,s} (I_{k,s} + N_0 B) \left(2^{\frac{\bar{\lambda}_u}{B}} - 1 \right), \quad \forall s \in \mathcal{S} \\ r_j^u &= \sum_{s \in \mathcal{S}} B \log_2 \left(1 + \frac{\alpha_{j,s} |h_j^u|^2 p_{j,s}^u}{N_0 B} \right), \quad \forall j \in \mathcal{C}_{\mathcal{W}} \quad \Rightarrow \quad |h_k^d|^2 p_{k,s}^d \geq \beta_{k,s} N_0 B \left(2^{\frac{\lambda_d}{B}} - 1 \right), \quad \forall s \in \mathcal{S} \end{aligned}$$

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

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

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

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

Then, we can get **$\mathcal{P2}$** here.



Complete $\mathcal{P}2$

$\mathcal{P}2$:

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

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

$$|h_k^d|^2 p_{k,s}^d \geq \beta_{k,s} N_0 B \left(2^{\frac{\lambda_d}{B}} - 1 \right), \quad \forall s \in \mathcal{S},$$

$$0 \leq \hat{\alpha}_{k,s} \leq \sum_{i \in \mathcal{C}_W} |h_i^u|^2 p_{i,s}^u, \quad \hat{\alpha}_{k,s} \leq \alpha_{k,s} \sum_{i \in \mathcal{C}_W} |h_i^u|^2 P_D,$$

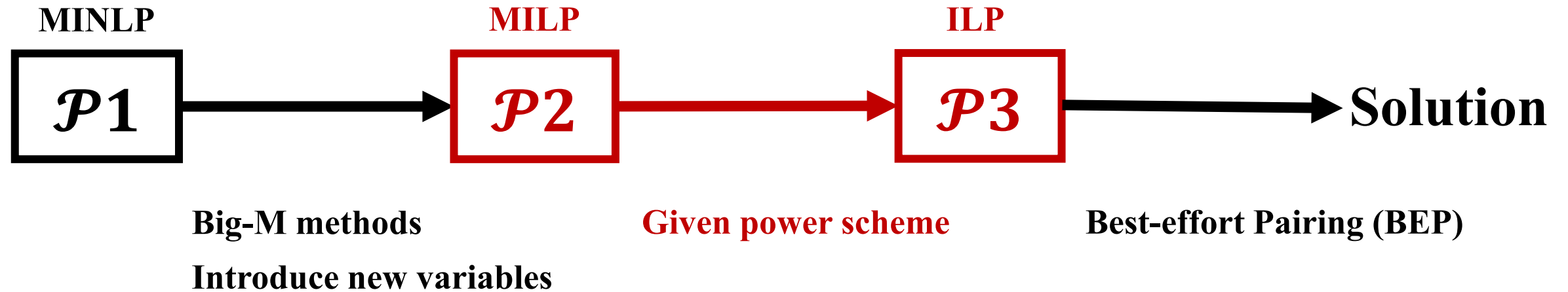
$$\hat{\alpha}_{k,s} \geq (\alpha_{k,s} - 1) \sum_{i \in \mathcal{C}_W} |h_i^u|^2 P_D + \sum_{i \in \mathcal{C}_W} |h_i^u|^2 p_{i,s}^u,$$

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 MTCs are not our main concern.

Power pre-allocation:

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

The pairing principle:

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

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

Then, we can get **P3** here.



Complete $\mathcal{P3}$

$\mathcal{P3}$:

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

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

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

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

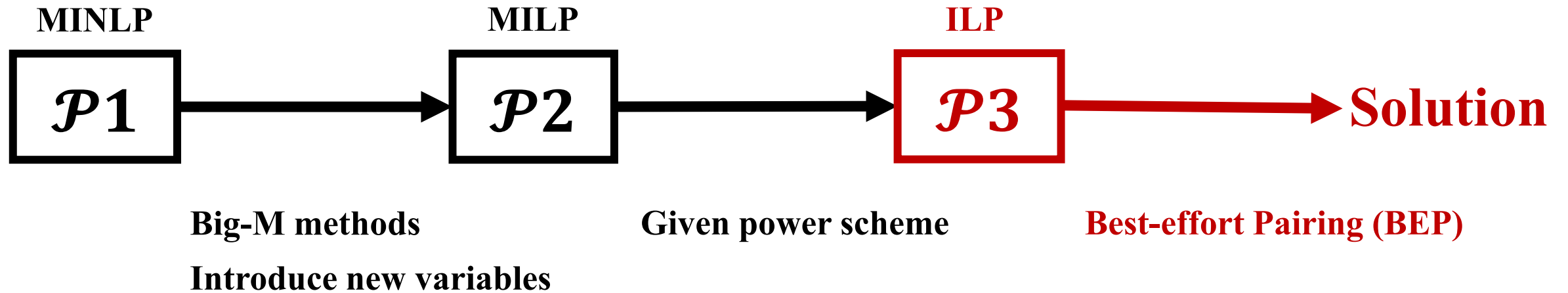
$$\sum_{k \in \mathcal{C}^A} \sum_{s \in \mathcal{S}} \beta_{k,s} p_{k,s}^{d*} \leq P_B$$

And other linear constraints

■ $\mathcal{P3}$ 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

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

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



First,

Calculate p_k^{u*} , p_k^{d*} , \tilde{p}_k^d , $\Lambda_{k,S}$, $\Omega_{k,S}$ to determine μ and ν .

Next,

Look for devices in μ and ν 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 $\mathcal{O}(|\mathcal{C}_{\mathcal{S}}| \cdot |\mathcal{C}_{\mathcal{W}}|)$

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

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 .

- 1: **Initialization:** p , s , par , $tol \leftarrow 0$, $\mathcal{C}' \leftarrow \emptyset$.
 - 2: Calculate p_k^{u*} , p_k^{d*} , and \tilde{p}_k^d , $k \in \mathcal{C}$ by (21) and (25).
 - 3: **if** $p_k^{u*} > P_D$ **or** $p_k^{d*} > P_B$ **then** $\mathcal{C} \leftarrow \mathcal{C} \setminus \{k\}$
 - 4: **end if**
 - 5: Calculate Λ_k and Ω_k , $k \in \mathcal{C}$ by (22).
 - 6: Calculate the order of pairing μ and ν , $k \in \mathcal{C}$ by (24).
 - 7: **for** $i \in \mu$, $j \in \nu$ **do**
 - 8: **if** $\Lambda_i \geq \Omega_j$ **then** $p \leftarrow p + p_i^{d*} + p_j^{d*}$,
 - 9: $s \leftarrow s + \left(p_i^{d*} > 0 \right) + \left(p_j^{d*} > 0 \right) + 1$.
 - 10: **if** $p \leq P_B$ **and** $s \leq S_{tol}$ **then** $par \leftarrow par + 1$,
 - 11: $\nu \leftarrow \nu \setminus \{j\}$, $\mathcal{C}' \leftarrow \mathcal{C}' \cup \{i, j\}$, **break**
 - 12: **else** $p \leftarrow p - p_i^{d*} - p_j^{d*}$,
 - 13: $s \leftarrow s - \left(p_i^{d*} > 0 \right) - \left(p_j^{d*} > 0 \right) - 1$,
 - 14: **continue**
 - 15: **end if**
 - 16: **end if**
 - 17: **end for**
 - 18: 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** $s + \sum_{k=1}^m \left(\left(p_k^{d*} > 0 \right) + 1 \right) \leq S_{tol}$.
 - 19: $tol \leftarrow 2 * par + m$.
-

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

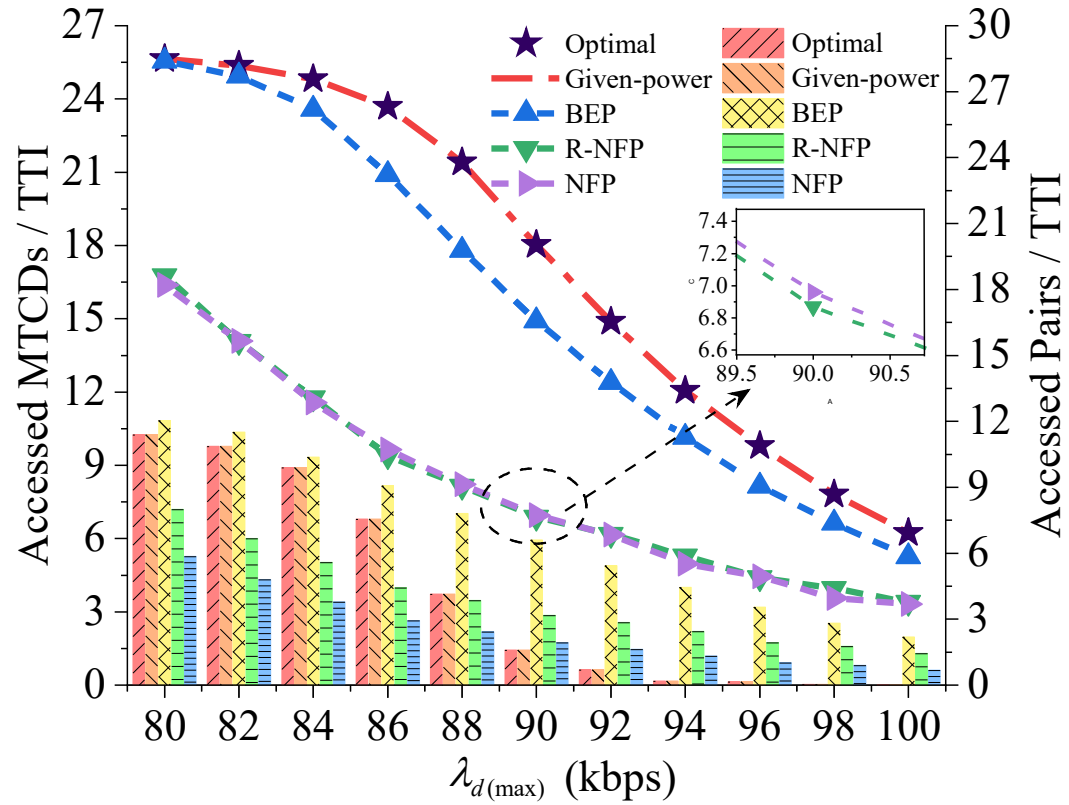


Fig. 6. Number of accessed devices and pairs versus downlink data rate $\lambda_{d(max)}$. ξ is set to 1.

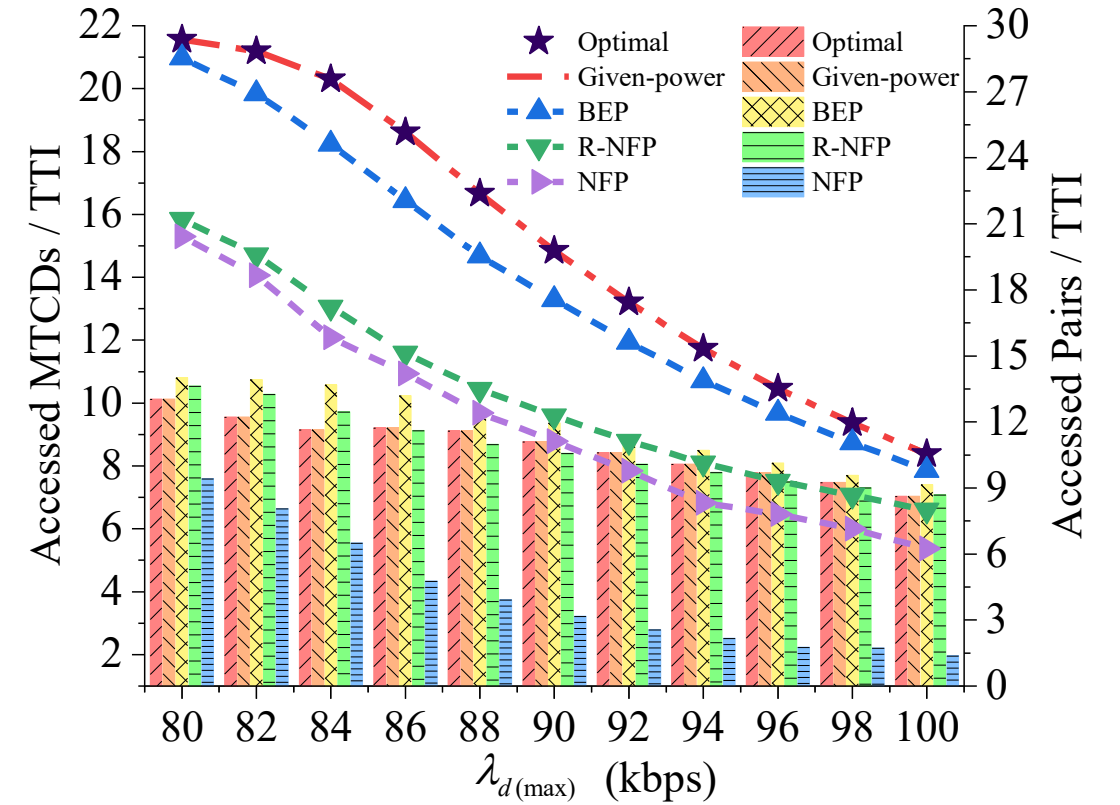


Fig. 7. Number of accessed devices and pairs versus downlink data rate $\lambda_{d(max)}$. ξ is set to 0.9.



Simulation Results

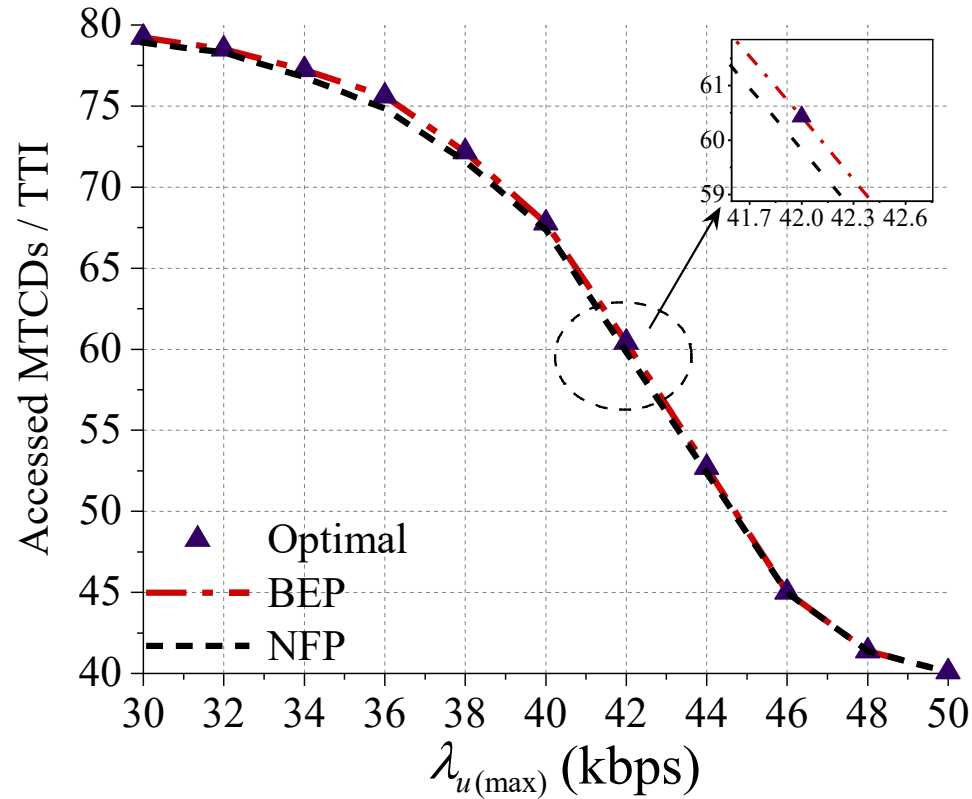


Fig. 8. Number of accessed devices versus uplink data rate $\lambda_{u(max)}$. ξ is set to 0.

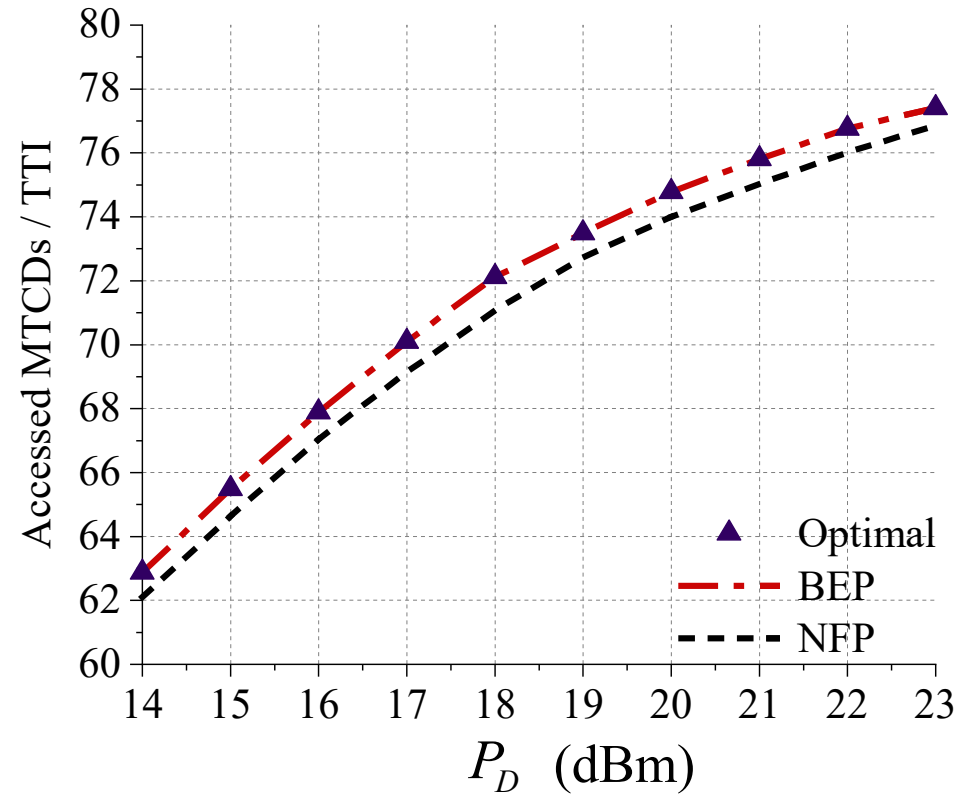


Fig. 9. Number of accessed devices versus power of devices P_D . ξ is set to 0.

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!

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Reference list

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- [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.*
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