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

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***Abstract*—The emergence of 5G brings unprecedented possibilities for deploying the anticipated Industrial Internet of Things (IIoT). To achieve high density connectivity with multiple services in 5G empowered IIoT, we consider the non-orthogonal network slicing in this work. In particular, we jointly utilize network slicing to incorporate two different types of services and exploit non-orthogonal multiple access (NOMA) to maximize the number of total devices that can be accessed to the system. We formulate the connectivity maximization problem as a mixed-integer nonlinear programming (MINLP) by jointly optimizing the transmit power and device-subcarrier association. To tackle the intractable MINLP, we first transform it into a mixed-integer linear programming (MILP) and then reduce the MILP by devising a simple but effective transmit power allocation scheme. Thereafter, we propose a low-complexity best-effort pairing (BEP) algorithm to solve the reduced MILP. By comprehensive simulations, we find that our proposed BEP significantly outperforms the benchmark schemes.**

***Index Terms*—5G, network slicing, IIoT, NOMA, resource allocation.**

I. Introduction

Recently, the growing popularity of the Internet of Things (IoT) is providing an up-and-coming scheme not only for the development of various home automation systems but also for different industrial applications. By grasping the advantages, Industrial Internet of Things (IIoT) is becoming a buzz word. IIoT is a group of interconnected static/mobile objects, such as devices equipped with communication, networked sensors, and control modules, connected through the Internet. On the basis of its essence, IIoT requires in possession of strong communication characteristics such as multiple services, high density, low latency, high reliability and scalability to promote the development of Industry 4.0. Nevertheless, indeed because of these characteristics, it is of difficulty to deploy an IIoT.

The 5G is expected to support a wide variety of usage scenarios including enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (URLLC) and massive machine type communications (mMTC) [1]. Meanwhile, the industry urgently needs to build wireless IIoT to connect the machines, consumers, and data, which is consistent with two of the 5G usage scenarios: URLLC and mMTC [2]. In this context, the advent of 5G cellular systems, with the availability of a wireless connectivity technology, which is at once truly ubiquitous, multi-service, reliable, scalable, and cost-efficient, is considered as a potentially key driver to set up IoT/IIoT [3]. This initially motivates this work.

There are many works on 5G empowered IIoT. For instance, to achieve flexible and highly secure edge service management, the authors propose an edge intelligence and blockchain empowered IIoT framework [4]. Different from the prior arts, we consider the environment with a large number of machine type communications devices (MTCDs) that provide multiple types of services. This is based on the fact that IIoT can provide multiple data services, such as collecting massive process data, communicating with industrial robots, and tracking machines/parts/products on the factory [5]. To accomplish high density connectivity with multiple services, we jointly consider and resort to the following two emerging technologies in this work:

- Non-orthogonal multiple access (NOMA). By allocating one time-frequency channel to multiple users at the same time within the same cell, it brings a number of advantages, including higher spectrum efficiency, improved network capacity and higher cell-edge throughput [6], which is a promising technology in IIoT cellular networks.
- Network slicing. By facilitating multiple logical selfcontained networks on top of a common physical network, it enables various service types for IIoT [7].

A. Related work

The traditional orthogonal multiple access (OMA) technology cannot meet the high density requirement of IIoT. To access a large number of MTCDs, power-domain NOMA that utilizes superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver is adopted in [8]. Considering the limited processing capabilities of MTCDs, uplink NOMA is widely studied in [9]–[11], and used to enhance the connectivity of IIoT.

To realize the high density and massive connectivity in 5G empowered IIoT, there are already some studies that introduce the power-domain NOMA scheme into mMTC scenario. The maximum access problem (MAP) for uplink networks

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with NOMA is studied in [12]–[15]. More specifically, the authors in [12] propose an algorithm to solve MAP which can be recast as the maximum independent set problem in graph theory. In [13], a scheme of power-domain NOMA is proposed to allow multiple ultra-reliable MTC (uMTC) devices and mMTC devices to share the same subcarrier. In [14], [15], different modes (single-tone and multi-tone) and more general sub-carrier allocation scheme for maximizing the connection density in NB-IoT with NOMA have been discussed. In addition, the authors in [16] propose a power-domain NOMA scheme with user clustering for an NB-IoT system to maximize the total throughput of the network. However, all of the aforementioned works just focus on the fact that the system only provides one sole service.

With the advances of 5G, one of the key technologies, network slicing, is expected to create different service capabilities for IIoT. The investigations in [17] and [18] incorporate two different types of services, i.e., URLLC and eMBB, into a single physical network by wireless network slicing. With effective admission control, the network operator obtains the maximum revenue. However, the studies in [17] and [18] are still in the category of orthogonal slicing, i.e., OMA is employed to isolate different slices.

B. Our contributions

In this work, we consider the non-orthogonal slicing in IIoT to support two distinct types of services, one of them has both uplink and downlink data transmissions and another one only requires uplink transmission. Our aim is to maximize the number of devices accessed to the system simultaneously, i.e., maximizing the connectivity. To satisfy the QoS requirements for each service/slice, we utilize NOMA scheme for the uplink and OMA scheme for the downlink. The main contributions of this paper are summarized as follows:

- We build up the system with the coexistence of NOMA and OMA to provide two distinct services, and formulate the connectivity maximization problem by jointly considering device-subcarrier association and transmit power allocation. The problem is formulated as a mixed-integer nonlinear programming (MINLP).
- We transform the MINLP into a mixed-integer linear programming (MILP) and then further reduce the MILP by finding out the optimal transmit power. Moreover, we propose a low-complexity best-effort pairing (BEP) algorithm to solve the reduced MILP.
- We provide extensive simulations that suggest our proposed low-complexity BEP algorithm outperforms other existing methods under different system settings and has close performance to the global optimal result (which is computationally prohibited).

II. System Model

We consider an Industrial Internet-of-Things which contains one base station (BS) and many MTCDs. We denote the collection of all MTCDs as $\mathcal{C}$. In which, there are two types of services that these MTCDs can provide:

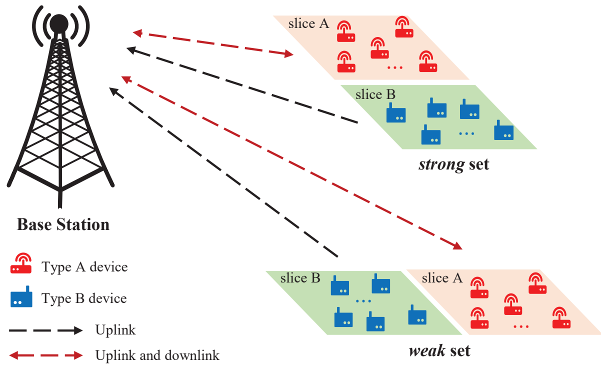


Fig. 1. System framework.

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

We assume that each MTCD can only provide one type of service and hence we can classify MTCDs into two disjoint sets, i.e., type A set, $\mathcal{C}^A$, and type B set, $\mathcal{C}^B$. To facilitate these two types of services in one single IIoT, we employ two disparate network slices: slice A and slice B, respectively.

Within one transmission time interval (TTI), all MTCDs share the physical resource block (PRB), which is evenly divided into S_{tol} sub-carriers with each sub-carrier of bandwidth B Hz. We denote the set of all sub-carriers as $\mathcal{S} = \{1, \dots, S_{tol}\}$. To fully utilize the physical resource, there are two different access methods involved in this work:

- 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.

In this work, for simplicity, we assume both BS and MTCDs are equipped with single antenna (The approaches in work can be readily extended to multi-antenna cases).

From the perspective of the decoding order of uplink NOMA [19], each device is labeled to a particular *decoding set*, defined as *strong* or *weak* set, if the device has a large or small channel gain respectively. Thus, for each one of the two decoding sets, both type A and type B devices may exist at the same time. Denote $\mathcal{C}_{\mathscr{S}}$ as devices in the *strong* set and $\mathcal{C}_{\mathscr{W}}$ as that in the *weak* set. In this work, we assume the two *decoding sets* are given and uplink power-domain NOMA is applied. Further, considering the decoding complexity of SIC in practical systems, we assume that each sub-carrier can accommodate at most two devices in the uplink NOMA, i.e., one device from each of the two decoding sets respectively. The system framework is shown in Fig. 1.

A. NOMA Uplink

We use power-domain NOMA to access devices from different sets. We define a binary variable $\alpha_{k,s}$ to identify the association between device and sub-carrier, i.e., $\alpha_{k,s} = 1$ if the s-th sub-carrier is allocated to the k-th device, and $\alpha_{k,s} = 0$ otherwise. In view of the uplink power-domain NOMA, devices in the *strong* set should be decoded first. The interference of the i-th *strong* set device over the s-th sub-carrier, caused by devices in the *weak* set over the s-th sub-carrier, can be given by

$$I_{i,s} = \sum_{j \in \mathcal{C}_{\mathscr{W}}} \alpha_{j,s} |h_j^u|^2 p_{j,s}^u, \quad \forall i \in \mathcal{C}_{\mathscr{S}}, s \in \mathcal{S}, \tag{1}$$

where h_j^u is uplink flat fading channel gain, between the j-th device and BS, and $p_{j,s}^u$ represents the uplink transmit power for the j-th device over the s-th sub-carrier. Then, the achievable transmission rate for the i-th device in the *strong* set can be expressed as

$$r_i^u = \sum_{s \in \mathcal{S}} B \log_2 \left(1 + \frac{\alpha_{i,s} |h_i^u|^2 p_{i,s}^u}{I_{i,s} + N_0 B}\right), \quad \forall i \in \mathcal{C}_{\mathscr{S}}, \tag{2}$$

where N_0 is power spectral density of the additive white Gaussian noise. At the BS, the component of devices in the *strong* set is subtracted from received signal. Therefore, devices in the *weak* set can be decode without interference and the achievable transmission rate for the j-th device can be given by

$$r_j^u = \sum_{s \in \mathcal{S}} B \log_2 \left(1 + \frac{\alpha_{j,s} |h_j^u|^2 p_{j,s}^u}{N_0 B}\right), \quad \forall j \in \mathcal{C}_{\mathscr{W}}. \tag{3}$$

B. OMA Downlink

As aforementioned, slice A provides both uploading and downloading services at the same time. In view of the computational ability of MTCDs, OMA scheme is chosen for the downlink. That is, when accessed, a single sub-carrier is exclusively assigned to support the downlink of each type A device. Similarly, we define a binary variable $\beta_{k,s}$ to indicate this association, i.e., $\beta_{k,s} = 1$ if the s-th sub-carrier is allocated to the k-th device for the downlink, and $\beta_{k,s} = 0$ otherwise.

Then, the downlink achievable transmission rate for the k-th device can be written as

$$r_k^d = \sum_{s \in \mathcal{S}} B \log_2 \left(1 + \frac{\beta_{k,s} |h_k^d|^2 p_{k,s}^d}{N_0 B}\right), \quad \forall k \in \mathcal{C}^A, \tag{4}$$

where h_k^d is downlink flat fading channel gain and $p_{k,s}^d$ is the downlink transmit power for the k-th device over the s-th sub-carrier.

C. Constraints

There are some primary constraints to be considered while using NOMA and OMA schemes.

1) Constraints for each sub-carrier: Each sub-carrier can be accessed by at most one *strong* device and one *weak* device in the uplink, i.e.,

$$0 \leq \sum_{k \in \mathcal{C}_{\mathscr{S}}} \alpha_{k,s} \leq 1, \quad \forall s \in \mathcal{S}, \text{ and}, \tag{5}$$

$$0 \leq \sum_{k \in \mathcal{C}_{\mathscr{W}}} \alpha_{k,s} \leq 1, \quad \forall s \in \mathcal{S}. \tag{6}$$

For the downlink, a single sub-carrier is exclusively provided for each accessed type A device, i.e., OMA scheme. we have,

$$0 \leq \sum_{k \in \mathcal{C}^A} \beta_{k,s} \leq 1, \quad \forall s \in \mathcal{S}. \tag{7}$$

More importantly, to ensure that each sub-carrier can be only assigned to either downlink or uplink, the association between $\alpha_{k,s}$ and $\beta_{k,s}$ can be expressed as

$$0 \leq \frac{1}{2} \sum_{k \in \mathcal{C}} \alpha_{k,s} + \sum_{k \in \mathcal{C}^A} \beta_{k,s} \leq 1, \quad \forall s \in \mathcal{S}. \tag{8}$$

2) Constraints for each device: For simplicity, we consider that each device can only occupy at most one sub-carrier for transmission, i.e.,

$$0 \leq \sum_{s \in \mathcal{S}} \alpha_{k,s} \leq 1, \quad \forall k \in \mathcal{C}, \text{ and}, \tag{9}$$

$$0 \leq \sum_{s \in \mathcal{S}} \beta_{k,s} \leq 1, \quad \forall k \in \mathcal{C}^A. \tag{10}$$

3) Constraints among devices/sub-carriers: Type A devices provide both uploading and downloading services, simultaneously. Therefore, when a type A device is accessed, it occupies both uplink and downlink sub-carrier, i.e.,

$$\sum_{s \in \mathcal{S}} \alpha_{k,s} = \sum_{s \in \mathcal{S}} \beta_{k,s}, \quad \forall k \in \mathcal{C}^A. \tag{11}$$

In addition, since the number of all sub-carriers is limited, not every type A or type B devices are able to get accessed, we have,

$$\frac{1}{2} \sum_{k \in \mathcal{C}} \sum_{s \in \mathcal{S}} \alpha_{k,s} + \sum_{k \in \mathcal{C}^A} \sum_{s \in \mathcal{S}} \beta_{k,s} \leq \mathcal{S}_{tol}. \tag{12}$$

4) Constraints for power: The transmit power of the k-th device over the s-th sub-carrier, $p_{k,s}^u$, should not exceed the maximum transmit power of the device, P_D, in the uplink, i.e.,

$$0 \leq p_{k,s}^u \leq \alpha_{k,s} P_D, \quad \forall k \in \mathcal{C}, \, s \in \mathcal{S}. \tag{13}$$

In the downlink, the transmit power assigned to the k-th device over the s-th sub-carrier does not exceed the maximum power of the BS, P_B, i.e.,

$$0 \leq p_{k,s}^d \leq \beta_{k,s} P_B, \quad \forall k \in \mathcal{C}^A, \, s \in \mathcal{S}. \tag{14}$$

And the sum of the transmit power of all devices in the downlink should not exceed the P_B, i.e.,

$$0 \leq \sum_{k \in \mathcal{C}^A} \sum_{s \in \mathcal{S}} p_{k,s}^d \leq P_B. \tag{15}$$

III. Problem Formulation

A. Formulation

Our goal is to maximize the connectivity while satisfying the QoS of different type devices. The optimization problem is formulated as follows:

$$
\begin{aligned}
\mathscr{P}1: \quad & \underset{p^u_{k,s}, p^d_{k,s}, \alpha_{k,s}, \beta_{k,s}}{\text{maximize}} \ \xi \textstyle\sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}} \alpha_{k,s} \\
& \qquad\qquad +(1-\xi)\textstyle\sum_{k\in\mathcal{C}^B}\sum_{s\in\mathcal{S}} \alpha_{k,s} \\
\text{s.t.} \quad & C1: r^u_k \geq (\textstyle\sum_{s\in\mathcal{S}} \alpha_{k,s})\bar{\lambda}_u, \quad \forall k\in\mathcal{C}, \\
& C2: r^d_k \geq (\textstyle\sum_{s\in\mathcal{S}} \beta_{k,s})\bar{\lambda}_d, \quad \forall k\in\mathcal{C}^A, \\
& C3: \alpha_{k,s}\in\{0,1\}, \quad \forall k\in\mathcal{C},\, s\in\mathcal{S}, \\
& C4: \beta_{k,s}\in\{0,1\}, \quad \forall k\in\mathcal{C}^A,\, s\in\mathcal{S}, \\
& \text{and (5)–(15),}
\end{aligned}
$$

where $0\leq\xi\leq 1$ is a weight to indicate the preference of type A or type B devices. $\bar{\lambda}_u$ and $\bar{\lambda}_d$ is the minimum required rate for devices in the uplink and downlink, respectively. $\mathscr{P}1$ is a mixed-integer nonlinear programming (MINLP).

B. Transformation

To handle the difficulty in problem $\mathscr{P}1$, we first transform the $C1$ and $C2$ into linear constraints. According to (4), (10) and (14), for $k\in\mathcal{C}^A$, $C2$ can be written as

$$|h^d_k|^2 p^d_{k,s} \geq \beta_{k,s} N_0 B\big(2^{\frac{\bar{\lambda}_d}{B}}-1\big), \quad \forall s\in\mathcal{S}. \tag{16}$$

For $k\in\mathcal{C}$, with (2), (9) and (13), $C1$ can be replaced by

$$|h^u_k|^2 p^u_{k,s} \geq \alpha_{k,s}\big(I_{k,s}+N_0B\big)\big(2^{\frac{\bar{\lambda}_u}{B}}-1\big), \quad \forall s\in\mathcal{S}. \tag{17}$$

To further simplify (17), we dissect the set $\mathcal{C}$ into two disjoint sets $\mathcal{C}_{\mathscr{S}}$ and $\mathcal{C}_{\mathscr{W}}$. For $k\in\mathcal{C}_{\mathscr{S}}$, we define a new variable, $\hat{\alpha}_{k,s}=\alpha_{k,s}I_{k,s}$, to linearize (17). Using the Big-M method [14], (1) and (13), $\hat{\alpha}_{k,s}$ can be reformulated as

$$
\begin{aligned}
& 0\leq\hat{\alpha}_{k,s}\leq \sum_{i\in\mathcal{C}_{\mathscr{W}}} |h^u_i|^2 p^u_{i,s}, \\
& \hat{\alpha}_{k,s}\leq \alpha_{k,s}\sum_{i\in\mathcal{C}_{\mathscr{W}}} |h^u_i|^2 P_D, \text{and,} \\
& \hat{\alpha}_{k,s}\geq(\alpha_{k,s}-1)\sum_{i\in\mathcal{C}_{\mathscr{W}}} |h^u_i|^2 P_D+\sum_{i\in\mathcal{C}_{\mathscr{W}}} |h^u_i|^2 p^u_{i,s}.
\end{aligned} \tag{18}
$$

For $k\in\mathcal{C}_{\mathscr{S}}$, the transformation of (17) can be expressed as

$$|h^u_k|^2 p^u_{k,s} \geq \big(\hat{\alpha}_{k,s}+\alpha_{k,s}N_0B\big)\big(2^{\frac{\bar{\lambda}_u}{B}}-1\big), \quad \forall s\in\mathcal{S}. \tag{19}$$

For $k\in\mathcal{C}_{\mathscr{W}}$, $I_{k,s}=0$ (since the devices in the weak set do not experience the interference), then we have,

$$|h^u_k|^2 p^u_{k,s} \geq \alpha_{k,s} N_0 B\big(2^{\frac{\bar{\lambda}_u}{B}}-1\big), \quad \forall s\in\mathcal{S}. \tag{20}$$

Therefore, $C1$ can be replaced by (18)–(20) and problem $\mathscr{P}1$ is now reformulated as

$$
\begin{aligned}
\mathscr{P}2: \quad & \underset{p^u_{k,s}, p^d_{k,s}, \beta_{k,s}, \alpha_{k,s}, \hat{\alpha}_{k,s}}{\text{maximize}} \ \xi \textstyle\sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}} \alpha_{k,s} \\
& \qquad\qquad +(1-\xi)\textstyle\sum_{k\in\mathcal{C}^B}\sum_{s\in\mathcal{S}} \alpha_{k,s} \\
\text{s.t.} \quad & \text{(5)–(16), (18)–(20), C3 and C4.}
\end{aligned}
$$

$\mathscr{P}2$ is a mixed-integer linear programming (MILP) which can be solved by employing some standard toolboxes, such as CVX with Gurobi. However, the complexity of which is still high and the acquired results can be only used as the benchmark. We propose a low-complexity algorithm in the following section.

IV. Optimization And Proposed Algorithm

In this section, we first introduce approaches to simplify the MILP $\mathscr{P}2$ and then propose a heuristic algorithm to solve the simplified MILP.

A. Transmit Power Optimization

Since our objective is to maximize the connectivity, and the power from both BS and MTCDs are not our main concern, we can derive a straightforward approach to find out the optimal $p^u_{k,s}$ and $p^d_{k,s}$.

From the QoS constraints $C1$ and $C2$, when a device is accessed, the minimum $p^u_{k,s}$ and $p^d_{k,s}$ are

$$
\begin{aligned}
& {p^u_{k,s}}^* = \frac{N_0B(2^{\frac{\bar{\lambda}_u}{B}}-1)}{|h^u_k|^2}, \quad \forall k\in\mathcal{C}, s\in\mathcal{S}, \text{ and,} \\
& {p^d_{k,s}}^* = \frac{N_0B(2^{\frac{\bar{\lambda}_d}{B}}-1)}{|h^d_k|^2}, \quad \forall k\in\mathcal{C}^A, s\in\mathcal{S},
\end{aligned} \tag{21}
$$

respectively. And we use these minimum transmit power as the optimal ones for problem $\mathscr{P}2$.

In what follows, we propose and utilize the idea of best-effort pairing (BEP). From the interference perspective, a device in the strong set should allocate as much power as possible to accommodate interference from the weak set. We define $\Lambda_{k,s}$ as the maximum interference that a *strong* set device can tolerate and $\Omega_{k,s}$ as the minimum interference that a *weak* set device causes. From (2) and (3), we have,

$$
\begin{aligned}
& \Lambda_{k,s} = \frac{|h^u_k|^2 P_D}{(2^{\frac{\bar{\lambda}_u}{B}}-1)} - N_0B, \quad \forall k\in\mathcal{C}_{\mathscr{S}}, s\in\mathcal{S}, \text{ and,} \\
& \Omega_{k,s} = (2^{\frac{\bar{\lambda}_u}{B}}-1)N_0B, \quad \forall k\in\mathcal{C}_{\mathscr{W}}, s\in\mathcal{S}.
\end{aligned} \tag{22}
$$

For any given sub-carrier $s\in\mathcal{S}$, if two devices are accessed at the same time, which needs to meet $\Lambda_{k,s}\geq\Omega_{k,s}$. In other words, for $s\in\mathcal{S}$, we have,

$$\sum_{k\in\mathcal{C}_{\mathscr{W}}}\alpha_{k,s}\Omega_{k,s} \leq \sum_{k\in\mathcal{C}_{\mathscr{S}}}\alpha_{k,s}\Lambda_{k,s}+M\left(1-\sum_{k\in\mathcal{C}_{\mathscr{S}}}\alpha_{k,s}\right), \tag{23}$$

where M is a large positive number that can take the maximum value of $\Omega_{k,s}$.

With the given $p^u_{k,s}={p^u_{k,s}}^*$, $p^d_{k,s}={p^d_{k,s}}^*$, problem $\mathscr{P}2$ is now simplified as:

$$
\begin{aligned}
\mathscr{P}3: \quad & \underset{\alpha_{k,s}, \beta_{k,s}}{\text{maximize}} \ \xi \textstyle\sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}} \alpha_{k,s} \\
& \qquad\qquad +(1-\xi)\textstyle\sum_{k\in\mathcal{C}^B}\sum_{s\in\mathcal{S}} \alpha_{k,s} \\
\text{s.t.} \quad & C5: \alpha_{k,s}\leq P_D/{p^u_{k,s}}^*, \quad \forall k\in\mathcal{C}, s\in\mathcal{S}, \\
& C6: \beta_{k,s}\leq P_B/{p^d_{k,s}}^*, \quad \forall k\in\mathcal{C}^A, s\in\mathcal{S}, \\
& C7: \textstyle\sum_{k\in\mathcal{C}^A}\sum_{s\in\mathcal{S}}\beta_{k,s}{p^d_{k,s}}^* \leq P_B, \\
& \text{(5)–(12), (23), C3 and C4,}
\end{aligned}
$$

where $C5$ and $C6$ mean that, in order to get accessed, one should have $P_D\geq{p^u_{k,s}}^*$ and $P_B\geq{p^d_{k,s}}^*$.

B. Best-effort Pairing Algorithm

Although $\mathscr{P}3$ greatly reduces the complexity of $\mathscr{P}2$, it is still an MILP problem. In this subsection, we still utilize the idea of best-effort pairing to design a heuristic algorithm.

To maximize the connectivity, in some ways, is to maximize the number of NOMA pairs. That is, if we want to access as many devices as possible, the more pairs, the better, i.e., $\forall s \in \mathcal{S}$, $\sum_{k\in\mathcal{C}_{\mathscr{S}}} \alpha_{k,s} = \sum_{k\in\mathcal{C}_{\mathscr{W}}} \alpha_{k,s} = 1$. Based on (22), for a given sub-carrier s, if we can find two devices satisfying $\Lambda_{k,s} \geq \Omega_{k,s}$, it realizes a pairing. To be more specific, our best-effort pairing algorithm has two principles:

1) For any sub-carrier s, a device (in strong set) has large $\Lambda_{k,s}$ should also accommodate a device (in weak set) has large $\Omega_{k,s}$.
2) With the limited downlink transmit power P_B, devices with smaller ${p_{k,s}^d}^*$ should be paired and accessed with higher priority.

Following these two principles, we define vectors $\boldsymbol{\mu}$ and $\boldsymbol{\nu}$ as (we drop the subscript s here since we consider the flat fading channel):

$$\begin{aligned}\boldsymbol{\mu} &= \left[\Lambda_k/p_k^{d^*}\,\big|_{\Lambda_k/p_k^{d^*} \geq \Lambda_{k+1}/{p_{k+1}^{d}}^*}\right] \in \mathbb{R}^{1\times|\mathcal{C}_{\mathscr{S}}|}, \text{ and,}\\ \boldsymbol{\nu} &= \left[p_k^{d^*}/\Omega_k\,\big|_{p_k^{d^*}/\Omega_k \leq {p_{k+1}^{d}}^*/\Omega_{k+1}}\right] \in \mathbb{R}^{1\times|\mathcal{C}_{\mathscr{W}}|},\end{aligned} \tag{24}$$

where the entries in $\boldsymbol{\mu}$ are sorted in descending order and in $\boldsymbol{\nu}$ are sorted in ascending order. Since type B devices do not require downlink transmission, i.e., $p_k^{d^*} = 0$ for $k \in \mathcal{C}^B$. However, to make (24) defined, we set $p_k^{d^*}$, for $k \in \mathcal{C}^B$, a virtual value $\tilde{p}_k^d$. To reasonably set $\tilde{p}_k^d$, there are two facts to be considered:

1) When ξ changes from 0 to 1, the preference of type B devices is decreasing. From aforementioned principle 2), we should set the virtual value $\tilde{p}_k^d$ as an increasing function of ξ.
2) Since type A and type B devices share the power at the BS side, when designing the virtual $\tilde{p}_k^d$ (for $k \in \mathcal{C}^B$), $p_k^{d^*}$ (for $k \in \mathcal{C}^A$) should be used as the references.

On these basis, we design $\tilde{p}_k^d$ as follows:

$$\tilde{p}_k^d = \begin{cases} \min\{p_i^{d^*}\}_{i\in\mathcal{C}_{\mathscr{S}}^A}\left(\dfrac{\max\{p_i^{d^*}\}_{i\in\mathcal{C}_{\mathscr{S}}^A}}{\min\{p_i^{d^*}\}_{i\in\mathcal{C}_{\mathscr{S}}^A}}\right)^{\xi}, & k \in \mathcal{C}_{\mathscr{S}}^B,\\ \min\{p_j^{d^*}\}_{j\in\mathcal{C}_{\mathscr{W}}^A}\left(\dfrac{\max\{p_j^{d^*}\}_{j\in\mathcal{C}_{\mathscr{W}}^A}}{\min\{p_j^{d^*}\}_{j\in\mathcal{C}_{\mathscr{W}}^A}}\right)^{\xi}, & k \in \mathcal{C}_{\mathscr{W}}^B. \end{cases} \tag{25}$$

Now, the best-effort pairing algorithm is ready to be devised. For example, the *strong* set device with the largest Λ_k and smallest $p_k^{d^*}$ (hence largest $\Lambda_k/p_k^{d^*}$) and the *weak* set device with the smallest $p_k^{d^*}$ and largest Ω_k (hence smallest $p_k^{d^*}/\Omega_k$) can be paired first. We present the best-effort pairing algorithm in Algorithm 1, which has time complexity $\mathcal{O}(|\mathcal{C}_{\mathscr{S}}|\cdot|\mathcal{C}_{\mathscr{W}}|)$.

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** $s + \sum_{k=1}^{m}\left(\left(p_k^{d^*} > 0\right) + 1\right) \leq S_{tol}$.
$tol \leftarrow 2 * par + m$.

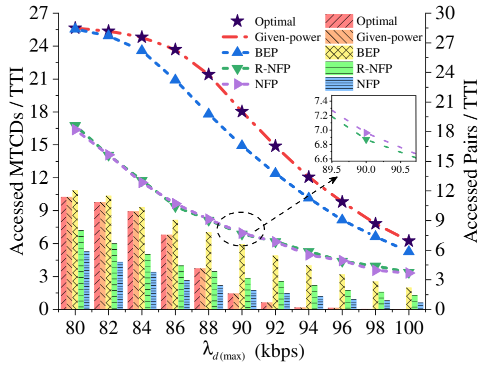
V. Simulation

In this section, we evaluate the system performance of the proposed algorithms. We consider a single cell where all devices are uniformly distributed within the radius of 500 m. Flat Rayleigh fading channels are considered since the total system bandwidth is as narrow as 200 kHz. The distance-dependent path loss is modeled as $d^{-\beta}$, where β is the path loss exponent. We set $\beta = 4$ and d is varied from 1 to 500 m. The power spectral density of the noise is -174 dBm/Hz and noise figure is 5 dB. The maximum transmit power for each device, P_D, is set to 23 dBm and the maximum transmit power of BS, P_B, is set to 30 dBm. We assume there are 40 sub-carriers to serve 40 strong set devices and 40 weak set devices.

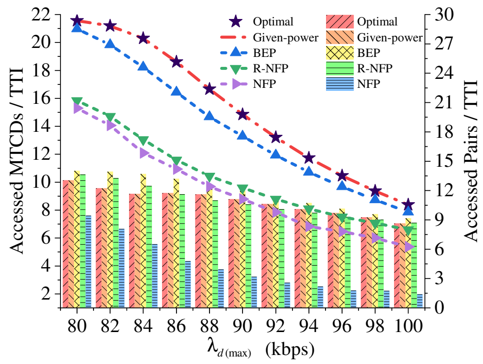
To show the effectiveness of our proposed BEP algorithm, we compare our simulation results with the following benchmark algorithms:

- Optimal: The result from solving MILP $\mathscr{P}2$ by toolbox.
- Given-power: It is from solving MILP $\mathscr{P}3$ by toolbox.
- Near-far Pairing (NFP): It is a conventional NOMA scheme that pairs the closest (second closest, ...) device in the strong set with the furthest (second furthest, ...) device in the weak set respectively.
- Refined Near-far Pairing (R-NFP): It is a scheme that refines the pairs from NFP with respect to the downlink transmit power. Since the pairs in NFP may require more power than the maximum power of BS, in R-NFP, we only choose the devices that do not violate the maximum power constraint when pairing.

In Fig. 2, we examine the impact of downlink rate on the connectivity. We can learn from Fig. 2 that the connectivity performance of Given-power is identical with the Optimal, which validates our approach to optimize the transmit power. In addition, BEP has close performance to Optimal and Given-

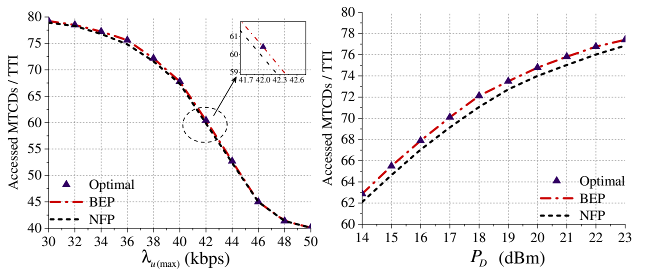


(a) $\xi = 1$



(b) $\xi = 0.9$

Fig. 2. Number of accessed devices (in curve) and pairs (in histogram) versus $\lambda_{d(max)}$. $\bar{\lambda}_u$ is set to 47 kbps.



(a) (b)

Fig. 3. Number of accessed devices versus $\lambda_{u(max)}$ and P_D, when $\xi = 0$.

power w.r.t. the accessed MTCDs, and for some cases, BEP has better performance than Optimal and Given-power w.r.t. the accessed pairs. This is because that, in BEP, pairing is our primary goal. Besides, the performance of BEP surpasses both the celebrated NFP and R-NFP. For example, at $\xi = 1$, BEP accesses up to 15% more devices compared to NFP.

In Fig. 3, we show the impact of uplink transmission rate and uplink transmit power on the connectivity when $\xi = 0$. The uplink transmission rate $\bar{\lambda}_u$ is randomly and uniformly distributed in the range $(28, \lambda_{u(max)})$. From Fig. 3, we learn that, when $\xi = 0$, the performance of BEP overlaps with Optimal and outperforms the conventional method NFP.

VI. Conclusions

In this paper, we considered a high density IIoT which provides two distinct services. We leveraged non-orthogonal network slicing to facilitate the system and aim to maximize the number of accessed MTCDs. We formulated the optimization problem as an MINLP and proposed a series of approaches to solve it, e.g., the low-complexity best-effort pairing algorithm. In the future, we will extend our approach to the system with multiple service types and multiple antennas.

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