Peer-to-Peer Packet Dispatching for Multi-Router Local Area Packetized Power Networks

Hongliang Zhang, *Student Member, IEEE*, Lingyang Song, *Fellow, IEEE*, Yonghui Li, *Fellow, IEEE*, and H. Vincent Poor, *Fellow, IEEE*

***Abstract*—With a large penetration of distributed energy resources, DC power packet transmission has emerged as a promising technique to achieve efficient peer-to-peer (P2P) power dispatching. In this paper, a multirouter local area packetized power network (LAPPN) is considered, consisting of multiple power routers employed to dispatch power packets among demander and supplier subscribers connected to different routers. To realize the efficient P2P power transmission in the LAPPN, a power packet dispatching protocol is developed to determine the optimal routes for power packets to maximize the power packets utilization efficiency. The transmission schedule is then determined by allocating different power packets on different power channels simultaneously to accommodate the urgency requirements of different demander energy subscribers (ESs). Simulation results demonstrate the effectiveness of the proposed LAPPN power dispatching protocols in achieving high power packet utilization and meeting the urgency requirements of different demander ESs in P2P power delivery.**

***Index Terms*—Packetized-power network, multi-router, P2P power packet dispatching protocol, routing, scheduling.**

I. Introduction

A KEY feature in future smart grids is the large penetration of distributed energy resources (DERs) [3]. Energy subscribers (ESs) can control their energy needs with modular DERs through a standardized plug-and-play interface [2]. This enables energy sharing among the distributed ESs via flexible peer-to-peer (P2P) power dispatching to achieve demand-and-supply balance, thus alleviating the demand load fluctuation to the utility grid [4] and reducing wasted power consumption [5].

Manuscript received December 22, 2017; revised June 29, 2018 and October 27, 2018; accepted December 17, 2018. Date of publication January 4, 2019; date of current version August 21, 2019. This work was supported in part by the National Natural Science Foundation of China under Grant 61625101, and in part by the U.S. National Science Foundation under Grant ECCS-1824710. Part of this work has been presented at the 2018 IEEE Global Communications Conference [1]. Paper no. TSG-01879-2017. *(Corresponding author: Lingyang Song.)*

H. Zhang and L. Song are with the National Engineering Laboratory for Big Data Analysis and Applications, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China (e-mail: hongliang.zhang@pku.edu.cn; lingyang.song@pku.edu.cn).

Y. Li is with the School of Electrical and Information Engineering, University of Sydney, Sydney, NSW 2006, Australia (e-mail: yonghui.li@sydney.edu.au).

H. V. Poor is with the Department of Electrical Engineering, Princeton University, Princeton, NJ 08544 USA (e-mail: poor@princeton.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2019.2890975

In the literature, P2P energy dispatching is categorized into two types according to the operation of currents, i.e., AC and DC. In the current AC power grids, various techniques have been developed to achieve P2P energy sharing. For example, the FREEDM architecture was proposed in [2] to integrate plug-and-play DERs and enable P2P energy sharing. A distributed coordinated control method was designed to provide accurate power sharing and reduce circulating currents in [6]. A graph theory based routing algorithm was proposed for power transmission in [7]. As the energy consumption behaviors of ESs can be dynamically changing, it is necessary to manage the energy to utilize DERs more efficiently, especially when the DERs' capacity is limited. Reference [8] investigated the cooperative energy transportation and storage for future usage. A pricing based scheme was developed in [9] to achieve efficient distributed energy management.

In addition to energy dispatching, information exchange is also necessary for stable operations. Advanced metering infrastructure (AMI) is a typical way to create communication networks among the ESs and the utility grid (UG) [10]. According to the data rate and communication range, the communication networks can be categorized into three types: wide-area networks (WANs), neighborhood-area networks (NANs), and home-area networks (HANs) [11]. Therefore, it is important for the AMI to satisfy the various communication requirements, such as security, reliability, and Quality-of-Service (QoS) [12]. Reference [13] discussed a hierarchical communication system to reduce the control messages and the bandwidth required of WANs.

However, since most DERs have DC outputs [14], incorporation of a large number of DERs brings new challenges for steady and efficient operation of AC power grids. To tackle these challenges, DC P2P power dispatching is considered where the information is transmitted together with the energy. The concept of an open-electric-energy network (OEEN) was first proposed in [15]. In an OEEN, the energy is transmitted in power packets tagged with information about the transmitter and the receiver. Following the pioneering work on OEEN, an in-home DC packetized power distribution system was proposed in [16] and extended to a generalized DC power packet distribution network in [17]. As the key component of the power packet distribution network, the power router was designed and experimentally verified in [5] and [18] to realize P2P power dispatching. Reference [19] extended the work in [15] and proposed a local area packetized power network (LAPPN) with a power router, where multiple demander and supplier ESs are matched into pairs, and interchange power packets simultaneously via the router. A time division multiplex (TDM) based dispatching protocol was proposed to balance the load and generation.

However, existing works considered the scheduling and dispatching of power only among supplier and demander ESs connected to the same router. In this paper, we consider a more general setting consisting of multiple supplier and demander ESs as well as multiple routers. To improve the utilization of the power packets, we optimize the flows of power packets in the whole network by allowing the power packets to interchange in the whole network through different routers. That is, power packets can be transmitted among different ESs connected to different routers. The routers need to determine the demander ES of a power packet based on the demand requirements, select the optimal route from the supplier ES to the demander ES, and allocate the proper power channel for each packet at the same time. This is different from the work in [19] where a single router controls the pairing between supplier and demander ESs. Since the power packet transmission among routers is enabled, the scheduling of the power channel in one router will affect the packets to be scheduled in neighboring routers. The scheduling among different routers is coupled, and thus regulating the transmission of a multi-router LAPPN is very challenging. Therefore, it is necessary to develop an efficient power dispatching protocol for multi-router LAPPNs.

In this paper, we consider an LAPPN with multiple power routers connected to different ESs and also to the UG to realize P2P power packet transmission. We develop an efficient power packet dispatching protocol in the LAPPN. Our contributions are summarized below.

- We propose a packetized power dispatching protocol consisting of four steps, i.e., registration, routing, scheduling, and transmission, to realize the efficient regulation of an LAPPN.
- We formulate the routing problem to maximize the power packets' utilization efficiency of the whole network. We show that it is an NP hard problem. To solve it efficiently, we propose a branch-and-bound (BB) method based on continuous relaxation [21].
- To meet the urgency requirements of different demander ESs and allow multiple power packets to transmit on different power channels simultaneously, we formulate the scheduling problem as a two-dimensional geometric knapsack (2D-GK) problem [20] and develop a dynamic programing (DP) based algorithm to solve it.
- Simulation results demonstrate the effectiveness of the proposed scheme in achieving more energy usage by demander ESs and meeting the urgency requirements of different demander ESs in P2P power delivery.

The rest of this paper is organized as follows. In Section II, we introduce the LAPPN architecture and power transmission model. In Section III, a packetized power dispatching protocol is proposed. Power packet routing and scheduling problems are considered in Sections IV and V, respectively. Simulation results and discussions are presented in Section VI. Finally, Section VII concludes this paper.

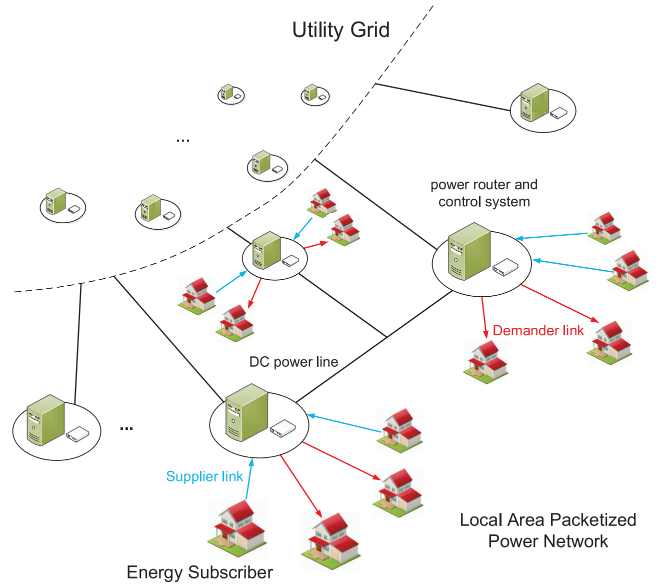


Fig. 1. Illustration of a multi-router LAPPN.

II. System Model

In this section, we present the multi-router LAPPN configuration and mathematical model.

A. Configuration

As presented in Fig. 1, the multi-router LAPPN consists of R power routers that are connected via DC power lines, denoted by $\mathcal{R} = \{1, \dots, R\}$. Each power router is equipped with a controller that can process the trading and operating information and control the power dispatching. In addition, each router is connected to the UG[1] and to some ESs which are equipped with DERs and batteries.[2] These ESs can be divided into two classes: S supplier ESs, denoted by $\mathcal{S} = \{1, \dots, S\}$, and D demander ESs, denoted by $\mathcal{D} = \{1, \dots, D\}$. We define $\mathcal{N}_i$ as the set of nodes connected to node i, $i \in \mathcal{S} \cup \mathcal{R} \cup \mathcal{D}$, where

$$j \begin{cases} \in \mathcal{N}_i, & \text{node } j \text{ is connected to node } i, \\ \notin \mathcal{N}_i, & \text{otherwise.} \end{cases} \tag{1}$$

We use the term power channel to describe the power lines in the router to transmit power between two ESs. Power channel operates in a TDM manner, i.e., a power channel can deliver one packet at a time. Multiple power packets can transmit on different power channels at same time as long as they are not transmitted from the same supplier or sent to the same demander. We further assume that power router r has K_r power channels to support the power packet transmissions between the router and its connected demander ESs, denoted by $\mathcal{K}_r = \{1, \dots, K_r\}$. In addition, there also exit K'_r power channels to support power transmission between two routers, denoted by $\mathcal{K}'_r = \{1, \dots, K'_r\}$.

[1]Although the LAPPN is a DC power packet distribution network, the UG can be operated by either DC or AC. If the UG is an AC power distribution system, the generated power needs to go through the DC/AC conversion when it enters the UG.

[2]Since the generated power packet cannot be transmitted immediately, the energy will be stored in its corresponding battery for future usage.

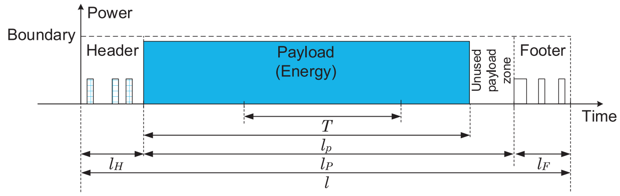


Fig. 2. Structure of the power packet.

Each ES has an unique IP address and communicates with the connected router independently. They transmit power packets tagged with the respective address information of demander ESs to the router. The router allocates a power channel for this transmission, and then forwards the packet to the corresponding demander ES or to the adjacent router towards the target demander ES according to the tagged address. The demander ES receives the power packet to store or consume the energy.

B. Power Packet Structure

As presented in Fig. 2, a power packet is a voltage wave, with a header, a payload, and a footer. A header, at the beginning of the power packet, consists of a start signal and the addresses of the supplier and the demander ESs. A payload carries transmitted energy. The footer includes a mark at the end of power packet. Moreover, the electric power and the information are transmitted together in a power packet over the same power line at the same velocity for synchronization.

In addition, the transmission is slotted into time slots with the time length T. Let l denote the time duration of a power packet, we have $l = nT$, where n is a positive integer with $n \leq N^{max}$. Let l_H and l_F respectively be the time duration of the header and the footer, which are fixed in a power packet. The voltage and time duration of the payload can be flexible. Let l_p be the duration for the payload and l_P be the maximum payload duration. To transmit efficiently, the unused payload zone needs to be less than a slot, i.e., $l_P - l_p < T$. Therefore, a standard power packet satisfies $l = l_H + l_P + l_F = nT$ and $0 \leq l_P - l_p < T$. In this paper, we define t_s^r as the power packet length for supplier ES s^r.

C. Power Transmission

Let p_s^{exp} and p_d^{rec} denote the export power of supplier s and the received power of demander ES d. Let p_{max} be the maximum capacity of a power channel. Therefore, they satisfy $p_d^{rec} < p_s^{exp} \leq p^{max}$. In this paper, we assume that the exported power is always less than the maximum capacity of power channel for all supplier ESs.

We use $\epsilon_{s,d}$ to denote the transmission loss factor from node s to node d. For simplicity, we do not consider the power loss due to router forwarding, and thus, the received power can be expressed by $p_d^{rec} = p_s^{exp}(1 - \epsilon_{s,d})$.

III. Power Packet Dispatching Protocol

The power packet transmission consists of four steps: registration, routing, scheduling, and transmission. In the registration step, the ES registers on the trading platform as a demander or supplier. Note that a power packet might be transmitted to the demander ESs which are connected to the neighboring router, and thus, in the routing step, the controller needs to determine the received demander ES and the intermediate passing routers towards the demander ES. Besides, the limited power channels are the bottleneck in time scheduling, therefore, the routers also need to allocate the power channels in the scheduling step. In the transmission step, the routers will forward the power packets according to the tagged IP and the scheduling results.

To realize an efficient power dispatching over time, routing, scheduling, and transmission are performed in three sequential cycles, and each cycle contains C time slots. The routing and scheduling are performed in the first time slot of a cycle and the transmission will occupy the whole cycle, as illustrated in Fig. 3.

A. Registration

ESs that demand or supply energy need to register on the centralized trading and control platform as demanders or suppliers. For supplier ES s, it needs to report the exported energy E_s^{exp}, and for demander ES d, it also needs to report its demanded energy range $[E_d^{min}, E_d^{max}]$. Besides, demander ES d needs to inform the trading platform of an urgency factor $\kappa_0(d) \geq 1$ which indicates its urgency for buying power packets, and supplier ES s needs to inform the platform of a factor $\vartheta(s) \geq 1$ which indicates its willingness to sell power packets. $\kappa_0(d)$ can be regarded as the cost that the demander ES can offer to buy power packet s,[3] and $\vartheta(s)$ can be regarded as the price to sell power packet s.

B. Routing

We assume that the controller has all the information of the routers and ESs, such as the topology connections and the transmission loss factors among the routers and ESs. The supplier ESs will send requests to the router before transmission. The controller needs to determine which demander ES is matched with the supplier ES based on the network information and the requests in the last cycle. If the paired demander ES is not connected to the same router as the supplier ES, the controller also needs to plan the transmission route to maximize the total received energy. The routing problem will be formulated and solved in Section IV.

C. Scheduling

The scheduling for power packets is performed by each router individually. When the routes of the requested power packets are determined, the router will schedule these power packets according to the mechanism which will be introduced in Section V. However, the total power channels may not be sufficient to schedule all the power packets. Then the unscheduled power packets need to wait for the next scheduling cycle. If all the power packets have been scheduled, these power channels can also be used to support power interchange between some demander ESs and the UG.

[3]For simplicity, a power packet from supplier ES s is called power packet s.

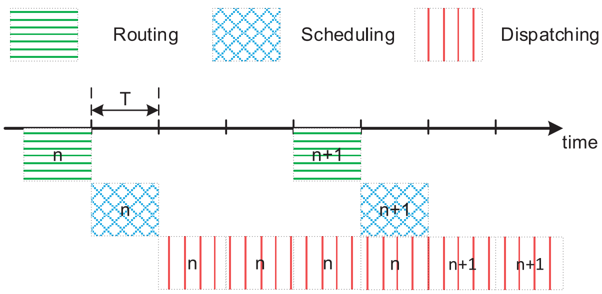


Fig. 3. Real-time scheduling for LAPPN.

D. Transmission

After the controller solves the dispatching route information, the results will be sent to the supplier ESs and the routers. The supplier ES will tag the IP information to the header of its power packet. The routers will maintain a routing table and dispatch the power packets over the allocated power channel according to the routing table.

IV. Power Packet Routing

In this section, we first formulate the power packet routing problem, and then utilize the branch-and-bound (BB) method with continuous relaxation to solve it.

A. Problem Formulation

Note that not all the demands of the demander ESs can be satisfied, thus, some demander ESs may utilize the power from the UG. In addition, the generated power packets may not be utilized fully by the supplier ES, and therefore, the supplier ES can sell the power to the UG as well. We define selection vector $z = [z_d]$ to represent whether demander ES d utilizes the power from the UG, where

$$z_d = \begin{cases} 0, & \text{ES } d \text{ utilizes the power from the UG,} \\ 1, & \text{ES } d \text{ utilizes the power from supplier ESs.} \end{cases} \quad (2)$$

Further, define a routing matrix $\boldsymbol{X}_{S\times(S+R)\times(R+D)} = [x^s_{i,j}]$ to indicate whether packet s goes through link $i-j$, where

$$x^s_{i,j} = \begin{cases} 1, & \text{power packet } s \text{ goes through link } i-j, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

Thus, the received energy from power packet s can be expressed as

$$E^{rec}_s = E^{exp}_s \prod_{\substack{i\in\mathcal{S}\cup\mathcal{R},\\ j\in\mathcal{D}\cup\mathcal{R}}} \left(1-\epsilon_{i,j}\right)^{x^s_{i,j}}. \quad (4)$$

Likewise, we define a supplier-demander pair matching matrix $\boldsymbol{Y}_{S\times D} = [y^s_d]$ to indicate whether node d is the demander ES of packet s. Specifically,

$$y^s_d = \begin{cases} 1, & \text{power packet } s \text{ is sent to demander ES } d, \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

Note that in a router, the incoming degree is always equal to the outgoing one. Besides, the incoming degree for a supplier ES is equal to the number of supplier-demander pairs. Therefore, we have the following constraints:

$$\sum_{j\in\mathcal{N}_r} x^s_{j,r} - \sum_{j\in\mathcal{N}_r} x^s_{r,j} = 0, \forall r \in \mathcal{R}, s \in \mathcal{S}, \quad (6)$$

$$\sum_{j\in\mathcal{N}_d} x^s_{j,d} = y^s_d, \forall d \in \mathcal{D}, s \in \mathcal{S}. \quad (7)$$

Moreover, a power packet can only be delivered to at most one selected demander ES. That is to say,

$$\sum_{i\in\mathcal{D}} y^s_d \le 1, \forall s \in \mathcal{S}. \quad (8)$$

Finally, the received energy needs to satisfy the demand of the demander ES. That is, the received energy needs to satisfy

$$E^{min}_d z_d \le \sum_{s\in\mathcal{S}} E^{rec}_s y^s_d \le E^{max}_d z_d, \forall d \in \mathcal{D}. \quad (9)$$

Our objective is to maximize the total received energy by optimizing z_d and $x^s_{i,j}$. Thus, the optimization problem is formulated as

$$\text{P1:} \ \underset{\boldsymbol{X};z}{\text{maximize}} \sum_{s\in\mathcal{S}} E^{rec}_s \sum_{d\in\mathcal{D}} y^s_d, \quad (10a)$$

$$\text{s.t.} \ \sum_{j\in\mathcal{N}_r} x^s_{j,r} - \sum_{j\in\mathcal{N}_r} x^s_{r,j} = 0, \forall r \in \mathcal{R}, s \in \mathcal{S}, \quad (10b)$$

$$\sum_{d\in\mathcal{D}} y^s_d \le 1, \forall s \in \mathcal{S}, \quad (10c)$$

$$E^{min}_d z_d \le \sum_{s\in\mathcal{S}} E^{rec}_s y^s_d \le E^{max}_d z_d, \forall d \in \mathcal{D}, \quad (10d)$$

$$x^s_{i,j}, z_d \in \{0, 1\}, \quad (10e)$$

where E^{rec}_s is defined in (4) and y^s_d is given in (7). Constraints (10b) correspond to the flow constraints in (6). Constraints (10c) imply that one power packet can be sent only to one demander ES. Constraints (10d) are the demand requirements for the demander ESs.

B. Algorithm Design

Problem (P1) is a 0-1 program, which has been proved to be NP-hard [22]. To solve this problem, we utilize the BB algorithm. The key idea of the BB algorithm is to split the feasible region into smaller ones and eliminate those that will not contain an optimal solution. To be specific, each feasible region has an upper bound of the objective function, the search will keep track of the region with the largest upper bound and skip the others. In what follows, we will elaborate on how to calculate the bound and perform branching.

1) Bound Calculation: Relax the binary variables $x^s_{i,j}$ and z_d to continuous values in [0, 1], and thus, problem (P1) can be rewritten as

$$\text{P2:} \ \underset{\boldsymbol{X};z}{\text{maximize}} \sum_{s\in\mathcal{S}} E^{rec}_s \sum_{d\in\mathcal{D}} y^s_d, \quad (11a)$$

$$\text{s.t.} \ \sum_{j\in\mathcal{N}_r} x^s_{j,r} - \sum_{j\in\mathcal{N}_r} x^s_{r,j} = 0, \forall r \in \mathcal{R}, s \in \mathcal{S}, \quad (11b)$$

$$\sum_{d\in\mathcal{D}} y^s_d \le 1, \forall s \in \mathcal{S}, \quad (11c)$$

$$E_d^{min} z_d \le \sum_{s\in\mathcal{S}} E_s^{rec} y_d^s \le E_d^{max} z_d, \forall d \in \mathcal{D}, \quad (11d)$$

$$x_{i,j}^s, z_d \in [0, 1]. \quad (11e)$$

As the solution of problem (P1) is also a feasible solution of problem (P2), the optimal solution of problem (P2) provides an upper bound for problem (P1). On the other hand, since the terms $E_s^{rec} y_d^s$ are concave functions, problem (P2) is a convex problem, and the optimal solution can be obtained by Lagrange dual method [23]. That is, we can solve problem (P2) through maximizing its Lagrangian function and minimizing the corresponding dual function.

Let $\boldsymbol{\eta} = [\eta_r^s], \boldsymbol{\theta} = [\theta^s]$, and $\boldsymbol{\lambda} = [\lambda_d^l, \lambda_d^u]$ be the vectors of the Lagrangian dual variables corresponding to constraints (11b), (11c), and (11d), respectively. Therefore, the Lagrangian of the primal objective function is given by

$$\begin{aligned} L(\boldsymbol{\eta}, \boldsymbol{\theta}, \boldsymbol{\lambda}) = &\sum_{s\in\mathcal{S}} E_s^{rec} \sum_{d\in\mathcal{D}} y_d^s + \sum_{s\in\mathcal{S}} \theta^s \left(\sum_{d\in\mathcal{D}} y_d^s - 1 \right) \\ &+ \sum_{s\in\mathcal{S}} \sum_{r\in\mathcal{S}\cup\mathcal{R}\cup\mathcal{D}} \left(\sum_{j\in\mathcal{N}_r} x_{j,r}^s - \sum_{j\in\mathcal{N}_r} x_{r,j}^s \right) \\ &+ \sum_{d\in\mathcal{D}} \lambda_d^l \left(-\sum_{s\in\mathcal{S}} E_s^{rec} y_d^s + E_d^{min} z_d \right) \\ &+ \sum_{d\in\mathcal{D}} \lambda_d^u \left(\sum_{s\in\mathcal{S}} E_s^{rec} y_d^s - E_d^{max} z_d \right). \end{aligned} \quad (12)$$

The Lagrangian dual function can be given by

$$\begin{aligned} D(\boldsymbol{\eta}, \boldsymbol{\theta}, \boldsymbol{\lambda}) = &\max_{\boldsymbol{X}, z} L(\boldsymbol{\eta}, \boldsymbol{\theta}, \boldsymbol{\lambda}) \\ s.t. \quad & x_{i,j}^s, z_d \in [0, 1], \end{aligned} \quad (13)$$

and the dual problem is given by

$$\begin{aligned} \max_{\boldsymbol{\eta}, \boldsymbol{\theta}, \boldsymbol{\lambda}} \quad & D(\boldsymbol{\eta}, \boldsymbol{\theta}, \boldsymbol{\lambda}) \\ s.t. \quad & \eta_r^s, \theta^s, \lambda_d^l, \lambda_d^u \ge 0. \end{aligned} \quad (14)$$

Based on the Karush-Kuhn-Tucker conditions, we have

$$\left(x_{i,j}^s\right)^* = \left[\frac{\ln\left(\frac{\theta_s \rho_{i,j} \chi_j + \left(\lambda_j^s - \lambda_i^s\right) \rho_{i,j}}{\left(\lambda_d^l - \lambda_d^u - 1\right) \ln\left(1 - \epsilon_{i,j}\right) \sum_{d\in\mathcal{D}} y_d^s} \right)}{\ln\left(1 - \epsilon_{i,j}\right)} \right]^+, \quad (15)$$

$$(z_d)^* = \min\left\{ \frac{\sum_{s\in\mathcal{S}} E_s^{rec} y_d^s}{\lambda_d^l E_d^{min}}, 1 \right\}. \quad (16)$$

and

$$\lambda_d^l E_d^{min} = \lambda_d^u E_d^{max}, \quad (17)$$

where $[x]^+ = \max\{x, 0\}$,

$$\rho_{i,j} = \begin{cases} 1, & i \in \mathcal{N}_j, \\ 0, & \text{otherwise}, \end{cases} \quad (18)$$

and

$$\chi_j = \begin{cases} 1, & j \in \mathcal{D}, \\ 0, & \text{otherwise}. \end{cases} \quad (19)$$

We also substitute (17) into the Lagrangian function and eliminate λ_d^u to reduce the computational complexity.

To obtain the optimal primal solution, the dual variables are then iteratively computed by using the subgradient method [24], i.e.,

$$\left(\eta_r^s\right)^{(n+1)} = \left[\left(\eta_r^s\right)^{(n)} + \xi^{(n)}\left(\eta_r^s\right) \nabla^{(n+1)}\left(\eta_r^s\right) \right]^+, \quad (20)$$

$$\left(\theta^s\right)^{(n+1)} = \left[\left(\theta^s\right)^{(n)} + \xi^{(n)}\left(\theta^s\right) \nabla^{(n+1)}\left(\theta^s\right) \right]^+, \quad (21)$$

$$\left(\lambda_d^l\right)^{(n+1)} = \left[\left(\lambda_d^l\right)^{(n)} + \xi^{(n)}\left(\lambda_d^l\right) \nabla^{(n+1)}\left(\lambda_d^l\right) \right]^+, \quad (22)$$

where n is the iteration index, $\xi^{(n)}(\eta_r^s)$, $\xi^{(n)}(\theta^s)$, and $\xi^{(n)}(\lambda_d^l)$ are the step sizes at the n-th iteration to guarantee convergence, respectively. $\nabla^{(n+1)}(\eta_r^s)$, $\nabla^{(n+1)}(\theta^s)$, and $\nabla^{(n+1)}(\lambda_d^l)$ are the subgradients of the dual function, which are given by

$$\nabla^{(n+1)}\left(\eta_r^s\right) = \sum_{j\in\mathcal{N}_r} \left(x_{j,r}^s\right)^{(n)} - \sum_{j\in\mathcal{N}_r} \left(x_{r,j}^s\right)^{(n)}, \quad (23)$$

$$\nabla^{(n+1)}\left(\theta^s\right) = \sum_{d\in\mathcal{D}} \left(y_d^s\right)^{(n)} - 1, \quad (24)$$

$$\nabla^{(n+1)}\left(\lambda_d^l\right) = E_d^{min} (z_d)^{(n)} - \sum_{s\in\mathcal{S}} \left(E_s^{rec}\right)^{(n)} \left(y_d^s\right)^{(n)}. \quad (25)$$

2) Branching Algorithm: The algorithm consists of branching variable and branching node selections. In branching variable selection, we will determine which variable to recover from the relaxed value. The basic idea is to select the variable with the largest difference between the relaxed value and the boundary. In this way, we can find a tighter bound on the objective function value so that more nodes can be pruned. The rule of branching variable v selection can be expressed as

$$v = \arg\max_{x_{i,j}^s \in \boldsymbol{X}, z_d \in \boldsymbol{z}} \left\{ \min\left\{1 - x_{i,j}^s, x_{i,j}^s\right\}, \min\{1 - z_d, z_d\} \right\}. \quad (26)$$

The branching node selection selects a node for generating new subproblems, i.e., it determines whether the selected variable v is 0 or 1. Suppose E_0 and E_1 are the upper bounds for nodes $v = 0$ and $v = 1$, respectively. The upper bounds E_0 and E_1 can be obtained by solving problem (P2) with constraints $v \le 0$ and $v \ge 1$, respectively. We define the upper bound to be negative if the problem does not have a feasible solution. If $E_0 < E_1$, we will update problem (P2) by adding a constraint $v \ge 1$. Otherwise, we will update problem (P2) by adding a constraint $v \le 0$. We will repeat the aforementioned steps until all the variables are integral.

The overall procedure of the power packet routing algorithm is summarized in Algorithm 1.

Remark 1: The power packet routing algorithm needs to solve at most $S * (R + S) * (R + D) + 1$ problems (P2).

Remark 1 implies that the computational complexity will increase quickly as the number of ESs. Therefore, we provide the following four propositions to accelerate the branching algorithm.

Proposition 1: If the relaxed value $z_d \le \frac{E_{min}^d}{E_{max}^d}$, then we have $z_d = 0$.

Proof: See in the Appendix. ■

Algorithm 1 Power Packet Routing Algorithm

Input: Supplier ESs $\mathcal{S}$; demander ESs $\mathcal{D}$; transmission loss factor $\epsilon_{s,d}$; exported energy E_s^{exp};

Output: Routing matrix $\boldsymbol{X}$; Selection vector $\boldsymbol{z}$;

1: Solve problem (P2) to obtain the initial solution;
2: **repeat**
3: Select the branching variable v according to (26);
4: Calculate the upper bounds E_0 and E_1 by solving problem (P2) with constraints $v \leq 0$ and $v \geq 1$, respectively;
5: If $E_0 > E_1$, update problem (P1) by adding a constraint $v \leq 0$, and adding a constraint $v \geq 1$ otherwise;
6: **until** All elements in $\boldsymbol{X}$ and $\boldsymbol{z}$ are integer.

Proposition 2: For power packet s, if $x_{s,r}^s = 0, \forall r \in \mathcal{R}$, then we have $x_{i,j}^s = 0, \forall i \in \mathcal{S} \cup R, j \in \mathcal{D} \cup R$.

Proposition 3: For power packet s and router r, there exist at most one d which satisfies $x_{r,d}^s = 1$.

Proposition 4: For power packet s and router r, if $x_{r,r'}^s = 1$, $r' \in \mathcal{R}$, then $x_{r,d}^s = 1, \forall d \in \mathcal{D}$.

Propositions 2, 3, and 4 are the direct derivations from the network topology. Since the power packet cannot be split to two smaller one, there exists at most one route for one power packet.

V. Power Packet Scheduling

In this section, we first formulate the packet scheduling problem and then propose a DP based algorithm to solve the scheduling problem.

A. Problem Formulation

Scheduling is performed by each router individually. For each router, there are two kinds of power channels: (1) intra-router power channels, which support the transmission between the router and its connected demander ESs; (2) inter-router power channels, which support the transmission among routers. If the supplier and demander ESs are connected to the same router, their power packets require only intra-router channels for transmission. The transmission between two routers requires an inter-router channel, and the second router will assign another channel to the power packet for its next hop transmission.

The objective of the controller is to schedule the power as much as possible in one cycle, and thus, it tries to schedule the power packets with more energy first. On the other hand, it also needs to consider the urgent requests of some demander ESs and the fairness of scheduling of these supplier ESs. To evaluate this, we design a utility model for each power packet, and derive the scheduling problem according to the model.

Define the set of demander ESs that utilize the power from supplier ESs by $\mathcal{D}'$, i.e., $\mathcal{D}' = \{d | z_d = 1\}$, and the set of supplier ESs that sell power to demander ESs by $\mathcal{S}'$, i.e., $\mathcal{S}' = \{s | \sum_{d \in \mathcal{D}} y_d^s = 1\}$. Let $d(s)$ denote the paired supplier ES for power packet s. For power packet s, we define the utility function $u(s)$ to be proportional to the received energy. Also, power packets with higher urgency of buying and willingness of selling have a higher priority.

It is worthwhile to mention that to ensure fairness and ensure that the packets with low priority have transmission opportunities, the urgency factor of an unscheduled power packet will increase in the next scheduling cycle. When the power channels are insufficient for scheduling power packets, the packets with low energy need to wait for a long time to be scheduled. Therefore, we define the urgency factor $\kappa(d(s)) = (1+\alpha)^\tau \kappa_0(d(s))$, where τ is the number of waiting cycles and α is the increased urgency factor. Therefore, $u(s)$ can be expressed as

$$u(s) = \frac{\kappa(d(s))}{\vartheta(s)} E_s^{rec}, \forall s \in \mathcal{S}'. \tag{27}$$

Let $\mathcal{A}^r$ and $\mathcal{B}^r$ denote the set of power packets transmitting on intra-router and inter-router channels for router r, where $\mathcal{A}^r, \mathcal{B}^r \subset \mathcal{S}'$. In addition, define the channel allocation matrix $\boldsymbol{\Omega} = [\omega_{s,k}]$ to indicate whether packet s is transmitted on channel k, where

$$\omega_{s,k} = \begin{cases} 1, & \text{packet } s \text{ transmits on channel } k, \\ 0, & \text{otherwise.} \end{cases} \tag{28}$$

Since one packet can be transmitted only on at most one channel, we have

$$\sum_{k \in \mathcal{K}_r \cup \mathcal{K}_r'} \omega_{s,k} \leq 1, \forall s \in \mathcal{A}^r \cup \mathcal{B}^r. \tag{29}$$

Likewise, define a time slot allocation matrix $\boldsymbol{\Phi} = [\phi_{s,t}]$ to indicate whether packet s occupies slot t, where

$$\phi_{s,t} = \begin{cases} 1, & \text{packet } s \text{ transmits on slot } t, \\ 0, & \text{otherwise.} \end{cases} \tag{30}$$

Let T_s denote the duration for power packet s; as the power packets require continuous time slots for transmission, we have the following constraints:

$$\sum_{t=0}^{C} |\phi_{s,t+1} - \phi_{s,t}| = 2 \sum_{k \in \mathcal{K}_r \cup \mathcal{K}_r'} \omega_{s,k}, \forall s \in \mathcal{A}^r \cup \mathcal{B}^r, \tag{31}$$

$$\sum_{k \in \mathcal{K}_r \cup \mathcal{K}_r'} \sum_{t=1}^{C} \phi_{s,t} \omega_{s,k} = T_s, \forall s \in \mathcal{A}^r \cup \mathcal{B}^r, \tag{32}$$

where we define $\phi_{s,0} = 0, \phi_{s,C+1} = 0$.

Based on this notation, the scheduling problem can be expressed as

$$\text{P3:} \ \underset{\boldsymbol{\Omega};\boldsymbol{\Phi}}{\text{maximize}} \sum_{s \in \mathcal{A}^r} u(s) \sum_{k \in \mathcal{K}_r} \omega_{s,k} + \sum_{s \in \mathcal{B}^r} u(s) \sum_{k \in \mathcal{K}_r'} \omega_{s,k}, \tag{33a}$$

$$s.t. \quad \sum_{k \in \mathcal{K}_r \cup \mathcal{K}_r'} \omega_{s,k} \leq 1, \forall s \in \mathcal{A}^r \cup \mathcal{B}^r, \tag{33b}$$

$$\sum_{t=0}^{C} |\phi_{s,t+1} - \phi_{s,t}| = 2 \sum_{k \in \mathcal{K}_r \cup \mathcal{K}_r'} \omega_{s,k}, \forall s \in \mathcal{A}^r \cup \mathcal{B}^r, \tag{33c}$$

$$\sum_{k \in \mathcal{K}_r \cup \mathcal{K}_r'} \sum_{t=1}^{C} \phi_{s,t} \omega_{s,k} = T_s, \forall s \in \mathcal{A}^r \cup \mathcal{B}^r. \tag{33d}$$

Constraints (33b), (33c), and (33d) correspond to (29), (31), and (32), respectively.

B. Algorithm Design

From problem (P3), we can observe that the scheduling problems on intra-router and inter-router channels are independent and has the same form. Therefore, we can decompose problem (P3) into two subproblems and solve them in parallel. In what follows, we only introduce how to solve the scheduling subproblem on intra-router channels for simplicity, which is listed below:

$$\text{P4:}\ \underset{\mathbf{\Omega};\mathbf{\Phi}}{\text{maximize}} \sum_{s\in\mathcal{A}^r} u(s) \sum_{k\in\mathcal{K}_r} \omega_{s,k}, \tag{34a}$$

$$s.t. \quad \sum_{k\in\mathcal{K}_r} \omega_{s,k} \le 1, \forall s \in \mathcal{A}^r, \tag{34b}$$

$$\sum_{t=0}^{C} |\phi_{s,t+1} - \phi_{s,t}| = 2 \sum_{k\in\mathcal{K}_r} \omega_{s,k}, \forall s \in \mathcal{A}^r, \tag{34c}$$

$$\sum_{k\in\mathcal{K}_r} \sum_{t=1}^{C} \phi_{s,t}\omega_{s,k} = T_s, \forall s \in \mathcal{A}^r. \tag{34d}$$

When we regard the channels and time slots as two dimensions in a plane, the problem (P4) can be reformulated as a 2D-GK problem.

Definition 1: From a set of blocks $\mathcal{A}^r$, each with utility $u(s)$, the optimization problem (P4) is to find a subset of blocks together with their locations $\mathcal{O}(s)$ in the channel-time grid $\mathcal{G}$ to maximize the total utilities, i.e.,

$$\text{P5:}\ \underset{\sigma}{\text{maximize}} \sum_{s\in\mathcal{A}^r} u(s)\sigma(s), \tag{35a}$$

$$s.t. \quad \bigcup_{s} \mu(\sigma(s)) \subseteq \mathcal{G}, \tag{35b}$$

$$\mu(\sigma(s_1)) \cap \mu(\sigma(s_2)) = \emptyset, s_1 \ne s2, \tag{35c}$$

$$\sigma(s) \in \{0, 1\}, \tag{35d}$$

where

$$\mu(\sigma(s)) = \begin{cases} \mathcal{O}(s), & \sigma(s) = 1, \\ \emptyset, & \sigma(s) = 0. \end{cases} \tag{36}$$

and

$$\mathcal{G} = [0, K_r] \times [0, C], \mathcal{O}(s) = \big[f_s, f_s + 1\big] \times [t_s, t_s + T_s]. \tag{37}$$

Constraint (35b) indicates that block locations cannot exceed the dimensions of the grid $\mathcal{G}$, and constraint (35c) implies that overlapping between any two blocks is not allowed. The constraint (35d) indicates whether a block is selected.

Since the 2D-GK problem is NP-hard [25], we propose a DP based algorithm [26] to solve it efficiently. Note that each power packet can utilize only one channel, and thus, the channel dimension of each block is one. In addition, different channels are independent. Therefore, we can divide the plane into K_r channels and maximize the total utilities for each channel. In this way, we can decompose the 2D-GK problem to K_r one dimensional knapsack problems (KPs) and solve these KPs successively.

Algorithm 2 Power Packet Scheduling Algorithm

Input: The set of blocks $\mathcal{A}^r$; the number of channels K_r; the number of time slots for one cycle C;
Output: Selection matrix $\sigma_k(l)$;

```
Initialize π = A^r, k = 1;
repeat
    Initialize F^k(l, b) = 0, 1 ≤ l ≤ |A^r|, 1 ≤ b ≤ C.
    Update F^k(l, b) according to (38) for all l ∈ π and b;
    Calculate the optimal solution σ*_k(l) using (39);
    k = k + 1;
until k = K_r;
```

Define π as the set of available blocks, $F^k(l, b)$ as the optimal value for channel k with the first l variables solved and the length of b left, and $\sigma_k(l)$ as the solution for block l in channel k. Initially, $\pi = \mathcal{A}^r$.

For channel k, we will search all the blocks in π. To begin with, we set $F^k(l, b) = 0, 1 \le l \le |\mathcal{A}^r|, 1 \le b \le C$. If we set $\sigma_k(l) = 0$, the objective value equals to $F^k(l-1, b)$. Otherwise, if we set $\sigma(l) = 1$, the objective value equals to $F^k(l-1, b-T_l) + u(l)$. We can calculate the optimal value $F^k(l, b)$ by taking the maximum of the preceding objective values. Thus, the dynamic programming recursion can be expressed as

$$F^k(l, b) = \max\Big\{F^k(l-1, b), F^k(l-1, b-T_l) + u(l)\Big\}, \tag{38}$$

for $2 \le l \le |\mathcal{A}^r|$ with an initial condition $F^k(1, b)$. Starting with $\sigma_k^*(1)$, we can calculate the optimal solution $\sigma_k^*(l)$ using

$$\sigma_k^*(l) = \underset{\sigma_k(l)\in[0,1]}{\arg\max} \Big\{F^k(l-1, b-T_l) + u(l)\Big\}. \tag{39}$$

Finally, we will remove any block s with $\sigma_k^*(s) = 1$ from π. The DP algorithm is summarized in Algorithm 2.

Remark 2: The computational complexity of the DP algorithm is $O(CK_r|\mathcal{A}^r|)$.

VI. SIMULATION RESULTS AND ANALYSIS

In this section, we compare the performance of the proposed multi-router power packet dispatching (MR) scheme with the intra-router (IR) scheme where the power packets can be transmitted only to the demander ESs which are connected to the same router.

We first introduce the simulation settings. The LAPPN consists of three routers which are connected by inter-router channels. In this simulation, we assume that the numbers of intra-router and inter-router channels for one router are equal, and the numbers of channels in different routers are also the same, i.e., $K_r = K_r' = K$. The maximum capacity for the battery of one ES is assumed to be 10 KWh. Since the demand load of a demander ES and the generated power of a supplier ES vary over time respectively, the stored energy in the batteries will fluctuate. To identify whether an ES is a supplier or demander, we define two thresholds for the remaining energy in the battery. An ES acts as a demander ES if the remaining energy in its battery is lower than 40% of its capacity, and thus, the maximum demanded energy E_d^{max} should be a

TABLE I
PARAMETERS FOR SIMULATION

Parameters	Values
Layout	3 connected routers
The duration of a time slot T	3 min
Transmission loss factor from ES to router $\epsilon_{s,r}$	$f(\epsilon_{s,r}) = \frac{2\epsilon_{s,r}}{\epsilon^2}$
Transmission loss factor among routers $\epsilon_{r,r'}$	$f(\epsilon_{r,r'}) = \frac{\epsilon_{s,r}}{2\epsilon^2}$
Loss factor ϵ	0.05
Maximum export power for a packet p^{max}	50 KW
Export power for a packet p_s^{exp}	$[0.8p^{max}, p^{max}]$
Maximum duration for a packet N^{max}	3
Maximum demanded energy E_d^{max}	$[6\ KWh, 10\ KWh]$
Minimum demanded energy E_d^{min}	$0.5E_d^{max}$
Urgency factor $\kappa_0(d)$	[1,3]
Willingness factor $\vartheta(s)$	[1/2,1]
Increased urgency factor α	0.1

value falling into the range from 6 KWh to 10 KWh and the minimum demanded energy is assumed to be $E_d^{min} = 0.5E_d^{max}$. If the remaining energy for an ES is larger than 80% of its capacity, it will serve as a supplier ES. The generated power of the ES, whose remaining energy in its battery is between these two thresholds, will be stored in its battery rather than being dispatched.

The generated power packet has a fixed power and different supplier ESs may export different amounts of power. We assume that the exported power follows a uniform distribution in $[0.8p^{max}, p^{max}]$. Since the transmission loss is proportional to the transmission distance, the transmission loss for different power packets is different. We assume that the maximum transmission loss between the router and ESs is ϵ and the maximum transmission loss between two routers is 2ϵ. Since the ESs and routers are uniformly distributed in the plane, the probability function (PDF) of the transmission loss factor $\epsilon_{s,r}$ is $f(\epsilon_{s,r}) = \frac{2\epsilon_{s,r}}{\epsilon^2}$ and the PDF of $\epsilon_{r,r'}$ is $f(\epsilon_{r,r'}) = \frac{\epsilon_{s,r}}{2\epsilon^2}$. The urgency factor $\kappa_0(d)$ and willingness factor $\vartheta(s)$ follow uniform distribution in $[1, 3]$ and $[1/2, 1]$, respectively.

The duration of a time slot T is set as 3 minutes. The time lengths of the header and footer are neglected in the simulation, because they are about tens of microseconds [5], which costs less than 0.1% of a time slot. In addition, we assume that the time length of a power packet is no more than three time slots, and one supplier ES will produce only one power packet for one cycle. The simulation parameters are given in Table I.

A. Performance Analysis

Fig. 4 demonstrates the received power versus the number of supplier ESs with $K = 2$ and $C = 20$, and provides the exported energy as the benchmark. There are $[2, 3, 5]$ supplier ESs and $[3, 8, 2]$ demander ESs connected to router 1, 2, and 3, respectively. Besides, the increased supplier ES are all connected to router 1. We can observe that the received power using the MR scheme increases with the number of supplier ESs while the one using the IR scheme saturates when the number of supplier ESs exceeds 16. This is because the redundant power packets cannot be utilized by local demander ESs without power packet routing when the supplied power packets exceeds the demand. It further verifies the effectiveness

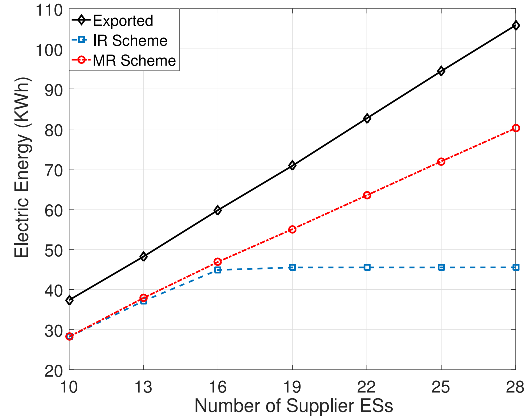


Fig. 4. Received electric energy versus number of supplier ESs with $K = 2$ and $C = 20$.

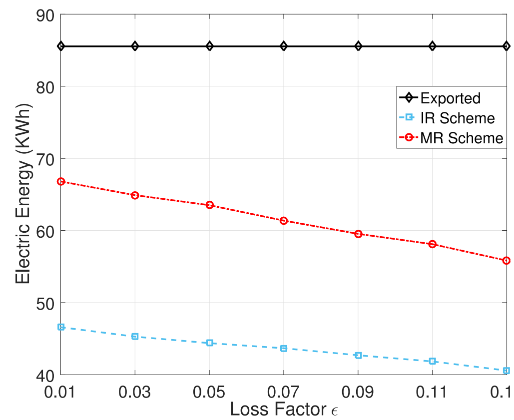


Fig. 5. Received electric energy versus loss factor ϵ with $K = 2$ and $C = 20$.

of the power packet routing among different routers. In addition, we can infer that router 1 will perform the transmission among routers when the number of supplier ESs connected to router 1 exceeds 8.

In Fig. 5, we plot the received power as the function of the loss factor ϵ with $K = 2$ and $C = 20$. Suppose that there are $[15, 3, 5]$ supplier ESs and $[3, 8, 2]$ demander ESs connected to router 1, 2, and 3, respectively. In this figure, we can observe that the received energy power decreases with the increasing loss factor. In addition, the descending rate of the received power using MR scheme is larger than that using IR scheme due to the transmission loss between two routers. Since loss factor generally indicates the distance between routers, the results suggest that routing will be no longer effective if the distance among routers is sufficiently long, and this is the reason why we implement the MR scheme in a local network.

In Fig. 6, we demonstrate the proportion of the occupied time slots versus the number of suppliers for different numbers of channels K and the time slots in one cycle C. It is noted that the utilization of time slots increases as the number of supplier ESs and becomes saturated when the number of supplier ESs exceeds a certain threshold. The LAPPN can support more power packets with more power channels, but it may lead to low system utilization if the number of ESs is small. Therefore, proper selection of the number of channels may affect the

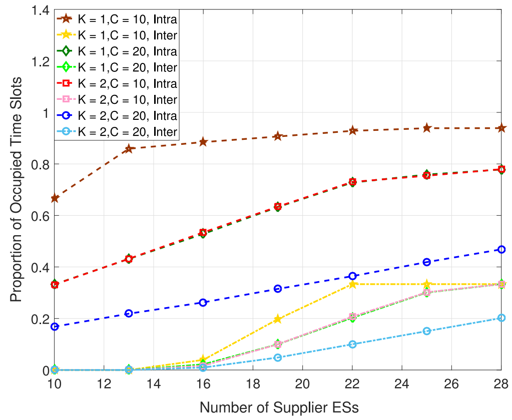


Fig. 6. Proportion of occupied time slots versus number of supplier ESs.

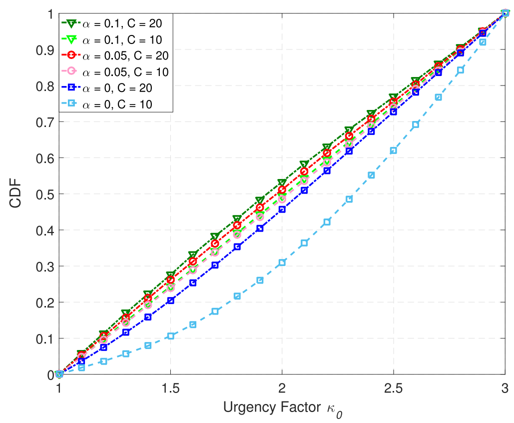


Fig. 7. Cumulative distribution function of the urgency factor κ_0 with $K = 1$ and $S = 25$.

performance of the LAPPN. We can also observe from the figure that the number of time slots in one cycle C will affect the performance of the proposed scheduling scheme. The saturation threshold will increase as C grows. In addition, the curve with $K = 2, C = 10$ and that with $K = 1, C = 20$ basically overlap for both inter-router and intra-router channels. This indicates that the LAPPN will have equivalent scheduling performance if the values of KC are equal. Besides, the figure shows that the inter-router channels are activated when the number of supplier ESs is around 16, and this is consistent with Fig. 4.

In Fig. 7, we present the cumulative distribution function (CDF) of the urgency factor κ_0 with $K = 1$ and $S = 25$ for different values of the increased factor α and the number of time slots in one cycle C. We can observe that more power packets with low urgency factor are scheduled if the LAPPN is equipped with more power channels. This implies that the power packets with higher urgency will be scheduled first. For comparison, we also illustrate the CDF of the scheme where urgency factor remains the same in different cycles, i.e., $\alpha = 0$. These results show that the proportion of scheduled power packets with $\kappa_0 \leq 2$ for $\alpha = 0$ is at least 50% less than that for $\alpha = 0.1$ when $C = 20$. The reason is that the scheme with $\alpha = 0.1$ tends to schedule the waiting power packets first to avoid long waiting times to ensure that the power packets with low urgency factors also have more opportunities to be scheduled. Though it achieves better fairness for power packets, it is not efficient from the perspective of the network. This implies that we can achieve a trade-off between fairness and efficiency by adjusting the value of α. However, when $C = 20$, comparing the proportion of scheduled power packets whose urgency factor κ_0 is less than 2, we can observe that the gap between the proportions with $\alpha = 0.1$ and with $\alpha = 0.05$ is less than the gap between the proportions with $\alpha = 0.05$ and with $\alpha = 0$. This implies that the sensitivity of tuning α decreases as α grows.

B. Cost-Effectiveness Analysis

In this section, we will analyze the cost-effectiveness [27] of the multi-router deployment. We first give some definitions on unit cost and cost-effectiveness.

Definition 2: The unit cost is defined as the cost per unit of the received energy, that is,

$$UC = \frac{\zeta}{E^{total}}, \tag{40}$$

where ζ is the total cost for the router deployment and E^{total} is the total received energy.

We denote the total cost and received energy for the MR scheme as ζ_{MR} and E^{total}_{MR}, and the total cost and received energy for the IR scheme as ζ_{IR} and E^{total}_{IR}, respectively. Note that the total cost consists of the cost for routers, which is a constant denoted by L, and the cost for power lines, which is proportional to the number of power lines. Since the cost for a power line is proportional to its length of the power line, the cost is also proportional to the transmission loss factor. Define the proportion as β. Note that the PDF of $\epsilon_{s,r}$ is $\frac{2\epsilon_{s,r}}{\epsilon^2}$ and the PDF of $\sqrt{\epsilon_{r,r'}}$ is $\frac{2\epsilon_{s,r}}{4\epsilon^2}$. Therefore, the average cost for a intra-router channel is $\frac{2\beta}{3}\epsilon$ and a inter-router channel is $\beta\frac{4}{3}\epsilon$, respectively. Under the aforementioned simulation settings, we have

$$\begin{aligned} \zeta_{IR} &= RL + 2RK\frac{2\beta}{3}\epsilon = 3L + 4K\beta\epsilon, \\ \zeta_{MR} &= RL + 2RK\frac{2\beta}{3}\epsilon + R(R-1)K\beta\frac{4}{3}\epsilon = 3L + 10K\beta\epsilon. \end{aligned} \tag{41}$$

Definition 3: Cost-effectiveness of the MR scheme is defined as

$$\delta = \frac{UC_{IR}}{UC_{MR}} = \frac{\zeta_{IR}}{\zeta_{MR}}\frac{E^{total}_{MR}}{E^{total}_{IR}}. \tag{42}$$

The cost-effectiveness captures the relation between the cost and the outcome. $\delta > 1$ implies that the unit cost of the MR scheme is less than that of the IR scheme, and we can call that the MR scheme is more cost-effective than the IR scheme. $\delta < 1$ means that the IR scheme is more cost-effective than the MR scheme. According to (41) and (42), the cost-effectiveness can be given by

$$\delta = \frac{E^{total}_{MR}}{E^{total}_{IR}}\frac{3L(\epsilon\beta)^{-1} + 4K}{3L(\epsilon\beta)^{-1} + 10K}. \tag{43}$$

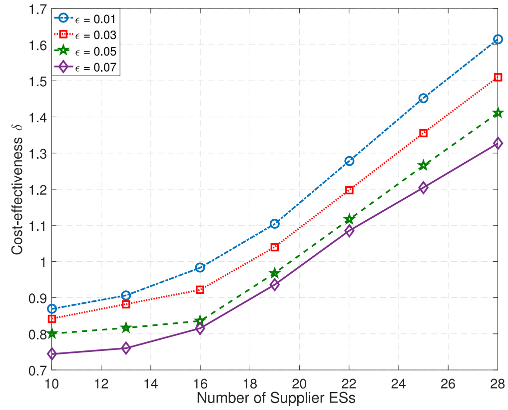


Fig. 8. Cost-effectiveness δ versus number of supplier ESs with $K = 2$, $C = 20$, $L = 10^5$, and $\beta = 10^5$.

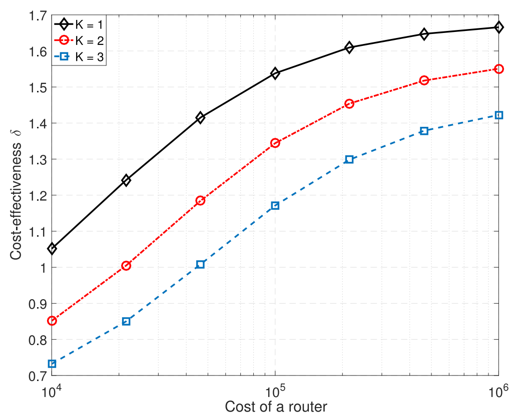


Fig. 9. Cost-effectiveness δ versus cost of a router L with $\epsilon = 0.05$, $C = 20$, $\beta = 10^5$, and $S = 25$.

In Fig. 8, we plot the cost-effectiveness δ versus the number of supplier ESs with $K = 2$, $C = 20$, $L = 10^5$, and $\beta = 10^5$. There are [2, 3, 5] supplier ESs and [3, 8, 2] demander ESs connected to router 1, 2, and 3, respectively. Besides, the increased supplier ES are all connected to router 1. From this figure, we can observe that δ increases with the number of supplier ESs. This is because the received energy using the IR scheme saturates when the number of supplier ESs exceeds 16 while that using the MR scheme increases with the number of supplier ESs due to power packet routing. The MR scheme is more cost-effective than the IR scheme when the number of supplier ESs exceeds 20 when $\epsilon = 0.05$, which implies that MR scheme is cost-effective in the scenario with significant demand-and-supply imbalance. In addition, we can also observe that δ decreases as ϵ grows. Since the average transmission distance increases as ϵ grows, the total received energy decreases but the cost for channels increases. This also implies that the MR scheme is suitable to be implemented in a local network.

Fig. 9 demonstrates the cost-effectiveness versus the cost of a router L with $\epsilon = 0.05$, $C = 20$, $\beta = 10^5$, and $S = 25$ for different values of K. This figure shows that δ increases with L and δ converges to a constant when $L \gg K\epsilon\beta$, which can also be derived from (43). In addition, we can also find out that δ decreases with K. There are two reasons. First, deploying more channels will lead to a lower cost ratio $\frac{\zeta_{IR}}{\zeta_{MR}}$. Second, since the capacity of intra-router channels is the bottleneck, deploying more channels will bring more benefits to the intra-router power packet transmissions, and thus, the received energy ratio $\frac{E_{MR}^{total}}{E_{IR}^{total}}$ decreases with more channels.

VII. Conclusion

In this paper, we have proposed a packetized power dispatching protocol to realize power dispatching in an LAPPN with multiple routers. The power packet routing and scheduling in this protocol have been formulated, respectively. We have proposed a BB method with continuous relaxation to solve the power packet routing problem. In addition, a DP based algorithm has been developed to tackle the power packet scheduling problem. Simulation results have shown the effectiveness of the proposed routing algorithm in maximizing the received energy of demander ESs and verified that the proposed scheduling mechanism can achieve a trade-off between fairness among the ESs and system efficiency by tuning the factor α. The cost-effectiveness analysis has shown that the MR scheme is cost-effective in scenarios with significant demand-and-supply imbalances.

Appendix
Proof of Proposition 1

When we substitute $z_d \frac{E_d^{min}}{E_d^{max}}$ into constraint (11d), we can have $\sum_{s\in\mathcal{S}} E_s^{rec} y_d^s \leq E_d^{min}$. Since the received power for ES d in problem (P2) is the upper bound of the one for problem (P1) and the upper bound of the received power cannot satisfy the minimum received energy constraint, the received power for ES d in problem (P1) also cannot satisfy the constraint. Therefore, $z_d = 0$.

References

[1] H. Zhang, L. Song, Y. Li, and H. V. Poor, "Peer to peer power packet dispatching for local area packetized power networks with multiple routers," in *Proc. IEEE GLOBECOM*, Abu Dhabi, UAE, Dec. 2018.

[2] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, "The future renewable electric energy delivery and management (FREEDM) system: The energy Internet," *Proc. IEEE*, vol. 99, no. 1, pp. 133–148, Jan. 2011.

[3] A. Ipakchi and F. Albuyeh, "Grid of the future," *IEEE Power Energy Mag.*, vol. 7, no. 2, pp. 52–62, Mar./Apr. 2009.

[4] W. Su, H. Eichi, W. Zeng, and M.-Y. Chow, "A survey on the electrification of transportation in a smart grid environment," *IEEE Trans. Ind. Informat.*, vol. 8, no. 1, pp. 1–10, Feb. 2012.

[5] R. Takahashi, K. Tashiro, and T. Hikihara, "Router for power packet distribution network: Design and experimental verification," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 618–626, Mar. 2015.

[6] Q. Sun, R. Han, H. Zhang, J. Zhou, and J. M. Guerrero, "A multiagent-based consensus algorithm for distributed coordinated control of distributed generators in the energy Internet," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 3006–3019, Nov. 2015.

[7] R. Wang, J. Wu, Z. Qian, Z. Lin, and X. He, "A graph theory based energy routing algorithm in energy local area network," *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 3275–3285, Dec. 2017.

[8] W. Hou *et al.*, "Cooperative mechanism for energy transportation and storage in Internet of energy," *IEEE Access*, vol. 5, pp. 1363–1375, 2017.

[9] Y. Zhou, S. Ci, H. Li, and Y. Yang, "A new framework for peer-to-peer energy sharing and coordination in the energy Internet," in *Proc. IEEE ICC*, Paris, France, May 2017, pp. 1–6.

[10] H. Sui, H. Wang, M.-S. Lu, and W.-J. Lee, “An AMI system for the deregulated electricity markets,” *IEEE Trans. Ind. Appl.*, vol. 45, no. 6, pp. 2104–2108, Nov./Dec. 2009.

[11] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, “Communication network requirements for major smart grid applications in HAN, NAN and WAN,” *Comput. Netw.*, vol. 67, pp. 74–88, Jul. 2014.

[12] V. C. Gungor *et al.*, “A survey on smart grid potential applications and communication requirements,” *IEEE Trans. Ind. Informat.*, vol. 9, no. 1, pp. 28–42, Feb. 2013.

[13] K. Samarakoon, J. Ekanayake, and N. Jenkins, “Reporting available demand response,” *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1842–1851, Dec. 2013.

[14] R. Takahashi, S. Azuma, M. Hasegawa, H. Ando, and T. Hikihara, “Power processing for advanced power distribution and control,” *IEICE Trans. Commun.*, vol. E100-B, no. 6, pp. 941–947, Jun. 2017.

[15] J. Toyoda and H. Saitoh, “Proposal of an open-electric-energy-network (OEEN) to realize cooperative operations of IOU and IPP,” in *Proc. EMPD*, Singapore, Mar. 1998, pp. 218–222.

[16] T. Takuno, M. Koyama, and T. Hikihara, “In-home power distribution systems by circuit switching and power packet dispatching,” in *Proc. IEEE Int. Conf. Smart Grid Commun.*, Gaithersburg, MD, USA, Oct. 2010, pp. 427–430.

[17] N. Fujii, R. Takahashi, and T. Hikihara, “Networked power packet dispatching system for multi-path routing,” in *Proc. IEEE/SICE Int. Symp. Syst. Integr.*, Tokyo, Japan, Dec. 2014, pp. 357–362.

[18] Y. Xu, J. Zhang, W. Wang, A. Juneja, and S. Bhattacharya, “Energy router: Architectures and functionalities toward energy Internet,” in *Proc. IEEE Int. Conf. Smart Grid Commun.*, Brussels, Belgium, Oct. 2011, pp. 31–36.

[19] J. Ma, L. Song, and Y. Li, “Optimal power dispatching for local area packetized power network,” *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4765–4776, Sep. 2018.

[20] S. Martello and P. Toth, *Knapsack Problems: Algorithms and Computer Implementations*. Chichester, U.K.: Wiley, 1990.

[21] D. Li and X. Sun, *Nonlinear Integer Programming*. New York, NY, USA: Springer, 2006.

[22] R. M. Karp, “Reducibility among combinatorial problems” in *Complexity of Computer Computations*, R. E. Miller and J. W. Thatcher, Eds. New York, NY, USA: Plenum, 1972, pp. 85–103.

[23] S. P. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[24] D. P. Bertsekas, *Nonlinear Programming*. Belmont, MA, USA: Athena Sci., 1999.

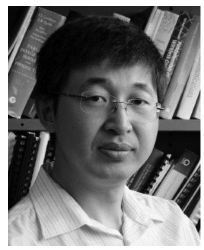
[25] C. Cicconetti *et al.*, “Efficient two-dimensional data allocation in IEEE 802.16 OFDMA,” *IEEE/ACM Trans. Netw.*, vol. 22, no. 5, pp. 1645–1658, Oct. 2014.

[26] D. Bertsimas and R. Demir, “An approximate dynamic programming approach to multidimensional knapsack problems,” *Manag. Sci.*, vol. 48, no. 4, pp. 550–565, Apr. 2002.

[27] P. Tuominen *et al.*, “Economic appraisal of energy efficiency in buildings using cost-effectiveness assessment,” *Procedia Econ. Finance*, vol. 21, pp. 422–430, 2015.

Hongliang Zhang (S’15) received the B.S. degree in electronic engineering from Peking University, Beijing, China, in 2014, where he is currently pursuing the Ph.D. degree with the School of Electrical Engineering and Computer Science. His research interests include device-to-device communications, unmanned aerial vehicle networks, and hypergraph theory. He has also served as a TPC Member for GlobeCom 2016, ICC 2016, ICCC 2017, ICC 2018, and GlobeCom 2018.

Lingyang Song (S’03–M’06–SM’12–F’19) received the Ph.D. degree from the University of York, U.K., in 2007. He was a Research Fellow with the University of Oslo, Norway, until rejoining Philips Research U.K., in 2008. In 2009, he joined the School of Electronics Engineering and Computer Science, Peking University, China. He is currently a Boya Distinguished Professor. His research interests include wireless communication and networks, signal processing, and machine learning. He was a recipient of the IEEE Leonard G. Abraham Prize in 2016, the IEEE Asia–Pacific Young Researcher Award in 2012, and the K. M. Stott Prize for Excellent Research from the University of York. He has been an IEEE Distinguished Lecturer since 2015.



Yonghui Li (M’04–SM’09–F’19) received the Ph.D. degree from the Beijing University of Aeronautics and Astronautics, Beijing, China, in 2002. From 1999 to 2003, he was affiliated with Linkair Communication Inc., where he held a position of Project Manager with responsibility for the design of physical layer solutions for the LAS-CDMA system. Since 2003, he has been with the Centre of Excellence in Telecommunications, University of Sydney, Australia, where he is currently a Professor with the School of Electrical and Information Engineering. He was a recipient of the Australian Queen Elizabeth II Fellowship in 2008 and the Australian Future Fellowship in 2012.

His research interests are in the area of wireless communications, with a particular focus on MIMO, millimeter wave communications, machine to machine communications, coding techniques, and cooperative communications. He holds a number of patents granted and pending in these fields. He was a recipient of the Best Paper Awards from IEEE International Conference on Communications 2014, IEEE PIMRC 2017, and IEEE Wireless Days Conferences 2014. He is currently an Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS and the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. He was also a Guest Editor of IEEE JSAC Special issue on Millimeter Wave Communications for Future Mobile Networks.

H. Vincent Poor (S’72–M’77–SM’82–F’87) received the Ph.D. degree in EECS from Princeton University in 1977. From 1977 to 1990, he was on the faculty of the University of Illinois at Urbana-Champaign. Since 1990, he has been on the faculty at Princeton, where he is currently the Michael Henry Strater University Professor of Electrical Engineering. From 2006 to 2016, he served as the Dean of Princeton’s School of Engineering and Applied Science. He has also held visiting appointments at several other universities, including most recently at Berkeley and Cambridge. His research interests are in the areas of information theory and signal processing, and their applications in wireless networks, energy systems and related fields. Among his publications in these areas is the recent book *Information Theoretic Security and Privacy of Information Systems* (Cambridge University Press, 2017).

Dr. Poor is a member of the National Academy of Engineering and the National Academy of Sciences, and is a foreign member of the Chinese Academy of Sciences, the Royal Society, and other national and international academies. Recent recognition of his work includes the 2017 IEEE Alexander Graham Bell Medal, Honorary Professorships at Peking University and Tsinghua University, both conferred in 2017, and a D.Sc. *honoris causa* from Syracuse University, awarded in 2017.