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Delay-Aware Energy-Efficient Joint Power Control and Mode Selection in Device-to-Device Communications for FREEDM Systems in Smart Grids

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ABSTRACT Cellular technology with long-term evolution (LTE)-based standards is a promising technology for smart grid communication networks. However, the integration of cellular technology and smart grid communications is a significant challenge due to the transmission of simultaneous and delay-sensitive smart grid data. The Device-to-device (D2D) communications are proposed as critical solutions to enhance the performance of the LTE. In this paper, we study energy efficiency and delay problems in D2D underlaying cellular communications for the future renewable electric energy delivery and management (FREEDM) system in smart grid with different message sizes and varying channel conditions. We adopt a D2D-assisted relaying framework to assist links that meet poor channel conditions in order to increase the data rate of intelligent energy management devices with large size report. We propose a joint power control and mode selection scheme to deal with the problem and develop a brute-force-based algorithm to find the solutions. We conduct simulations to show the effectiveness of the proposed scheme in balancing the trade-off between energy efficiency and end-to-end delay and show significant energy efficiency improvements when exploiting the proposed scheme compared to direct and relaying schemes in a variety of different conditions.

INDEX TERMS Energy efficiency, end-to-end delay, device-to-device communications, cellular networks, smart grids.

I. INTRODUCTION

Smart grids have attracted a lot of attention due to their potential to significantly improve the efficiency and reliability of power grids [1]. One main feature of smart grid is the bidirectional communications between smart grid domains used to coordinate energy generation, transmission and distribution, therefore, the smart grid communication is an essential part of efficient grid control [2]. The smart grid communication, adopting a hierarchical structure, consists three kinds of networks: wide area networks (WANs), neighborhood area networks (NANs) and home area networks (HANs). Among them, the tasks of NANs include forming communication facilities in electric distribution networks [3], specifically for local energy management in the future renewable electric energy delivery and managements (FREEDM) system, one important model for electric distribution systems in smart grids [4]. The FREEDM system utilizes distributed renewable energy resources (DRERs) such as wind turbines and solar panels in large-scale and wide-scale installations, where the energy management decisions are done individually and locally.

Intelligent energy management devices (IEMs) manage energy in the FREEDM system by monitoring status and

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collecting data of all end-devices in a local area, and providing control references to each of them [4]. In particular, the tasks of IEMs include collecting and monitoring the status of DRERs, making energy management decisions and delivering reports to the control center for further actions. In this context, cellular technology with LTE-based standard is promising for communications in the FREEDM system because it is a widely-deployed and mature technology. Therefore, this kind of technology can provide services over a large area including to smart grid domains located in complex geographical areas [5]. However, integrating the cellular technology and the smart grid communication network is a significant challenge for LTE due to the simultaneous transmission of large volume delay-sensitive data. Specifically, when a fault occurs in a grid, for instance due to natural disasters such as floods, earthquakes or tsunamis, more information needs to be sent to the control center, resulting in a significant increment to the size of IEM reports [6]. In this kind of situations, the grid must have resilient and self-healing capabilities to prevent power losses and blackouts, which results in stringent delay requirements to the data transmissions. One critical way to enhance the performance of LTE in this kind of situations is to exploit device-to-device (D2D) communications. In D2D communications underlaying cellular networks, two devices located in a close proximity can exchange information directly by reusing cellular resources over a direct link, instead of exploiting cellular base station (BS) to receive and transmit reports. Exploiting the D2D-assisted relaying framework which utilizes the underlay D2D communications by sharing radio spectrum between links can improve signal quality of the links, enabling high data rates [7].

Energy efficiency is one critical parameter in D2D communications underlaying cellular networks especially when IEMs are considered. When an IEM in the fault zone, it will be isolated from the grid to protect other normal zones from any cascading failure due to fault current. In this situation, the IEM and all loads in the fault zone are powered by local energy sources, such as small wind turbines, photovoltaic panels and local energy storage equipment [8], which have limited power supply. Therefore, energy efficiency is critical in this kind of situations to ensure that reports of the IEMs can be transmitted to the control center successfully. However, researches in [9] and [10] prove that a trade-off between energy efficiency and delay exists in wireless cellular networks. Therefore, considering only energy efficiency maximization in D2D communications may not be sufficient to the network without taking delay performance into account [11], because delay is a key performance metric that reflects the users' experience. In the FREEDM system, if the delivery time of the IEM reports is after the delivery deadline, information loss could occur, where the control center receives incomplete information which might result in the transmission of false control command.

Many works have investigated energy efficiency and delay issues in D2D communications. Jiajia *et al*. studied the energy efficiency and delay trade-off in D2D communications for mobile applications and proposed the TRADEOFF algorithm as a model to evaluate the performance of any heuristic algorithms [12]. Yulei *et al*. investigated the fundamental trade-off between energy consumption and other network factors such as available bandwidth, buffer size and service delay, then formulated a minimum energy consumption resource allocation and transmission mode selection problem in a large scale human mobility condition using a dynamic graph model [13]. Yanli *et al*. studied content delivery problem based on a flow model and proposed an optimal resource allocation method to obtain energy-efficient D2D-aided content delivery with guaranteed delay constraints for hybrid content requests [14]. In [15], Kazi *et al*. proposed a novel architecture by combining two technologies, which are cloud radio access network (C-RAN) and D2D for mobile crowd sensing to solve the delay issue as well as capacity, energy efficiency, mobility, and cost in the networks. Luo *et al*. developed an Experience-based Irrelative State-action Abstraction (EISA) algorithm based on Q-Learning (QL) to address the energy efficiency and delay trade-off problem in energy harvesting-based D2D communication underlaying cellular network [16].

Although all previous works studied the energy efficiency and delay problem in D2D communications, all these works do not consider the special requirements in smart grid environments, specifically in FREEDM systems. In FREEDM systems, the size of reports generated by IEMs is varied according to its associated zones. Moreover, reports of IEMs are delay-sensitive and must be delivered at the control center within specific delay constraints, thus, specific data rate requirements are imposed to satisfy certain delay constraints.

In this paper, we exploit D2D communications underlaying cellular networks to improve the performance of smart grid communication networks by taking into account the transmission of different volume of simultaneous and delay-sensitive data due to faults, in varying channel conditions. A joint power control and mode selection scheme is proposed as an important solution to increase energy efficiency while satisfying stringent delay constraints in D2D communications underlaying cellular networks specifically for the FREEDM system in smart grids. The mode selection scheme can be exploited to satisfy delay in the network by properly select the transmission mode that satisfies the quality-of-service (QoS) of IEM report, while the power control scheme is one of the critical energy efficiency maximization techniques in D2D communications which permits transmission power regulation with respect to some power constraints [17]. The proposed scheme first calculates the optimal data rate of each IEM according to its report size. Then, depending on the proposed data rate and the channel quality of each IEM, the IEM will regulate its transmission power by exploiting the power control scheme. Based on the proposed transmission power, the BS obtains the actual channel state of each IEM and then calculates data rate of each transmission mode and selects the transmission mode that provides the highest data rate to satisfy the delay constraints of IEM. By selecting the transmission mode with the highest data rate, the delay requirement could be satisfied even when the size of IEM report increases due to fault.

The contributions of this work can be summarized as follows:

- We study energy efficiency and delay problems in D2D communications for the FREEDM system and adopt the D2D-assisted relaying framework to increase data rate of the IEMs in the fault zone and experiencing poor channel conditions.
- We propose a joint power control and mode selection scheme to enhance energy efficiency as well as to satisfy stringent delay constraints in the networks under different report size and varying channel conditions.
- We formulate the optimization problem as a combinatorial problem and develop a ***E***nergy ***E***fficiency and ***D***elay ***O***ptimization (EEDO) algorithm based on the brute-force searching method [18] to deal with the problem and find the solutions.

The remainder of this paper is organized as follows. The preliminary of FREEDM systems is explained in Section II. The system model is described in Section III. In Section IV, the joint power control and mode selection problem is formulated. Proposed solutions are derived in Section V. Simulation results are presented and discussed in Section VI and the paper is concluded in Section VII.

II. THE PRELIMINARY OF FREEDM SYSTEMS

In the FREEDM system, renewable energy resources are utilized in two ways: large-scale centralized installation by exploiting wind or solar farms in the grid, and wide-scale DRERs installation such as solar panels or small wind turbines attached to individual households, and electric or hydrogen fuel cell cars [4].

A. MODEL OF THE FREEDM SYSTEM

In the FREEDM system, distributed energy storages (DESs) which consist of hydrogen storages or batteries, are exploited as complements to distributed energy generations (DEGs). The small scale DESs and DEGs are used to help each household in managing its energy usage. In the system, energy management is done locally by the IEMs through performing real-time monitoring and data collection. In particular, IEMs collect data, monitor status as well as provide control commands to every end device. Another important kind of the devices in the FREEDM system are the intelligent fault management devices (IFMs). The roles of IFMs include fault identification and isolation to maintain the system stability. More specifically, multiple IFMs could divide IEMs into different zones. When faults occur in a zone, IFMs will isolate the fault zone to protect other normal zones from any cascading failure due to fault current [4].

The system model of the FREEDM system is shown in Figure 1. A substation of the control center is attached between the 69 kV transmission line and the 12 kV AC distribution line. IFMs are connected to each other by the

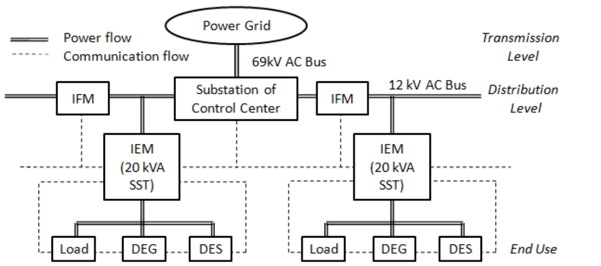

FIGURE 1. The model of the FREEDM system.

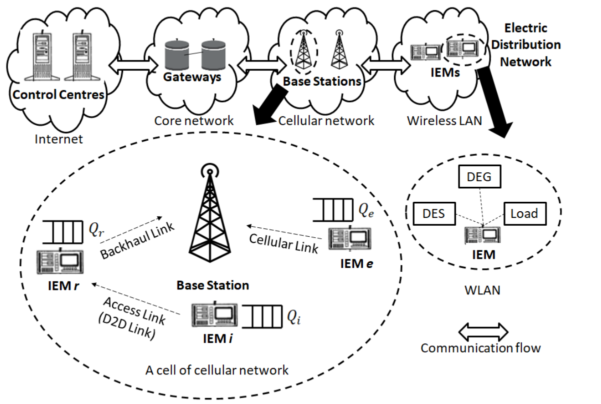

FIGURE 2. The communication structure of an electric distribution network.

12 kV line. A solid state transformer (SST) connects an IEM to the 12 kV AC distribution line, and the 120V AC bus and the 400V DC bus which are connected to the load, DES and DEG.

B. COMMUNICATION REQUIREMENTS FOR FREEDM SYSTEMS

A hierarchical structure consisting of several layers of wired and wireless networks [6] is considered due to its merits of good scalability and low investment cost [19]. As shown in Fig. 2, an IEM manages the load and DRERs, such as the DEG and the DES through a wireless local area network (WLAN). A local energy management decision is done by an IEM based on the information received and a report is transmitted to the control center in the internet architecture through the cellular network and the wired network. Connections between the BSs and the control center are managed by wired networks through gateways in the core network.

The communication technology for the FREEDM system must be able to meet delivery delay requirements of the reports. IEMs send protection data, control data and state reports to the control center with the acceptable delay from 3ms to 16ms for the protection data, and from 16ms to 100ms for the other data [20]. In fault situations, the delay requirements of the data may not be met because more information needs to be sent to the control center, which might result in an increase of the report length of up to 100 times of the normal size at the control center [21]. Moreover, in fault scenarios, the report transmission becomes data rate demanding in order to meet the delivery delay requirement. The report must be delivered at the control center within the specific time to trigger a respond from the corresponding device as soon as possible. Otherwise, the corresponding device is inaction, which may result in the expansion of damage area due to the fault current [20].

Multi-hop relaying communications are adopted in the system to improve the channel quality of IEMs in cellular networks. Multi-hop relaying communications have been used in wireless networks for machine type communication, specifically in scenarios where nodes experience high path loss due to a long distance between the source node and the destination node [22]. In multi-hop relaying communications, reports of an IEM can be relayed to another IEM before reaching the control center. Each IEM can act as a source node and also a relaying node that stores and forwards reports of other IEMs to the BS [23]. The link between an IEM and a relaying IEM (RI) is called the access link, while the link between a RI and the BS is called the backhaul link. When the access link suffers bottleneck effect, the D2D-assisted relaying framework is adopted to assist the access link.

III. SYSTEM MODEL

The detail of the system model of D2D communications underlaying the cellular networks for smart grid NANs are explained in this section. The D2D-assisted relaying framework is adopted in the orthogonal frequency-division multiple access (OFDMA) based cellular networks as shown in Figure 2. The nodes in a cell include a BS and M IEMs, in which all nodes are transceivers over multiple sub-channels. It is assumed that the BS has full knowledge of the channel gains in the system and it assigns sub-channels using a proportional fair scheduling method to satisfy each IEM's QoS and try to maximize the throughput of cellular users [24]. It is also assumed that when IEMs have data to transmit, they will immediately regulate their transmission power, and report the queue and power state to the BS as in the existing LTE system [25]. Compared with the existing 4G LTE system, the only additional signaling overhead is for reporting the channel gain of access links of IEM in the fault zone or meeting poor channel conditions to the neighboring IEMs. Further, the BS selects the transmission mode to each IEM after it receives the queue state and power reports from IEM. When an IEM is in a fault zone or experiences poor channel conditions, the data rate over the pre-assigned sub-channel might not able to meet delay requirement. Therefore, based on transmission power reported by the IEM, the BS selects a mode for each IEM and establishes a D2D link if required. The BS tells IEMs on the uplink resources decisions over the Physical downlink Control Channel (PDCC) signal.

In general, IEMs can communicate with end devices in the WLAN and the BS and other IEMs in the cellular network using two different interfaces. The existence of D2D communication functions in the cellular network enables the IEMs located in a close proximity to reuse the sub-channel of another IEM and directly transmit reports to other IEMs over the D2D link [6]. Let $\mathcal{M} = \{1, 2, \cdots, M\}$, $\mathcal{G} = \{1, 2, \cdots, G\}$ and $\mathcal{F} = \{1, 2, \cdots, F\}$ denote the set of IEMs, RIs and reuse IEMs respectively. $\mathcal{C} = \{1, 2, \cdots, C_u\}$ denotes the set of uplink sub-channels in the system. RIs are defined as the IEMs which can be used to forward reports of other IEMs, while reuse IEMs are defined as IEMs that can be used to establish D2D links by reusing their own sub-channels for direct transmission mode and D2D-assisted relaying mode. All RIs and reuse IEMs operate in the direct cellular mode. The whole uplink spectrum is divided into C_u same-sized sub-channels and each device in the cell is allocated with a sub-channel. Let $C_i, C_r, C_e, \in \mathcal{C}$ denote the sub-channel allocated to IEM $i \in \mathcal{M}$, IEM $r \in \mathcal{G}$, and IEM $e \in \mathcal{F}$ respectively. Time is slotted with equal lengths in our model.

A. RECEIVED SIGNAL-TO-INTERFERENCE-PLUS-NOISE RATIO OF IEMS

Let $G_{ij,t}^{C_i}$ denote the channel gain of link (i, j) on sub-channel C_i which consists of path loss, shadowing and slow fading effect under a Rayleigh channel. The channel gains are independent and identically distributed (i.i.d) between transmissions and remain constant during a transmission phase. The received signal-to-noise ratio (SNR) of link (i, j) on sub-channel C_i at timeslot t, $\gamma_{ij,t}^{C_i}$, representing the channel quality of the link on sub-channel C_i, can be calculated as follows [25]:

$$\gamma_{ij,t}^{C_i} = \frac{p_{i,t}^{C_i} G_{ij,t}^{C_i}}{N_{i,t}}, \tag{1}$$

where $N_{i,t}$ is the noise power and $p_{i,t}^{C_i}$ is the transmission power of IEM i over sub-channel C_i. The received signal-to-interference-plus-noise ratio (SINR) of IEM i may not be the same as its SNR value depending on whether IEM i selects the D2D mode, or the sub-channel C_i is reused by other IEM hence causing interference between the cellular link and the D2D link. Therefore, the received SINR of IEM i over sub-channel C_i becomes [25]

$$\mathrm{SINR}_{i,t}^{C_i} = \frac{\gamma_{ij,t}^{C_i}}{1 + \tilde{\gamma}_{ij,t}^{C_i}}, \tag{2}$$

where $\tilde{\gamma}_{ij,t}^{C_i}$ is the received SNR of the interference link to sub-channel C_i,which could be the SNR of IEM e, when IEM i reuses sub-channel C_e.

B. INSTANTANEOUS DATA RATE OF IEMS

Let $r_{ij,t}^{C_i}$ denote the instantaneous data rate of link (i, j) over sub-channel C_i. It is assumed that the adaptive modulation and coding (AMC) scheme is adopted in the physical layer. The AMC scheme has been used extensively in several wireless standards i.e., LTE, 802.11a and 802.16e, because it has the capability of enhancing the throughput in time-varying channel conditions [26]. The AMC scheme optimizes the data rate of each IEM depending on its SINR by exploiting the best modulation and coding technique from its perspective, therefore it creates a relationship between the received SINR and the transmission rate [27].

In the AMC scheme, received SINR values are divided into Z non-overlapping consecutive regions [27]. For any region $z \in \{1, 2, \cdots, Z\}$, if the received SINR of IEM i over sub-channel C_i at timeslot t, $\mathrm{SINR}_{i,t}^{C_i} \quad \forall \quad C_i \in \mathcal{C}$ falls within the zth region $[\beta_{z-1}, \beta_z]$, where β_z denotes the SINR threshold for state z with $\beta_0 = 0$, $\beta_Z = \infty$, the corresponding instantaneous data rate of link (i, j) over sub-channel C_i, $r_{ij,t}^{C_i}$ is a fixed value R_z according to the selected modulation and coding at region z. R_z denotes as a fixed instantaneous data rate at region z in the AMC scheme. The smallest region is $z = 1$ and if $\mathrm{SINR}_{i,t}^{C_i}$ falls into this region, the corresponding data rate value is $R_1 = 0$, in which no packet is sent at this state in order to obtain low transmission error probability. Therefore, the instantaneous data rate of link (i, j) over sub-channel C_i at timeslot t is given by [26]

$$r_{ij,t}^{C_i} = R_z. \tag{3}$$

Since the channel condition of links are the same as the channel condition of IEMs, the instantaneous data rate of IEM i at timeslot t can be formulated as follows [26]:

$$r_{i,t}^{C_i} = r_{ij,t}^{C_i} = R_{i,t}. \tag{4}$$

C. QUEUE DYNAMICS OF IEMS

In the FREEDM system, the report of an IEM is associated to its zone. We assume that an IEM is in a normal zone with probability P_n and the probability of IEM in the fault zone is $1 - P_n$. Each of the IEMs manages the same amount of end-devices, therefore it generates the same size of the report. Let $B_{i,t}$ denote the amount of packets generated by IEM i at timeslot t. In the normal zone, all IEMs generate report with the size of B_n packets while in the fault zone the IEMs generate report with the size of B_f packets. The IEMs transmit reports to the control center for every T interval [28].

A first-in-first-out (FIFO) behavior is adopted in the queue model. The arriving packets are placed in the queue throughout timeslot t and will be transmitted at the next timeslot, $t+1$. Packets exit the network once they reach the destination. A large buffer size is assumed and therefore no packet is dropped due to buffer overflow. Let $Q_{i,t}$ denote the queue length of IEM i at timeslot t. The queue dynamic at IEM i can be expressed as [26]

$$Q_{i,t+1} = \max\{0, Q_{i,t} - R_{i,t}\} + B_{i,t}. \tag{5}$$

The queue dynamic at IEM r as a RI consists of the data transmitted from IEM i, in which the forwarded report is placed in the queue before transmitted at the next timeslot, and can be expressed as follows

$$Q_{r,t+1} = \max\{0, Q_{r,t} - R_{r,t}\} + B_{r,t} + (Q_{i,t} - R_{i,t}). \tag{6}$$

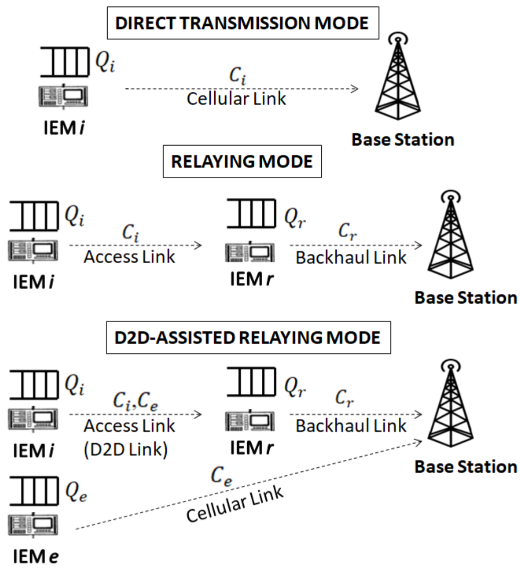

FIGURE 3. A diagram of the direct transmission mode, relaying mode and D2D-assisted relaying mode.

IV. JOINT POWER CONTROL AND MODE SELECTION PROBLEM FORMULATION

The system is partially centralized, where the BS determines the mode selection for each IEM based on IEMs' power and queue states. On the other hand, the transmission power of each IEM is determined by itself in a distributed manner. Therefore, the problem can be formulated as a combinatorial problem which consists of the power control and mode selection problems that maximize energy efficiency under power and mode selection constraints. To solve the problem, calculation of the data rate, the power consumption and the end-to-end delay of each transmission mode are performed.

A. DELAY AND POWER CONSUMPTION FOR DIFFERENT TRANSMISSION MODES

As shown in Figure 3, a report from an IEM can be sent in one of the three transmission modes, which are the direct transmission mode, the relaying mode and the D2D-assisted relaying mode. Mode selection and power control decisions are dependent to the data rate of each IEM, resulting in different delay and power consumption in each transmission mode.

It is assumed that all IEMs transmit data simultaneously, and the channel gain and the report length are fixed during the transmission phase, the end-to-end delay of link (i, j) over sub-channel C_i can be calculated as [25]

$$D_{ij}^{C_i} = 1 + \frac{B_{i,t}}{T_i}, \tag{7}$$

where 1 ms represents the time interval between the time when the packets are generated and the time when the packets are placed in the queue. The throughput of IEM i over sub-channel C_i can be calculated as [25]

$$T_{i,t} = \min\{B_{i,t}, R_{i,t}\}. \tag{8}$$

On the other hand, the total power consumption of each IEM consists of the circuit power due to signaling and active circuit blocks [29], the transmission power, and the additional power depending on the transmission mode selected. The circuit power can be modeled as the total of a static term and a dynamic term, $P_c = VI_{leak} + A_sCfV^2$, where V, I_{leak}, A_s, C and f denote the transistors supply voltage, the leakage current, the fraction of gate actively switching, the circuit capacitance, and the clock frequency respectively [30]. The frequency is assumed to be dynamically scaled with the sum rate, therefore the circuit power can be modeled as [31]

$$P_c = P_s + \xi R_{i,t}, \tag{9}$$

where P_s denotes the static term and ξ is a constant representing dynamic power consumption per unit data rate. In this work, the circuit power is calculated only when IEMs have reports to be transmitted to the control center. The end-to-end delay and the total power consumption for each IEM in different transmission mode can be calculated as follows.

1) DIRECT TRANSMISSION MODE

In the direct transmission mode, IEMs can transmit the reports directly to the BS over cellular links. Let $R_{i,t}^{DM}$ denote the data rate of IEM i over sub-channel C_i in the direct transmission mode at timeslot t, which can be formulated as [6]

$$R_{i,t}^{DM} = R_{i,t}^{C_i}. \tag{10}$$

The delay of IEM i in direct transmission mode, which is also the delay of cellular link is given as follows

$$D_i^{DM} = D_{i0}^{C_i}, \tag{11}$$

in which index 0 is referring to the BS. The total power consumed by IEM i in the direct transmission mode at timeslot t can be formulated as [32]

$$P_{i,t}^{DM} = P_c + p_{i,t}^{C_i} + \sigma(P_c + \tilde{p}_{i,t}^{C_i}), \tag{12}$$

where σ denotes the interfering phase. Note that $\sigma = 0$ if sub-channel C_i is not reused by any D2D link.

2) RELAYING MODE

In the relaying mode, IEM i relays its report to IEM r through the access link, and then IEM r forwards the report to the BS through the backhaul link over sub-channel C_r. Let $R_{i,t}^{RM}$ denote the data rate of IEM i in the relaying mode, which can be formulated as follows [6]

$$R_{i,t}^{RM} = \min\{R_{i,t}^{C_i}, R_{r,t}^{C_r}\}. \tag{13}$$

The delay of IEM i in the relaying mode when report is transmitted through the access link and the backhaul link can be calculated as follows

$$D_i^{RM} = D_{ir}^{C_i} + D_{r0}^{C_r}. \tag{14}$$

The total power consumption of IEM i in the relaying mode can be formulated as follows [32]

$$P_{i,t}^{RM} = P_c + p_{i,t}^{C_i} + \dot{p}_{r,t}^{C_r}, \tag{15}$$

where $\dot{p}_{r,t}^{C_r}$ denote the additional power consumed by IEM r to relay the report of IEM i, which is dependent on the queue length of IEM r, and can be formulated as

$$\dot{p}_{r,t}^{C_r} = \begin{cases} P_c + p_{i,t}^{C_i}, & \text{if } Q_{r,t} = 0, \\ p_{r,t}^{C_r}, & \text{otherwise.} \end{cases} \tag{16}$$

When IEM r has no report to send, the additional power is the same power consumed by IEM i at access link. Otherwise, the additional power is the transmission power used by IEM r to relay the report of IEM i.

3) D2D-ASSISTED RELAYING MODE

In the D2D-assisted relaying mode, IEM i transmits reports to IEM r through the D2D link over sub-channel C_e, that is allocated for the direct transmission mode of IEM e over cellular link to overcome the bottleneck effect of the access link. Then IEM r relays the report to the BS through the backhaul link over sub-channel C_r. Let $R_{i,t}^{DRM}$ represents the data rate of IEM i in the D2D-assisted relaying mode, that can be formulated as [6]

$$R_{i,t}^{DRM} = \min\{\tilde{R}_{i,t}, R_{r,t}\}, \tag{17}$$

where $\tilde{R}_{i,t}$ denotes the instantaneous data rate of IEM i over sub-channel C_e with interference from sub-channel C_i. This mode is enabled only when IEM i and IEM e are within the D2D proximity $L_{\max}$, where $L_{\max} = (\frac{p_{i,t}^{C_i}}{\rho_{\min}})^{1/\eta_d}$ [33]. $\rho_{\min}$ and η_d denote the receiver sensitivity and the path-loss exponent for the D2D links respectively. In the Rayleigh fading environment, various techniques could be used to relax the Rayleigh fading assumption to general fading channels [34]. As the result, the instantaneous D2D distance $L_{\max}$ only depends on the path loss exponent as formulated in [33]. Therefore, $\tilde{R}_{i,t}$ is obtained as follows

$$\tilde{R}_{i,t} = \begin{cases} {R_{i,t}}^{C_e}, & \text{if } L_{i,e} < L_{\max}, \\ 0, & \text{otherwise,} \end{cases} \tag{18}$$

in which $L_{i,e}$ is the distance of IEM i to IEM e. The delay of IEM i in the D2D-assisted relaying mode when the report is transmitted by the D2D link and the backhaul link can be calculated as

$$D_i^{DRM} = D_{ir}^{C_i,C_e} + D_{r0}^{C_r}. \tag{19}$$

The total power consumed by IEM i in the D2D-assisted relaying mode can be formulated as [32]

$$P_{i,t}^{DRM} = 2P_c + p_{i,t}^{C_i} + \tilde{p}_{e,t}^{C_e} + \dot{p}_{r,t}^{C_r}, \tag{20}$$

where $\tilde{p}_{e,t}^{C_e}$ denotes the transmission power of IEM e at timeslot t during interfering phase.

B. PROBLEM FORMULATION

The report transmission of each IEM could be operated in one of the three modes, indicated by α_i, ω_i and μ_i. These binary indicators show whether IEM i operates in the direct transmission mode, the relaying mode or the D2D-assisted relaying mode respectively. Considering the transmission mode decision, the delay of IEM i during a transmission can be expressed as

$$D_i = \alpha_i D_i^{DM} + \omega_i D_i^{RM} + \mu_i D_i^{DRM} \tag{21}$$

Energy efficiency can be defined as information bit per unit of energy, which corresponds to the ratio of the data rate to the unit power consumption [35], which expressed as [36]

$$\eta = \frac{\sum_{i=1}^{M} R_{i,t}}{\sum_{i=1}^{M} P_{i,t}}, \tag{22}$$

where $P_{i,t}$ denotes the total power consumption of IEM i at timeslot t.

A joint power control and mode selection problem is formulated to obtain maximum η_t under the mode selection and power constraints. The proposed solutions to the problem are p_i and a_i, which are defined as the proposed power control and the proposed transmission mode selection of IEM i respectively. Considering both proposed solution parameters, the energy efficiency can be expressed as

$$\eta(a_i, p_i) = \frac{\sum_{i=1}^{M}(\alpha_i R_{i,t}^{DM} + \omega_i R_{i,t}^{RM} + \mu_i R_{i,t}^{DRM})}{\sum_{i=1}^{M}(\alpha_i P_{i,t}^{DM} + \omega_i P_{i,t}^{RM} + \mu_i P_{i,t}^{DRM})}. \tag{23}$$

The joint power control and mode selection problem can be formulated as follows

$$P1 : \underset{a_i, p_i, i \in \mathcal{M}}{\text{maximize}} \quad \eta(a_i, p_i), \tag{24}$$

subject to

$$p_{i,t}^{C_i} \leq P^{\max}, \quad \forall i \in \mathcal{M}, \tag{25a}$$
$$\overline{D} \leq D_0, \tag{25b}$$
$$\alpha_i + \omega_i + \mu_i = 1, \quad \forall i \in \mathcal{M}, \tag{25c}$$
$$\sum_i \tau_{i,e} \leq 1, \quad \tau_{i,e} \in \{0, 1\},\ \forall e \in \mathcal{F}, \tag{25d}$$
$$\sum_e \tau_{i,e} \leq 1, \quad \tau_{i,e} \in \{0, 1\},\ \forall i \in \mathcal{M}, \tag{25e}$$
$$\sum_i \phi_{i,r} \leq 1, \quad \phi_{i,r} \in \{0, 1\},\ \forall r \in \mathcal{G}, \tag{25f}$$
$$\sum_r \phi_{i,r} \leq 1, \quad \phi_{i,r} \in \{0, 1\},\ \forall i \in \mathcal{M}, \tag{25g}$$
$$L_{i,e} < L_{\max}, \quad \forall \mu_i = 1, \tag{25h}$$

where $\tau_{i,e}$ and $\phi_{i,r}$ denote the resource reuse indicator for IEM i and IEM e, and relay indicator for IEM i and IEM r respectively. $\tau_{i,e} = 1$ when IEM i reuses the resource of IEM e and $\phi_{i,r} = 1$ when IEM i uses IEM r to relay it report, otherwise $\tau_{i,e} = 0$, $\phi_{i,r} = 0$. Constraint (25a) guarantees the transmission power of IEMs are within the maximum limit. Constraint (25b) ensures the average delay, $\overline{D} = \sum_i^M D_i/M$ under the delay constraint D_0 and constraint (25c) ensures that only one transmission mode is selected to each IEM. Constraint (25d) indicates that the sub-channel of IEM e can only be reused once only. While constraint (25e) ensures that IEM i can only reuse sub-channel of IEM e once. Constraints (25f) and (25g) ensure that IEM i can only relay its reports to one IEM only and IEM r can only forward the report of IEM i once. The last constraint limits the distance to establish a D2D link.

V. PROPOSED SOLUTION

The problem has a mixed integer nature, therefore P1 is decomposed into two subproblems. In the system, the transmission mode is selected by the BS and the power control is managed by each IEM, therefore it is realistic to decompose the problem. To solve problem P1, first the proposed power control under given mode selections is obtained. Then to further find the proposed mode selection, the brute-force searching method is exploited and the EEDO algorithm is proposed.

A. PROPOSED POWER CONTROL

In this subsection, it is assumed that the transmission mode selection of each IEM has been preset under condition (25c), *i.e.* a_i is fixed for i. Thus $P1$ is decomposed into a power control problem $P2$ and a mode selection problem $P3$. $P2$ is denoted as follows

$$P2 : \underset{p_i, i \in \mathcal{M}}{\text{maximize}} \quad \eta(p_i), \tag{26}$$

subject to

$$3p_{i,t}^{C_i} \leq P^{\max}, \quad \forall i \in \mathcal{M}. \tag{27a}$$

Power control decisions are done based on the proposed data rate values that are dependent to the size of IEM report at each transmission phase. The proposed data rate of each IEM is obtained by calculating the minimum data rate, $R_{i,t}^{\min}$, the maximum data rate, $R_{i,t}^{\max}$, and the average data rate, $R_{i,t}^{\text{ave}}$ at timeslot t. Based on (7) and (8), the maximum data rate of IEM i can be derived as

$$R_{i,t}^{\max} = \frac{B_{i,t}}{D^{\min}}, \tag{28}$$

where $D^{\min}$ denote the minimum delay of the grid. Equation (30) can be used to determine $R_{i,t}^{\text{ave}}$ and $R_{i,t}^{\min}$, simply by changing the value of $D^{\min}$ to D^{ave} and $D^{\max}$.

The proposed data rate of IEM i at timeslot t, $R_{i,t}^{*}$ is computed as [18]

$$R_{i,t}^{*} = \begin{cases} R_{i,t}^{\min}, & \text{if } R_{i,t}^{\text{ave}}, < R_{i,t}^{\min}, \\ R_{i,t}^{\text{ave}}, & \text{if } R_{i,t}^{\min} \leq R_{i,t}^{\text{ave}} \leq R_{i,t}^{\max}, \\ R_{i,t}^{\max}, & \text{if } R_{i,t}^{\text{ave}}, > R_{i,t}^{\max}. \end{cases} \tag{29}$$

Note that the queue length of IEM could vary depending on its associated zone, therefore the proposed data rate of each IEM at each transmission phase could also vary.

The proposed transmission power of IEM i, p_i^{*}, can be obtained by calculating the lowest SNR with respect to the proposed data rate $R_{i,t}^{*}$. Assume that perfect estimation of SNR over cellular link, based on AMC scheme, for any $R_{i,t}^{*}$ that fall in the region β_z, the $\gamma_{ij,t}^{*}$ is the minimum SNR value in region β_z. In this system, the accurate channel estimation is possible since the network operates in a slow fading environment with a static topology. The proposed transmission power of IEM i is obtained based on (3) as follows

$$p_i^* = \frac{\gamma_{ij,t}^* N_{i,t}}{G_{ij,t}}. \tag{30}$$

However, in cases of $p_i^* > P^{\max}$, the transmission power is set to the maximum, $p_i^* = P^{\max}$.

B. PROPOSED TRANSMISSION MODE SELECTION

Based on the above p_i^*, the proposed mode selection a_i for all $i \in M$ is further investigated, which is an equivalent form of $P1$ an is represented as $P3$:

$$P3 : \underset{a_i, i \in \mathcal{M}}{\text{maximize}} \quad \eta(a_i, p_i^*), \tag{31}$$

subject to

$$\overline{D} \le D_0, \quad \forall i \in \mathcal{M}, \tag{32a}$$
$$\alpha_i + \omega_i + \mu_i = 1, \quad \forall i \in M, \tag{32b}$$
$$\sum_i \tau_{i,e} \le 1, \quad \tau_{i,e} \in \{0,1\}, \ \forall e \in \mathcal{F}, \tag{32c}$$
$$\sum_e \tau_{i,e} \le 1, \quad \tau_{i,e} \in \{0,1\}, \ \forall i \in \mathcal{M}, \tag{32d}$$
$$\sum_i \phi_{i,r} \le 1, \quad \phi_{i,r} \in \{0,1\}, \ \forall r \in \mathcal{G}, \tag{32e}$$
$$\sum_r \phi_{i,r} \le 1, \quad \phi_{i,r} \in \{0,1\}, \ \forall i \in \mathcal{M}, \tag{32f}$$
$$L_{i,e} < L_{\max}, \quad \forall \mu_i = 1. \tag{32g}$$

Based on p_i^* reported by the IEM, the BS obtains a new $R_{i,t}^*$ that considers actual channel condition of IEM based on $\gamma_{ij,t}^*$ using (3), then calculates the data rate of each transmission mode and selects the transmission mode with the highest data rate in order to satisfy the end-to-end delay of each IEM. Selecting the transmission mode with highest data rate could improve the delay when data rate differentiation occurs due to significant increment in the report size. The proposed mode selection for IEM i represents by the binary indicators α_i, ω_i and μ_i. The proposed mode selection that maximizes energy efficiency and satisfy end-to-end delay in the network can be obtained by exploiting the EEDO Algorithm. Note that the channel and report length remain constant during transmission phase, therefore the BS only performs mode selection at the timeslot at the beginning or transmission phase.

C. THE EEDO ALGORITHM

The mode selection problem can be solved using the EEDO algorithm based on the brute-force searching method. In brute-force searching method, proposed solutions are obtained based on the enumeration of all possible actions and selecting one with the best value. Since the number of IEMs in a cell and the mode selection space are relatively low, the brute-force searching approach is a practical method for this scenario. The EEDO algorithm finds the mode selection for each IEM as described in Algorithm 1.

Algorithm 1 The EEDO Algorithm

```
Initialize
t = 1
for all i = {1, 2, ··· , M} do
   Based on p_i^*, obtain γ_{ij,t}^* by solving (3), then obtain R_{i,t}^*
   from the AMC scheme
   Perform Algorithm 2
   if i ∈ F or i ∈ G then
      a_i ← α_i
   else
      Initialize reuse IEM and RI counters, f = 1, g = 1
      if g ≤ G then
         if f ≤ F then
            Solve (12), (15), (19) to obtain R_{i,t}^{DM}, R_{i,t}^{RM},
            R_{i,t}^{DRM}
         else
            Set R_{i,t}^{DRM} = 0 and solve (12) and (15) to obtain
            R_{i,t}^{DM} and R_{i,t}^{RM}
         end if
      else
         Set R_{i,t}^{DRM} = 0 and R_{i,t}^{RM} = 0 and solve (12) to
         obtain R_{i,t}^{DM}
      end if
      if R_{i,t}^{DM} ≥ R_{i,t}^{RM} ≥ R_{i,t}^{DRM} then
         a_i ← α_i
      else if R_{i,t}^{RM} > R_{i,t}^{DM} ≥ R_{i,t}^{DRM} then
         a_i ← ω_i
         update Q_{g,t}, g = g + 1
      else if R_{i,t}^{DRM} > R_{i,t}^{RM} ≥ R_{i,t}^{DM} then
         a_i ← μ_i
         update Q_{g,t}, γ_{f,t}^*, γ_{i,t}^*, R_{i,t} and R_{f,t}, g = g + 1 and
         f = f + 1
      end if
   end if
end for
Output: the proposed mode selection a_i.
```

In this algorithm, the proposed data rate for each IEM is first obtained based on $\gamma_{ij,t}^*$ using the AMC scheme. Then, the set of RIs and reuse IEMs is obtained by performing Algorithm 2. Next, the data rate for each transmission mode is calculated and the proposed mode selection is determined. To protect the QoS of RIs and reuse IEMs, all sub-channel of IEMs can only be reused once and an IEM can act as RI once per transmission phase. Therefore, when the mode selection has been decided for an IEM, if the D2D-assisted relaying mode or the relaying mode is selected, the resource reuse and relay counters are increased by one. If all reuse IEMs and RIs have been used, then the remaining IEMs will operate in the direct transmission mode. The computational complexity of the algorithm is $O(M^A)$ [37] in one time iteration where A is the number transmission modes. The computational complexity of the algorithm is relatively low due to small number

TABLE 1. Simulation parameters.

Parameter	Value
BS Antenna Height	50 [m]
IEM Antenna Height	3 [m]
Rooftop Height	30 [m]
Rood Orientation	90 [degree]
Building Space	50 [m]
Street Width	12 [m]
Lognormal shadowing	0 [dB] mean, 8 [dB] standard deviation

of transmission modes, hence it is possible to obtain proposed solutions in the network.

Algorithm 2 Relay Selection Algorithm

Initialization
Set $i = 1$
Calculate $\overline{B}_t = \sum_{i=1}^{M} B_{i,t}/M$, and $\overline{\gamma}_t^* = \sum_{i=1}^{M} \gamma_{i,t}^*/M$
for $i \leq M$ **do**
  if $\gamma_{i,t}^* > \overline{\gamma}_t$ **then**
    if $B_{i,t} < \overline{B}_t$ **then**
      $i \in \mathcal{G}$
    else
      $i \in \mathcal{F}$
    end if
  end if
end for
Output: the set of $\mathcal{G}$ and $\mathcal{F}$

D. RELAY SELECTION ALGORITHM

In order to satisfy the delay constraints, the RIs with short report and high SNR are selected. Therefore, the relay selection is dependent on the report length and the channel state of each IEM at the beginning of transmission phase. Algorithm 2 [38] is also performed based on brute-force searching method [18] to obtain a set of potential RIs, $\mathcal{G}$ which is a set of IEMs that have higher SNR than the average SNR, $\overline{\gamma}_t^*$ and smaller queue length than the average packet length $\overline{B}_t$. Additionally, based on Algorithm 2, IEMs in $\mathcal{F}$ are assigned as reuse IEMs, in which the sub-channels of the IEMs in the set can be reused for D2D-Assisted relaying mode.

VI. SIMULATION RESULTS AND DISCUSSION

Computer simulations are used to evaluate energy efficiency and end-to-end delay of the proposed scheme in various conditions. System parameters are explained and simulation results are discussed in this section.

A. SYSTEM PARAMETERS

It is assumed that the coverage radius of the BS is 800m, and the total of 20 IEMs are uniformly distributed in the cell [6]. Each packet has the size of 1080 bits, and the number of packets generated in normal and fault zone are $B_n = 1$ packet and $B_f = 15$ packets respectively [6]. The timeslot length is 1ms [25] and each sub-channel has the bandwidth of 180kHz [39]. The channel model considers both the large-scale shadowing and the small-fading modeled as Rayleigh random variable for non-line-of-sight (NLOS) communications. The access and backhaul links are both NLOS, and COST-231 Walfish-Ikegami path loss model with the carrier frequency of 2GHz and the additive white Gaussian noise with power density of −174 dBm/Hz [6] is employed in the simulation. Assume that $\rho_{\min} = -90$ dBm and $\eta_d = 4$. Other channel model parameters are given in Table I. The channel state and the number of packets can be carried by the link in a timeslot under different channel states according to AMC scheme, i.e R_z with $z = \{1, 2, 3, 4, 5, 6\}$ are set to 0, 1, 2, 3, 6, 9 respectively according the SINR thresholds for channel states given in [27], Table II. 3.6kV-120V/10kVA IEMs model are used in this research [40] which result in $V = 120$V and $I_{leak} = 1.1$A. The prototype is an SST with a high-performance system controller that used in the FREEDM system. For simplicity we set $\xi = 1$. Values of $D^{\min}$, $D^{\max}$, D^{ave} and t^{end} are set to 0.1ms, 3.0ms, 1.5ms and 500ms respectively [5].

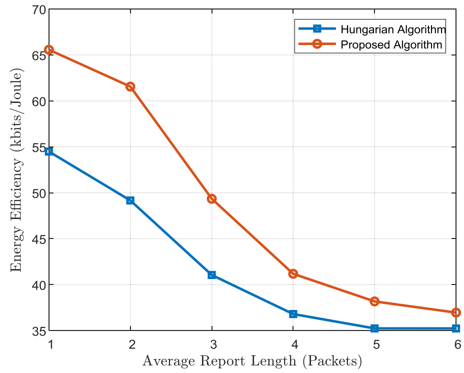

FIGURE 4. Energy efficiency comparison between the proposed algorithm and Hungarian algorithm with different average packet lengths.

To validate the effectiveness of the brute-force method, the simulation on energy efficiency and average delay of the brute-force method and the Hungarian algorithm [41] under different average report lengths is conducted. The results in Figure 4 and Figure 5 show that our proposed algorithm yields higher energy efficiency and lower delay than the Hungarian algorithm, respectively. The reason for that is because the brute-force method, also known as exhaustive method, searches for all possible actions and selects the best one.

In this paper, considering the transmission mode in device-to-device communications underlaying cellular networks for the FREEDM system, three different schemes are used for comparison, which are explained as follows

- Direct scheme: the scheme that only offers the direct transmission mode [6].
- Relay scheme: the scheme that offers the direct transmission mode and the relaying mode [6]. The RIs are selected using Algorithm 2.
- Proposed scheme: the scheme that offers three transmission modes which are the direct transmission mode, the relaying mode and the D2D-assisted relaying mode

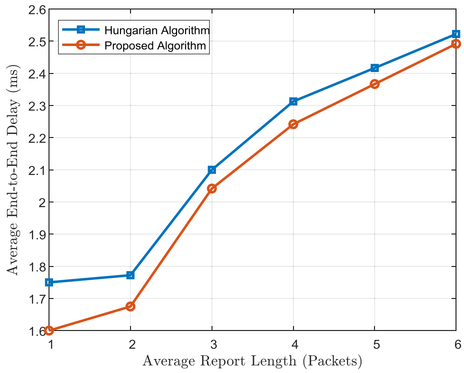

FIGURE 5. Average delay comparison among two algorithms under different average packet lengths.

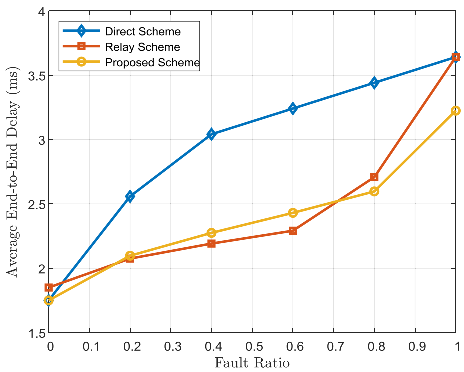

FIGURE 6. End-to-end delay comparison among three schemes under different fault ratios.

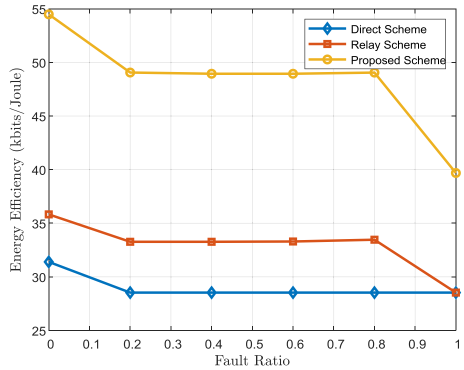

FIGURE 7. Energy efficiency comparison among three schemes under different fault ratios.

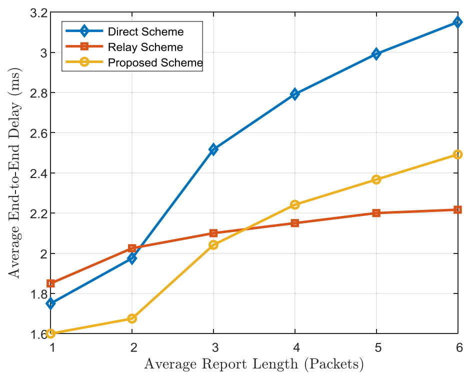

FIGURE 8. End-to-end delay comparison among three schemes with varying average report lengths.

with the power control method. The RIs are selected using Algorithm 2.

The performance of all three schemes is investigated under different fault ratios, average report lengths and average SNRs. Fault ratio is defined as the ratio of the number of IEMs in the fault zones to the total number of IEMs in a cell. A fault ratio of 0 indicates that there are no IEM in the fault zones. Considering the urban areas, the SNR of each IEM is varied with an average of 20 dB [26]. The maximum transmission power for each IEM is 14 dBm [6].

B. THE IMPACT OF FAULT RATIO

The impact of the fault ratio on the average end-to-end delay and energy efficiency of all three schemes is investigated. Figure 6 shows that as the fault ratio increases, the average end-to-end delay for all three schemes increases. The reason for that is because the average report length is increasing when increasing the fault ratio, hence increasing the delay. At fault ratio 0, the relay scheme has a higher delay because of the additional delay when IEMs select the relaying mode at short report length. In the proposed scheme, data rates are optimized for energy efficiency, which results in random delay improvements, therefore when the fault ratio varies from 0.2 to 0.6, the proposed scheme has higher delays than the relay scheme and when the fault ratio varies from 0.8 to 1, the proposed scheme has lower delay than the relay scheme. Moreover, it can be seen that the average delay of the relay scheme and the direct scheme are the same at fault ratio 1 because no IEMs can be used as the relaying node at fault ratio 1.

Figure 7 shows that the energy efficiency of the proposed and relay schemes decrease from fault ratio 0 to 0.2, then constant from fault ratio 0.2 to 0.8, and then decrease again from fault ratio 0.8 to 1. The reason for that is because when the fault ratio varies from 0.2 to 0.8, the number of RIs is the same, therefore the energy efficiency is constant, while in other values, the energy efficiency decreases as less number of IEMs can be used to support relay and D2D-assisted relaying modes due to more IEMs in the fault zone. The energy efficiency of the direct scheme decrease from fault ratio 0 to 0.2 then constant until fault ratio 1, because in the direct scheme, from fault ratio 0 to 0.2, more power is used to transmit more data due to more IEM in the fault zone, while the energy efficiency is constant because the number of IEMs meet poor channel conditions is the same, hence yielding the same energy efficiency. The proposed scheme has the highest energy efficiency at all fault ratios because it exploits the power control scheme. Additionally, based on both figures, the results show that there is a trade-off between energy efficiency and delay in the proposed method. However, the delay is not sacrificed too much when increasing the energy efficiency. Hence, the proposed scheme is an important method to balance the energy efficiency and the average end-to-end delay no matter what the fault ratio is.

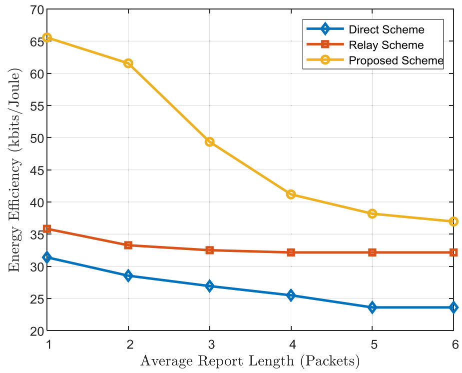

FIGURE 9. Energy efficiency comparison among three schemes with varying average report lengths.

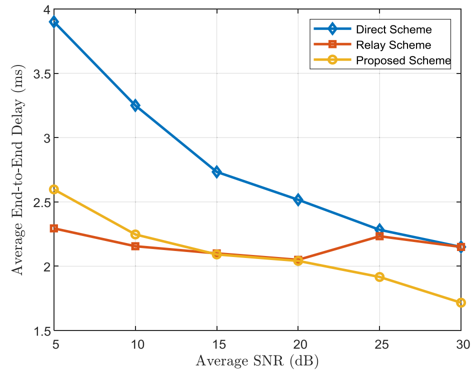

FIGURE 10. End-to-end delay comparison among three schemes under various average SNRs.

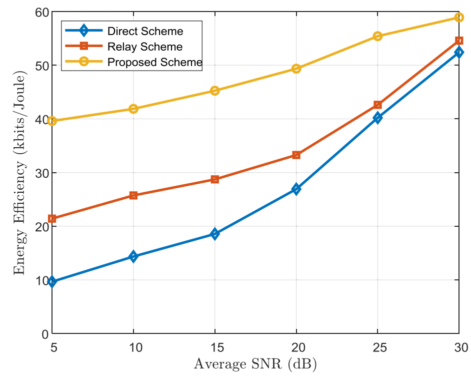

FIGURE 11. Energy efficiency comparison among three schemes under various average SNRs.

C. THE IMPACT OF AVERAGE REPORT LENGTH

The impact of the average report length on the performance of all three schemes with fault ratio 0.5 is investigated. The largest report size of IEMs from the fault zones is 15 packets, resulting the maximum average report length for 20 IEM with 0.5 fault ratio is 6 packets. Figure 8 shows that all IEMs require more time to complete the transmissions when the average report length increases, which occurs according equation (7). The relay scheme has higher delays than the direct scheme at average length 1 and 2 packets, that means the scheme is not suitable for small report lengths as selecting the relaying mode at this condition results in the excess delay due to the relaying process. Moreover, the proposed scheme has higher delays than the relay scheme when report length is more than 4 packets, because at large report lengths, optimizing data rate for energy efficiency results in the increase of delay. However the delay is still in an acceptable range, which is between 3 to 16 ms.

The energy efficiency of all three schemes for different average report lengths is shown in Figure 9. The energy efficiency is decreasing when increasing the average report length because the increase of data size associated to the increase of power consumption. In addition, the performance of the proposed scheme outperforms the other two schemes at all average report lengths. Based on both figures, the results show that there is a trade-off between energy efficiency and delay in the proposed method when varying the average report length. However, the delay is still acceptable when increasing the energy efficiency.

D. THE IMPACT OF AVERAGE SIGNAL-TO-NOISE RATIO (SNR)

The impact of the average SNR on the performance of all three schemes when the average report length is 3 packets, with fault ratio 0.5 is also studied. The value of SNR represents the channel quality, where low SNR indicates that the channel is in a poor condition and vice versa. Figure 10 shows that the average end-to-end delay of the proposed scheme and the direct scheme decrease as the channel quality gets better. The reason for that is because a high SNR enables a high data rate, therefore, the average end-to-end delay decreases. The average end-to-end delay is defined as the summation of the total delay of all IEMs divide by the total number of IEMs, which is 20, therefore, as more IEMs select the direct transmission mode after 20 dB in the relay scheme, the gap between the direct scheme and the relay scheme decreases. Moreover, the delay of the proposed scheme is higher than the relay scheme when the average SNR varies from 5 dB to 15 dB because less number of IEMs can be used to support the D2D-assisted relaying mode when more IEMs are in poor channel conditions.

The energy efficiency of all three schemes increase as the average SNR increases as shown in Fig. 11. The reason for that is because high SNR result in high data rate, and high data rate causes less waiting time to transmit data for all schemes, hence it is more energy efficient. Further, as the proposed scheme offers more modes and uses the power control method which optimized the data rate, it outperforms the other two schemes at all average SNR values. Based on both figures, the results show that there is a trade-off between energy efficiency and delay in the proposed method when the average SNR varies from 5 dB to 30 dB. The trade-off is a slightly higher delay, however still outperforming the direct transmission strategy. Hence, the proposed scheme is crucial for the network to balance energy efficiency and average end-to-end delay regardless of the average SNR.

VII. CONCLUSION

This paper investigated the application of D2D communications for FREEDM system in smart grid. D2D communications have the ability reduce power consumption and improve delay performance of smart grid applications with energy-hungry devices and real-time data. Energy efficiency and delay problems in D2D communications underlaying cellular networks under different data size and time-varying channel conditions were studied. A joint power control and mode selection scheme was proposed to satisfy delay constraints and improve energy efficiency in the network. A combinatorial power control and mode selection problem was formulated and the problem was decomposed into two subproblems. A brute-force searching method based algorithm was proposed to find proposed solutions. The performance of the proposed scheme was evaluated under various fault ratio, average SNR and average report length. Simulation results showed that the proposed scheme outperforms other two scheme in terms of energy efficiency in all scenarios but has higher delay when more IEMs in fault zone, longer average report length and low SNR, as there is a trade-off between energy efficiency and average end-to-end delay in the proposed scheme. However, the average end-to-end delay is still acceptable when enhancing the energy efficiency. Hence, the proposed scheme is one of the important solutions to improve the performance of the network under fault and poor channel conditions. Moreover, this paper showed that simple methods such as the brute-force method can also give significant improvements in certain situation, where the search space is not too large.

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