Delay-Optimal Relay Selection in Device-to-Device Communications for Smart Grid

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***Abstract*—The smart grid communication network adopts a hierarchical structure which consists of three kinds of networks which are Home Area Networks (HANs), Neighborhood Area Networks (NANs), and Wide Area Networks (WANs). The smart grid NANs comprise of the communication infrastructure used to manage the electricity distribution to the end users. Cellular technology with LTE-based standards is a widely-used and forward-looking technology hence becomes a promising technology that can meet the requirements of different applications in NANs. However, the LTE has a limitation to cope with the data traffic characteristics of smart grid applications, thus require for enhancements. Device-to-Device (D2D) communications enable direct data transmissions between devices by exploiting the cellular resources, which could guarantee the improvement of LTE performances. Delay is one of the important communication requirements for the real-time smart grid applications. In this paper, the application of D2D communications for the smart grid NANs is investigated to improve the average end-to-end delay of the system. A relay selection algorithm that considers both the queue state and the channel state of nodes is proposed. The optimization problem is formulated as a constrained Markov decision process (CMDP) and a linear programming method is used to find the optimal policy for the CMDP problem. Simulation results are presented to prove the effectiveness of the proposed scheme.**

I. INTRODUCTION

The smart grid communication network adopts a hierarchical structure which consists of three kinds of networks which are Home Area Networks (HANs), Neighborhood Area Networks (NANs), and Wide Area Networks (WANs). The NANs consist of the communication infrastructure used to manage the electricity distribution from the electric generation and transmission domains to the end users [1]. An electric distribution system in NANs can be represented by the Future Renewable Electric Energy Delivery and Managements (FREEDM) system [2]. In the FREEDM system, each household manages their energy demand with the assistance of small scale distribures energy resources (DERs) such as solar panels and wind turbines. On the other hand, the local energy management is done by an Intelligent Energy Management (IEM) which is responsible for collecting meter usage and device status from the end users, making energy management decisions and reporting the decisions to the control centre.

Cellular technology with LTE-based standards have been a preference for distributed controls and real-time communications in the smart grid NANs due to LTE widely-used and forward-looking technology features. However, LTE was designed for a medium number of users in a cell and cannot cope with the smart grid traffic characteristic that has short messages with a massive traffic volume [3]. Therefore, LTE needs enhancements to support the smart grid communications with stringent requirements. D2D communication is one of the possible alternatives to enhance the performance of LTE.

D2D communications enable direct transmissions between devices without the assistance of base stations by reusing the cellular resources. Enhancing LTE with D2D communications for NANs can lead to reliability improvements with the help of multi-path diversity. Moreover, direct D2D communications between smart grid domains in close distances could offer delay minimization for time-critical smart grid applications [4].

Delay is one of the important communication requirements for smart grid NANs [5]. In the FREEDM system, an IEM makes energy management decisions based on meter usage and device status data from the end users, and send reports to the control center. When a fault occurs, the affected IEM must transmit a report to trigger a response from the corresponding device as soon as possible. Out-of-date reports can be useless and might lead to potential system failures [6]. Existing network does not take the issue of delay into consideration and only provide direct transmission mode. Therefore, in this kind of situation, D2D communications can be used in order to minimize the delay performance of the LTEs.

A research on D2D communications in the smart grid applications has been done by Cao *et al.* in [7]. D2D-assisted relaying framework is proposed to increase the achievable data rate of the access link by exploiting D2D communications to minimize the information loss rate of links. However, this work does not consider the QoS of the cellular wireless network, such as delay performance. There is some research on delay in D2D communications or smart grid. Lei *et al.* used a CMDP problem to study the optimal decision on mode selection and resource allocation for single hop communication [8]. Wang *et al.* proposed a solution for delay-aware resource allocation by considering the instantaneous channel fading information and queue length information of the devices [9]. In [10] Wang *et al.* formulated stochastic optimization problem for dynamic power control by taking the conditions of Medium Access Channel (MAC) layer and physical layer into account. Chamralampos *et al.* studied the problem of Random Access Channel (RACH) in LTE standard technology and proposed Random Access for Distribution

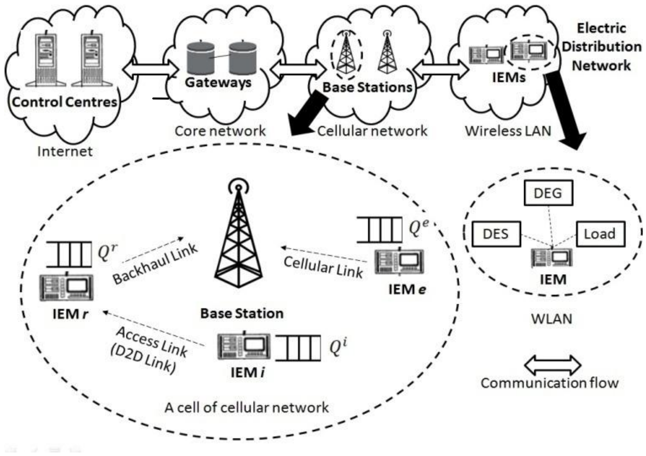

Fig. 1: The communication structure of an electric distribution network.

Automation (RADA) to improve the access latency and reliability [11].

In this paper, we study the delay optimization of D2D communications for the smart grid NANs. We use a practical model for the traffic of IEMs, namely a Markov modulated Poisson process (MMPP) model. We also propose a relay selection algorithm to identify potential relay IEMs with the features of short queue and high data rate. The reason is that relay scheme should be adaptive to both CSI and QSI in order to minimize the delay performance of the network. The delay optimization problem is formulated as a constrained a Markov decision problem (CMDP) and a linear programming method is used to obtain the optimal policy of the CMDP problem.

The rest of the paper is organized as follows. The system model is described in Section II. In Section III, the explanations on relay selection, mode selection and sub-channel allocation are presented. The performance metrics, the system state, control policy and state transition probability are derived in Section IV. The CMDP is formulated and solved in Section V. The simulation results are presented and discussed in Section VI and the paper is concluded in Section VII.

II. SYSTEM MODEL

We consider an electric distribution network with a hierarchical structure consisting of several layers of wired and wireless networks as shown in Fig. 1. The hierarchical structure has the ability to enhance the scalability and reduce the investment cost of the network. In the FREEDM system, an IEM collects information from end devices to manage loads and DERs, such as distributed energy generations (DEGs) and distributed energy storages (DESs) through a wireless local area network (WLAN). Based on the information received, an IEM makes an energy management decision and sends a report to the control center located in the internet architecture through the cellular network and wired network. Wired networks connect BSs to the control center through gateways in the core network. The network model in this paper is adopted from [7].

We adopt multi-hop relaying communications to improve the spatial diversity of the cellular network. The link between the IEM and the relaying IEM (RI) is the access link while the link between the RI and the BS is the backhaul link. We implement a D2D-assisted relaying framework to overcome the bottleneck effect of relaying communication in the smart grid communication situations. Let $i \in \{1, \dots, D\}$ denote the index of D IEMs in a cell. All IEMs are transceivers over multiple sub-channels and we assume that each IEM in the same cell can directly transmit the control message over the D2D control channel. The whole uplink spectrum is divided into N_u sub-channel and the time is slotted with an equal length.

A. Traffic model

We assume that the incoming traffic from an IEM is random and modelled by a MMPP. The MMPPs have been used to model the traffic of various applications such as multimedia traffic. The reason is that MMPPs have the ability to capture the variability and correlation between the inter-arrival times while staying analytically tractable [12].

The MMPP traffic model of an IEM consists of K-state of Markov chain. In any state $k \in \{1,2,..,K\}$, the traffic follows a Poisson distribution with average arrival rate λ_k packet/time-slot, and the transitions between states are governed by an underlying Markov chain. Let $P_{k,x}$ denotes as the probability of transition from state k to state x The transition probability matrix $\boldsymbol{P}$ for underlying Markov chain controling transition between states is

$$\boldsymbol{P} = \begin{bmatrix} P_{1,1} & \dots & P_{1,K} \\ \vdots & \ddots & \vdots \\ P_{K,1} & \dots & P_{K,K} \end{bmatrix}. \quad (1)$$

The arrival transition matrix $\boldsymbol{P}$ is a right stochastic matrix where the summation of each row is equal to 1, thus $\sum_{x=1}^{K} P_{A_k A_x} = 1.$ We can get the average arrival rate $\bar{\lambda} = \sum_{k=1}^{K} \pi_k \lambda_k$ from the row vector of the stationary distribution of IEM traffic, $\pi = [\pi_1, \pi_2, \dots, \pi_K]$ which satisfies $\pi = \pi\boldsymbol{P}$. Let B_t denotes the amount of packet generated between time intervals. From the MMPP model, we get

$$P(B_t = b|k) = \begin{cases} \frac{\lambda_k^b e^{-\lambda_k}}{b!} \ \forall\, k \in K, & if\ 0 \le b \le B; \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where b denotes the number of times a state is selected in an interval and B denotes the maximum of b in an interval.

B. Instantaneous data rate

1) Interference link

An interfere occurs when a sub-channel is reused by a D2D link. In the D2D-assisted relaying mode, IEM i reuses sub-channel v of IEM e for access link. Therefore, the access link of IEM i over subchannel m interferes with the direct link of IEM e over sub-channel v.

2) Instantaneous SINR of link

The instantaneous channel gain of link (i,j) in the link set $\mathcal{L}$ denoted as $G_t^{ij,m}$. We assume that the channel gain consists of path loss, shadowing and fast fading effect under Rayleigh channel and remains unchanged within a time slot and i.i.d between time slots. Let $P_t^{i,m}$ represents the transmission power of IEM i over sub-channel m at time slot t. $P_t^{i,m} \leq P^i$, where P^i is the power budget for IEM i over a sub-channel. If D2D-assisted relaying mode is selected, we denote the power at the duration phase that sub-channel v is reused as $P_t^{i,m,v}$, and the power of IEM v in interference duration is $P_t^{e,v,m}$ with the constraint $P_t^{i,m,v}, P_t^{e,v,m} \leq P^e$ in which P^e is transmit power budget of IEM e over a subchannel. The SNR of IEM i over sub-channel m is given by $\gamma_t^{ij,m} = \frac{P_t^{i,m} G_t^{ij,m}}{N_t^{i,}}$, where $N_t^{i,m}$ is the noise power. However, if IEM i selects D2D-assisted relaying mode, interference occurs and the SINR of IEM i becomes

$$SINR_t^{ij} = \frac{\gamma_t^{ij}}{1+\tilde{\gamma}_t^{ij}}, \tag{3}$$

where $\tilde{\gamma}_t^{ij}$ is the SNR of the interference link, which is the direct link of IEM e over the sub-channel v.

3) CSI of link

Let $r_t^{ij,m}$ denotes the instantaneous data rate of link (i,j) over sub-channel m. We assume that an AMC scheme is used in the physical layer, in which the SINR values are divided into Z nonoverlapping consecutive regions [13]. For any channel state $z \in \{1,\dots,Z\}$, if the SINR value of a link $SINR_t^{ij,m}$, falls within the region $[\beta_{z-1}, \beta_z)$, where β_z denotes the SINR threshold for z, the instantaneous data rate $r_t^{ij,m}$ of link $(i,j) \in \mathcal{L}$ over sub-channel m is a fixed value R_z according to the selected modulation and coding at channel state z. R_z is denoted as the maximum allowable number of packets can be transmitted at channel state z. We have $\beta_0 = 0, \beta_Z = \infty$ and at the lowest CQI, we set z = 1 and $R_1 = 0$. We assume that no packet is sent in channel state 1 to obtain low transmission error probability.

The CSI of link (i,j) over a sub-channel can be defined as $H_t^{ij} = \{H_t^{ij,M} | M \in \{1,\dots,N_u\}$. When $M = m$, $H_t^{ij,m}$ represents the channel state of link (i,j) over sub-channel m. $H_t^{ij,m} = z$ if $SINR_t^{ij,m}$ is between regions $[\beta_{z-1}, \beta_z)$. Therefore the instantaneous data rate of link (i,j) is given by

$$r_t^{ij,m} = R_{H_t^{ij,m}} = R_z \,. \tag{4}$$

4) Instantaneous data rates of IEMs and links

Defining r_t^i to be the instantaneous data rate of IEM i at time slot t, which is equal to the instantaneous data rate of link (i,j) over sub-channel m, $r_t^{ij,m}$ determined from (4)

$$r_t^i = \sum_{(i,j)\in\mathcal{L}} r_t^{ij,m}. \tag{5}$$

The instantaneous data rate of r_t^{ij} of the link (i,j) over all the N_u uplink subchannels at time slot t yields

$$r_t^i = \sum_{M=1}^{N_u} r_t^{ij,M}. \tag{6}$$

C. Queue dynamics

We adopt a first-in-first-out (FIFO) behavior in the queue model. We assume that each packet has the same size with J bits. The arriving data are placed in the queue throughout the time slot t and will be transmitted at the next time slot. The packets exit the network once they reach the destination. We assume that the buffer size is large and no packets are dropped due to buffer overflow. Let Q_t^i denotes the queue length of IEM i at time t. The queue dynamic at IEM i can be express as

$$Q_{t+1}^i = \max(0, Q_t^i - r_t^i) + B_t^i. \tag{7}$$

The queue dynamic at IEM r as the RI consisting the number of packets transmitted from IEM i and can be expressed as

$$Q_{t+1}^r = \max(0, Q_t^r + (Q_t^i - r_t^i) - r_t^r) + B_t^r. \tag{8}$$

III. RELAY SELECTION, MODE SELECTION AND SUB-CHANNEL ALLOCATION

In this section, we explain the relay selection algorithm and mode selection and sub-channel allocation procedure. Let a_t^{ij} denotes the transmission mode decision for link (i,j) at time slot t, and c_t^{ij} denotes the relay selection action for link (i,j) at time slot t.

A. Relay selection algorithm

At each time slot, the BS obtains a set of potential RIs with the features of short queue and high SNR as represented in Algorithm 1. Algorithm 1 will compare the SNR of each IEM with the average SNR, $\bar{\gamma}_t$ and allocates the IEMs with higher SNR in the set $\mathbb{F}_t$. Then, from $\mathbb{F}_t$, the number of packets in the queue of each IEM is compared with the average number of packets in a queue, $\bar{Q}_t$ and the IEMs with lower number of packets are allocated in $\mathbb{G}_t$. The BS selects IEM from $\mathbb{G}_t$ for relaying mode and D2D-assisted relaying mode.

Algorithm 1 Delay aware relay selection

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Calculate average queue length $\overline{Q_t} = \sum_{i=1}^{D} Q_t^i$
Calculate average SNR $\overline{\gamma_t} = \sum_{i=1}^{D} \gamma_t^i$
Initialization: Set $i = 1$,
while $i < D + 1$ do
  if $Q_t^i \leq \overline{Q_t}$, then $i \in \mathbb{F}_t$
        if $\gamma_t^i \leq \overline{\gamma_t}$, then $i \in \mathbb{G}_t$
        end if
  end if
Increment: $i = i + 1$
end while
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B. Mode selection and sub-channel allocation

The sub-channel allocation action is determined by the transmission mode decision. When an IEM experiences bad channel conditions the IEM has to wait until the channel returns to good conditions before transmitting the packets. While when an IEM in a fault zone, more information are sent to the BS which results in a larger report size. The delay requirement might not be achieved in both cases. Therefore, the BS will select the minimum delay transmission mode and allocate sub-channels accordingly. We assume that the cellular link pairing in the D2D/cellular link pairing should operate in the direct transmission mode while D2D link pairing can operate in the D2D-assisted relaying mode.

1) *Direct mode, d*: If the instantaneous data rate of the link from IEM i to BS (denoted as 0) over sub-channel m, $r_t^{i0,m}$ is the highest compared to the instantaneous data rate other two modes, the BS selects d for IEM i, allocates sub-channel m for IEM i and sets $P_t^{i,m} = P^i$ to obtain a minimum delay for the transmission.

2) *Relaying mode, τ*: If the total instantaneous data rate of the access link over sub-channel m $r_t^{ir,m}$, and backhaul link over sub-channel u $r_t^{r0,u}$, is the highest, the BS selects τ and allocates sub-channel m for IEM i and sub-channel u for IEM r which is the RI. Then the BS sets $P_t^{i,m} = P^i$ for IEM i and $P_t^{r,u} = P^r$ for IEM r. IEM r carries the packets of IEM i to the BS.

3) *D2D-assisted relaying mode, ω*: If the total instantaneous data rate of the access link over sub-channel v $r_t^{ir,v}$, and the backhaul link under sub-channel u $r_t^{r0,u}$, is the highest for IEM i, the BS selects ω and allocates sub-channel m for IEM i and sub-channel u for IEM r as the RI and allocates sub-channel v of IEM e for IEM i during the transmission phase of ω. In this mode, the IEM r acts as D2D receiver for IEM i. IEM e is selected from $\mathbb{F}_t$ which is not in $\mathbb{G}_t$. IEM i reuses sub-channel v after IEM e is done with the transmission.

IV. SYSTEM STATE, CONTROL POLICY AND STATE TRANSITION PROBABILITY

We adopt the model from [8] to obtain the solution for the optimization problem. In this section, we give explanations on the performance metrics, the system state, the control policy, and the state transition probability and steady state probability in this section.

A. Performance Metrics

For any given steady state of the policy π^{Ω}, the average delay can be calculated.

1) *Average Queue Length*: Average queue length of IEM i can be expressed as

$$\bar{Q}^i = E^{\pi^{\Omega}}[Q^i], \tag{9}$$

which is the expectation of queue length for IEM i taken with respect to the unique steady state distribution influenced by given policy Ω.

2) *Average Throughput*: We define $\bar{T}^i$ as the average throughput of IEM i, which is dependent on the control policy at state s, $\Omega(s)$. The value can be derived as

$$\bar{T}^i = E^{\pi^{\Omega}}[T^i(S^i, \Omega(s))]. \tag{10}$$

The throughput for IEM i at time slot t can be calculated from the equation

$$T_t^i = \min(Q_t^i, r_t^i). \tag{11}$$

3) *Average Delay*: Let $\bar{D}_{ij}$ represents the average delay of transmission link $(i,j) \in \mathcal{L}$ and $\bar{D}^i$ represents average delay of IEM i. The connections between the average delay of transmission link (i,j) and those transmission modes are given as follows:

$$\bar{D}_{ij} = \begin{cases} \bar{D}^i & \text{if } a_t^{ij} = d \\ \bar{D}^i + \bar{D}^r & \text{if } a_t^{ij} = \tau \\ \bar{D}^i + \bar{D}^r & \text{if } a_t^{ij} = \omega \end{cases} \tag{12}$$

The average delay of IEM i, $\bar{D}^i$, can be calculated according to Little's law [7] as follows

$$\bar{D}^i = \bar{Q}^i / \bar{T}^i. \tag{13}$$

B. System state

The global system state which denoted as $s_t = (H_t, Q_t)$ comprising of CSI and QSI. The QSI, $Q_t = \left\{Q_t^i \middle| i \in \{1, \dots, D\}\right\}$, is the queue length of IEM i at time t, while CSI of the system, $H_t = \{H_t^{ij} | (i,j) \in \mathcal{L}\}$, is the channel state of link (i,j) at time t. The BS maintains the system state, where the CSI of each IEM is measured. The CSI of D2D link is measured by the D2D destination, which is the RI, and reported to the BS. Each IEM reports the QSI to the BS at the beginning of each time slot.

C. Control policy

At each time slot, the BS observes the system state s_t and selects an action from the set of allowable action space $\mathcal{A}$ which contains transmission mode and sub-channel allocation action a_t, from the set of allowable action space $\mathcal{A}_a$, and chooses relay selection action c_t, from the set of allowable action space $\mathcal{A}_c$. Therefore an action y comprises of actions a and c with constraints as follow

1) Each transmission link can be served by at most one RI, $\sum_{ij \in \{1,\dots,\mathcal{L}\}} c_t^{ij} \le 1$.
2) Each transmission link can reuse at most one sub-channel, $\sum_{ij \in \{1,\dots,\mathcal{L}\}} a_t^{ij,M} \le 1 \; \forall \; M \in \{1, \dots, N_u\}$.
3) Each sub-channel can be reused by at most one transmission link, $\sum_{ij \in \{1,\dots,\mathcal{L}\}} M_t^{ij} \le 1 \;\; \forall \; M \in \{1, \dots, N_u\}$.
4) Each link can choose only one transmission mode $a_t^{ij} \in \{d, \tau, \omega\}$.

A control policy here is the mapping of $S \to \mathcal{A}$ from the state space to action space, which is $\Omega(s) = a \in \mathcal{A}_a, \mathrm{c} \in \mathcal{A}_c, \forall \; s \in S$.

D. State transition probability and steady state probability

The behavior of the queue is modelled as a discrete time Markov chain (DTMC), $\{s_t\}_{t=0,1,\dots} = \{(H_t, Q_t)\}_{t=0,1,\dots}$. The state transition of the DTMC for a system state s_t and action y (a, c) at time slot t is given by

$$\Pr\{\, s_{t+1} | s_t, y\} = \Pr\{H_{t+1} | H_t\} \Pr\{\, Q_{t+1} | s_t, y\}$$

$$= \Pr\{H_{t+1}\} \Pr\{\, Q_{t+1} | s_t, y\}. \tag{14}$$

The transition probability of the queue can be derived as $\Pr\{\, Q_{t+1} | s_t, y\}$ if $Q_{t+1}^i = \max(0, Q_t^i - r_t^i) + B_t^i$. Therefore, the queue transition probability for IEM $i \in \{1, \dots, D\}$ is given by

$$\Pr\{ Q_{t+1}|s_t, y\} = \prod_{i=1}^{D} \Pr\{ Q_{t+1}^{i}|s_t, y\} \quad (15)$$

To derive channel transition probability, $\Pr(H_{t+1})$ we need to find the channel state expression. When $H_t^{ij} = \{H_t^{ij,M}\}_{M\in\{1,\dots,N_u\}}$, in which $H_t^{ij,m} = z^{ij,m}$ given $z^{ij,m} \in \{1,\dots,Z\}$, we get $SINR_t^{ij,m} \in [\mathcal{X}_{(z^{ij,m}-1)}, \mathcal{X}_{(z^{ij,m})})$. $\mathcal{X}_{(z^{ij,m})}$ denotes the value of SINR at channel state z of link link (i,j) over sub-channel m. The SINR value of link (i,j) $SINR_t^{ij}$, depends on the SNR value of the link γ_t^{ij}, and the SNR of interfering link $\gamma_t^{i'j}$. Let $\tilde{\gamma}_t^{ij,m} = \{\gamma_t^{i'j,m}|(i',j') \in \mathcal{L}^i\}$ denotes the SNR vector of interfering link to link (i,j) over sub-channel m. For any $z \in \{1,\dots,Z\}$ if the SINR value of the link $SINR_t^{ij,m}$, falls within the region $[\beta_{z-1}, \beta_z)$, the $r_t^{ij,m}$ is a fixed value R_z according to the selected modulation and coding at state s. Therefore $SINR_t^{ij,m} \in \left[\mathcal{X}_{(z^{ij,m}-1)}, \mathcal{X}_{(z^{ij,m})}\right)$, $\tilde{\gamma}_t^{ij,m}$ at time t belongs to convex polyhedron such that

$$\Gamma_{z^{ij,m}} = \left\{ \tilde{\gamma}_t^{ij,m} \middle| \begin{array}{c} \gamma^{ij,m} - \mathcal{X}_{(z^{ij,m}-1)} \sum_{(i',j')\in\mathcal{L}} \gamma_t^{i'j,m} \geq \mathcal{X}_{(z^{ij,m}-1)}, \\ \gamma^{ij,m} - \mathcal{X}_{(z^{ij,m})} \sum_{(i',j')\in\mathcal{L}} \gamma_t^{i'j,m} < \mathcal{X}_{(z^{ij,m})}, \\ \tilde{\gamma}_t^{ij,m} \geq 0 \end{array} \right\}. \quad (16)$$

When $H_t^{ij,m} = z^{ij,m}, \tilde{\gamma}_t^{ij,m}$ belongs to convex polyhedron $\Gamma_{z^{ij,m}}$, the steady-state probability that $H_t^{ij,m} = z^{ij,m}$ can be obtaind from $\Pr\left(\pi^{H_t^{ij,m}}\right) = \int_{\Gamma_{z^{ij,m}}} f(\tilde{\gamma}_t^{ij,m}) d\tilde{\gamma}_t^{ij,m}$ where $f(\tilde{\gamma}_t^{ij,m})$ is the joint pdf of $\{\tilde{\gamma}_t^{i'j}\}_{(i',j')\in\mathcal{L}}$. Therefore, the global channel state transition probability can be expressed as

$$\Pr(H_{t+1}) = \prod_{(i,j)\in\mathcal{L}} \prod_{M\in\{1,\dots,N_u\}} \Pr(H^{ij,M}) \quad (17)$$

V. PROBLEM FORMULATION AND SOLUTION

The objective of this work is to find the optimal transmission mode selection, sub-channel allocation and relay node selection policy in order to minimize the average weighted sum delay of transmission links subject to instantaneous data rate constraint. The optimization problem can be formulated as a CMDP, given as follows

$$\begin{aligned} &min_{\Omega(S)} \sum_{ij=1}^{L} w_{ij} \overline{D}_{ij} \\ &s.t. \quad r_{ij} \geq r_{min} \qquad \forall\ (i,j) \in \mathcal{L} \end{aligned} \quad (18)$$

where r_{min} is the minimum instantaneous data rate required to transmit packets under the delay constraints. w_{ij} $\forall\, ij = \{1,\dots,L\}$ is the weight of the delay for link (i,j). The behavior of a probabilistic system in this problem is influenced by the transmission mode selection, sub-channel allocation and relay node selection policy, $\Omega(s) = a \in \mathcal{A}_a,\ c \in \mathcal{A}_c\ \forall\, s \in S$, respectively. We consider a randomized policy in which action y to be taken at state s is randomly chosen according to a probability distribution represented by $\mu(y)$ such that $\sum_{y\in\mathcal{A}} \mu(y) = 1$.

The solution for CMDP formulation is the optimal policy Ω^*. To determine Ω^*, the CMDP problem is transformed into an equivalent linear programming problem, in which generates a one to one mapping between the optimal solution of the linear programming problem π^* and the optimal policy Ω^*. Let $\pi(s,y)$ denotes as the steady state probability of the action y be selected at state s. The linear programming problem with respect to the CMDP problem can be expressed as follows

$$min: \quad \sum_{s\in S} \sum_{y\in\mathcal{A}} \pi(s,y) \sum_{ij=1}^{L} w_{ij} \overline{D}_{ij}\ (s,y) \quad (19)$$

$$\begin{aligned} s.t \quad &\sum_{s\in S} \sum_{y\in\mathcal{A}} r_{ij}(s,y)\pi(s,y) \geq r_{min} \quad \forall\, ij \in \{1,\dots,L\} \\ &\sum_{y\in\mathcal{A}} \pi(s',y) = \sum_{s\in S} \sum_{y\in\mathcal{A}} P(s'|s,y)\pi(s,y) \\ &\sum_{y\in\mathcal{A}} \pi(s',y) = \sum_{s\in S} \sum_{y\in\mathcal{A}} \pi(s,y) = 1, \quad \pi(s,y) \geq 0. \end{aligned}$$

For any $s' \in S$, the transition probability $\Pr(s'|s,y)$ is the probability of transition from state s to state s' when action y is taken. The objective function and constrained function defined by linear programming problem are corresponding to the CMDP formulation. The second last constraint satisfies the Chapman-Kolmogorov equation and the last constraint satisfies the basic property of probability. The optimal solution for the linear programming problem is $\pi^*(s,y)$. The optimal policy Ω^* is a randomized policy which can be obtained by the uniquely mapped from the optimal solution of the linear programming problem

$$\mu(y = \Omega^*(s)) = \frac{\pi^*(s,y)}{\sum_{y'\in\mathcal{A}} \pi^*(s,y')}, \quad (20)$$

and the optimal solution $\pi^*(s,y)$ can be determined by using the standard linear programming solving method.

VI. SIMULATION RESULT

We use computer simulations to evaluate the performance of proposed scheme. We assume that the coverage radius of the BS is 800m, and the total of 20 IEMs are randomly located in the cell. The MMPP has 2 states with λ_1=1 packet/time-slot and λ_2=2 packets/time-slot and transition probability matrix is given by $P^A = [0.3\ 07; 0.7\ 0.3]$. Each packet has the size of 1080 bits and the time slot length is 1ms. The access link and backhaul link are both NLOS and experience a lognormal shadowing with 0 mean and 8dB standard deviation. The path loss is modelled as NLOS COST-231 Walfish-Ikegami with a carrier frequency of 2GHz and white noise power density value -174 dBm/Hz [7]. The Rayleigh fading channel and the number of packets can be carried by the link in a time slot under different channel states, i.e R_z with z = 1,2,3,4,5,6 are set to

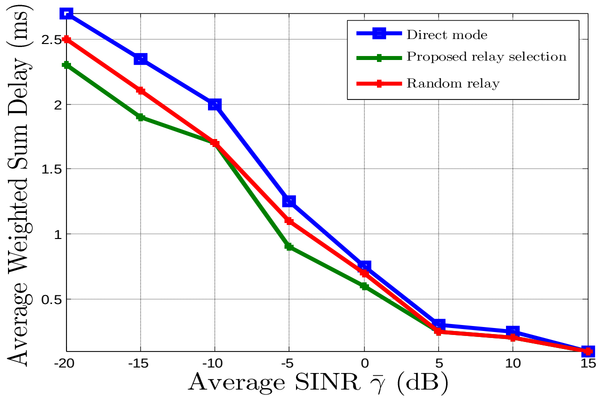

Fig. 2: Average weighed end to end delay with average SINR for three different schemes

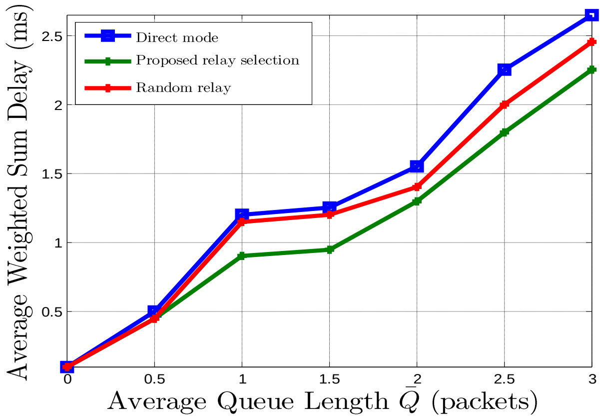

Fig. 3: Average weighed end to end delay with average SINR for three different rate requirements

0,1,2,3,6,9 respectively according the SINR thresholds for channel states given in [13,Table II].

First, we analyze the influence of the average SINRs to the average weighted sum delays for the proposed relay selection scheme and random relay selection scheme for the framework proposed in [7] at $r_{min} = 1$, and the direct transmission scheme. Fig. 2 shows the average weighted sum delay of these three schemes when the average SINR varies from -20dB to 15dB, where low SINR means the system is in bad channel condition. The results still show that the proposed scheme has the lowest delay among these three schemes. From Fig. 2 we can observe that the delay decreases when the channel becomes good. This is because more packets can be sent in one time slot, therefore delay is smaller. We can also see that when average SINR reaches -10 dB, the delay values of the proposed scheme and random relay selection scheme are the same. The reason is that relays of random scheme are selected randomly and might be the same as the relays of the proposed scheme at -10dB thus produces the same average weighted sum delay values.

When an IEM in a fault zone, report size increases significantly. Therefore, we observe the effect of the average queue length to the average weighted sum delay. The average weighted sum delay increases as the average queue length increases as shown in Fig. 3. The reason is that queue length is directly related to the delay in accordance with Little's Law [8]. At average queue length is 3 packets, the proposed scheme outperforms the direct transmission scheme by 13.2% and the random relay selection scheme by 6.12%.

VII. CONCLUSION

The smart grid NANs responsible for electricity distribution of distributed domains in smart grid. Cellular technology has been widely deployed and might be used in a long term period, which make it a preference for the NANs. However, LTE cannot cope with the data characteristics of smart grid traffic thus demands for enhancements from D2D communications. Application of D2D communications for smart grid NANs has been studied in this paper to optimize the delay performance of the network. An algorithm has been proposed for the relay selection scheme which is adaptive to CSI and QSI of the system. The simulation results show the effectiveness of the proposed scheme.

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