Analysis of the influence of device-to-device communication on the access terminal of electric power data communication network

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Abstract
The expansion of the electric power communication network year by year has enabled a large number of intelligent terminals to be accessed exponentially. Massive intelligent terminals connected to the power communication network have a huge processing demand, which causes a heavy maintenance burden on the equipment of communication networks. In order to solve this problem, this study proposes a flexible communication mechanism based on the device-to-device (D2D) technique for the intelligent terminals to deal with the processing pressure of massive information in the network. This proposed mechanism introduces where and how to use the D2D technique. In this study, this communication mechanism makes terminals give a high priority to transferring the information of important services. The D2D communication model is formulated for this communication mechanism, and the influence of different conditions on the D2D communication is analysed. The D2D communication mechanism is simulated to optimise the existing network indexes, such as traffic and sum of service level.

1 INTRODUCTION
The daily operation of the smart grid needs the support of a highly reliable communication network. To satisfy the operation demand of the grid, advanced metering infrastructure (AMI) is deployed widely to collect various kinds of data or information from intelligent terminals or sensors [1]. More and more information from the demand side (i.e. the information of prosumers) is uploaded to the network, especially to the electric power data communication network. The access to the demand-side management (DSM) information brings risks to the security of power systems. Additionally, DSM information is easy to cause the processing and maintenance pressure of some equipment of networks [2]. The research on optimisation of electric power data communication networks for terminals is particularly important. Furthermore, the access ability of terminals to the network needs to be improved.

However, the current optimisation of electric power communication networks mainly focuses on improving the reliability of cyber-physical systems or enhancing the quality of service (QoS) in networks. For example, Li et al. [3] estimated the dynamic state of generators under cyberattacks, in which attacks mainly include false data injection and denial of service attacks in networks. Qu et al. [4] proposed a novel method to improve the prediction of power cyber-physical systems risk, where the method of the dependent Markov chain theory was employed. Zhang et al. [5] made a pattern analysis of topological attacks in cyber-physical power systems considering cascading outages. Meanwhile, the IEEE 39-node system was used to verify the representativeness of the above-mentioned patterns. Qu et al [6] designed a quantitative assessment method based on seepage theory to estimate the risk propagation of power cyber-physical system. Yan et al [7]. has defined a wide range of QoS requirements for different services. They obtained the result that the packet delay of service was expected to range from 12 to 20 ms, and the packet error rate should not exceed 6% [8]. Some works investigated the application style of Zigbee and WiFi in electric power communication networks [9, 10]. Zigbee and WiFi were commonly adopted to send metering or energy usage data from intelligent terminals in the smart grid. Meanwhile, the technique of cellular-assisted communications for data transmissions between AMI equipment was also considered [11]. To improve the transmission of information, the technique of cellular-assisted communication was introduced, which

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can make terminals communicate with each other directly [12]. Cellular-assisted communication can be regarded as a device-to-device (D2D) communication method.

The D2D communication method shows great potential in improving the access ability of terminals to networks. Current D2D studies mainly explore how to improve the utilisation of radio resource allocation, which can make terminals share their spare channels. For instance, the authors in [13] illustrated a hybrid resource allocation scheme based on a deep neural network, where the scheme aimed at maximising the sum rate of terminals with a given QoS constraint. By using this scheme, terminals can transmit their information in a multi-channel environment. The authors in [14] presented a network-assisted communication mechanism to improve the transmission capability of D2D communication. This mechanism ensured the QoS in multiple communication networks. In [15], the authors presented a D2D-assisted mechanism that can be applied in wireless communications networks, when networks suffer from natural disasters and the destruction of communication infrastructures. This mechanism is considered the limitation of delay in D2D. In [16], the authors developed a novel fractional frequency reuse architecture to maximise the sum rate of the uplink. In [17], the authors proposed a scheme that combined radio resource selection with transmission power minimisation for a D2D network. In [18], the authors devised a novel joint admission control and radio resource allocation strategy that can guarantee the long-term QoS of communication in D2D. In [19], the authors proposed an improved scheme to enhance the spectrum efficiency and performance of the D2D channel by jointly considering multiple QoS constraints. In [20], the authors established a joint optimisation for D2D pair assignment and power control, where optimisation can maximise the rate of D2D communications while guaranteeing QoS. In [21], the authors proposed a strategy to achieve the goal of radio resource allocation while making the subchannel matching based on graph theory. In [22], the authors designed a radio resource allocation mechanism that does not require the full channel-state information about terminals in D2D communication.

However, it can be seen that the above-mentioned works prefer to optimise the access ability of terminals to the network while improving the transmission rate of terminals under a D2D environment. Few studies research on how to apply the D2D communication method in electric power data communication networks. Specifically, most of the studies optimise the access ability of terminals to the network without considering the difference of service levels. In power systems, the service level is more important than the transmission rate, as some services may involve in power dispatching. In other words, the service level needs to be considered when the terminal adopts the D2D technique to transfer some information. Service with a higher level means that the information is more important, which needs to be guaranteed first.

To further improve the access ability of terminals to the network, more important information of the terminal can be uploaded to the network concurrently. This study proposes a D2D communication mechanism considering the service level. The proposed D2D communication mechanism is applied when some uncertain cases exist (e.g. the network failure, signal blind area of the channel, or deterioration channel). By using the D2D communication mechanism, the access ability of terminals to the network will be improved. Also, this study will analyse the feasibility and effectiveness of the D2D communication method in solving the problem of massive information transmission. The main contributions of this study can be summarised as follows:

1. We first develop a framework for applying the D2D communication mechanism in electric power data communication networks, where the mechanism considers the difference of service level. It should be noted that utilising the D2D communication mechanism is aimed at improving the access ability of terminals to networks, especially when there exist some uncertain cases (e.g. the network failure, signal blind area of the channel, or deterioration channel).

2. The relevant communication models are formulated for the D2D mechanism. Designed communication models allow the terminals to share their communication links by using the D2D mechanism until the information can be transferred to the network. Because the mechanism considers the difference in service level, service with a high level will be guaranteed first. More important information from terminals can be uploaded to the network.

3. To verify the effectiveness of the proposed D2D communication mechanism in information transmission, we use parameters from the realistic system in simulation. Numerical results show that more important information can be uploaded to the network by using the proposed communication mechanism, even if exists some uncertain cases (e.g. the network failure, signal blind area of the channel, or deterioration channel).

2 D2D COMMUNICATION MECHANISM OF INTELLIGENT TERMINALS

As shown in Figure 1, some intelligent terminals are deployed on the demand side of the power grid to collect the necessary information from electricity consumers. Terminals transmit their information via the field servers or base stations. Then, the collected information will be uploaded to the power system operator through the electric power data communication network. Therefore, the power system operator can deal with collected information with relevant data management platform and dispatching platform. The power system operator collects all kinds of information and controls the terminal with a centralised method, which can be realised easily. However, this communication mode has some disadvantages, which can cause a great processing and maintenance burden on network equipment. To be specific, the equipment of the network which is nearby the consumer will have problems processing massive concurrent information. Therefore, this study proposes a novel communication mechanism, which is aiming at reducing the
burden of communication and optimising the access ability of terminals.

The proposed communication mechanism is represented in Figure 2. In Figure 2, the intelligent terminal is permitted to use the D2D communication technique, when some uncertain cases exist (e.g. the network failure, signal blind area of the channel, or deterioration channel). Therefore, terminals can share their spare communication link, which means that some services can be transferred from terminal to terminal until the information is uploaded to the network. The utilisation of D2D
communication can ensure the reliability of uplink and downlink between the intelligent terminal and the network. Therefore, the information can be transmitted to the designated communication node in time, which is not affected by external uncertain cases.

3 | END-TO-END COMMUNICATION MODEL OF INTELLIGENT TERMINAL

3.1 D2D access mechanism considering service level

In general, if one intelligent terminal under electric power data communication network works in a normal stage without being affected by some uncertain cases, they will use their original transmission channel instead of adopting spare channels provided by other terminals, where spare channels are supported by the D2D communication technique. Only when the communication channel between terminals and the base station has network failure, signal blind area, or deterioration of channel, D2D communication technique is allowed to use in improving the QoSs. Furthermore, the D2D communication technique should mainly focus on improving the quality of important services.

Suppose that there are \( S \) intelligent terminals under the network. \( S \) intelligent terminals have service interaction requirements and need to send corresponding instructions. However, the network environment is bad and the service access ability is declining. Considering that there are \( N \) channels to ensure reliable communication \( (N < S) \). In order to improve the ability of service access to the electric power data communication network as much as possible, it is necessary to ensure that there are enough channels for the intelligent terminal to interact with the base station under the electric power data communication network. Intelligent terminals are divided into two parts. First of all, the first group of \( M \) intelligent terminals always maintain normal communication, occupying the channel of the base station. Then, the remaining \( K \) intelligent terminals need to select \( K \) terminals from \( M \) intelligent terminals that can carry out the D2D communication technique and share their spare channel so as to use end-to-end D2D communication. The relationship between the number of terminals is represented by

\[
S = M + K
\]

The relationship between the number of channels and the number of intelligent terminals is as follows:

\[
N - M \leq K
\]

The service level of terminals that use D2D communication should be less than that of terminals maintaining normal communication. Therefore, terminals will be selected and assigned the channel according to the service level. The services with high levels have priority to occupy the reliable channel of the base station, while the services with low service level will use the channel provided by D2D communication.

3.2 D2D communication channel model of intelligent terminal

First, the channel noise of one terminal is analysed. The noise power model of the channel is shown in Formula (3).

\[
N_0 = 10\log_{10} \left( 10^{(N_0_{\text{sepc}}/10)\times (\text{BW} / N) } \right) \tag{3}
\]

In formula (3), \( N_0 \) is the noise power caused by white Gaussian noise, whose symbol is represented by dBm. \( N_0_{\text{sepc}} \) is the corresponding noise power spectral density, whose symbol is denoted by dBm/Hz. \( \text{BW} \) is the frequency of the signal. \( N \) is the total number of channels of all intelligent terminals, where numbers do not include the spare channels provided by the D2D communication technique.

Second, the model of channel gain between terminals and the base station is analysed. According to the introduction in Section 2.1, there are \( M \) intelligent terminals that will not adopt the D2D communication technique. Geographical location of the terminal is denoted by \( i \in \mathbb{S}=\{(x_i,y_i)\} \). Furthermore, the geographical location of the base station is assumed as \( (x_0,y_0) \). According to the location of terminals and the base station, the distance \( d_i \) between the terminal \( i \) and the base station can be expressed by Equation (4)

\[
d_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \tag{4}
\]

The distance set between each terminal \( i \) and the base station is represented as the matrix \( d = [d_1, d_2, \ldots, d_M] \), where the set is a \( 1 \times M \) matrix. After obtaining distances between terminals and the base station, the path loss from the intelligent terminals to the base station is calculated by Equation (5).

\[
p_{L_{\text{LS},i}} = \overline{\text{PL}}(d_i) + 10\alpha \log \left( \frac{d_i}{d_0} \right) + X_\sigma \tag{5}
\]

where \( p_{L_{\text{LS},i}} \) represents the path loss between the intelligent terminal \( i \) and the base station without the interference of D2D. Path loss \( p_{L_{\text{LS},i}} \) also represents the power intensity of transmission between terminals and the base station, whose symbol is dBm. In Equation (4), \( d_0 \) is the standard distance, which is used for normalisation distances between terminals and the base station in this study. \( X_\sigma \) is distributed with a Gaussian function, whose mean value is set as zero. In practice, \( \overline{\text{PL}}(d_0) \) is calculated or measured at \( d_0 \) in free space. This value represents the average large-scale fading containing the propagation loss at the distance \( d_0 \). \( d_i \) is obtained from Equation (4) and represents the distance from each intelligent terminal to the base station. Considering the effect of shadow fading in communication, the corresponding shadow fading model is provided in Equation (6).

\[
p_{\text{SD},i} = \frac{1}{\sqrt{2\pi\sigma_{\psi}} \psi_{\text{sh}}} \exp \left( -\frac{(\psi_i - \mu_{\psi})^2}{2\sigma_{\psi}^2} \right) \tag{6}
\]
In formula (6), $p_{SD,i}$ denotes the power loss caused by shadow fading of the terminal $i$, which does not adopt the D2D communication technique. $\psi_k$ represents the ratio of transmission power to receive power after shadowing fading of the terminal channel. $\mu_{dB}$, $\sigma_{dB}$ and $\sigma_{\psi_k}$ represent parameters of shadow fading. After obtaining the path loss $p_{LS,i}$, shadow fading $p_{SD,i}$, noise $N_0$ between the base station and the intelligent terminal $i$, the expected transmission power $p_{send,i}$ of terminal $i$ is calculated as follows:

$$p_{send,i} = p_{Limit,i} + N_0 + p_{LS,i} - p_{SD,i}$$

where $p_{Limit,i}$ represents the minimum signal to interference plus noise ratio (SINR) required by the intelligent terminal $i$. By using Equation (7), the transmission power of each terminal $i$ is obtained. Note that the calculation of $p_{send,i}$ does not consider the interference of the D2D communication technique. Meanwhile, $p_{send,i}$ is an expected value, which may exceed the maximum transmission power $P_{max}$ set by the terminal $i$. Therefore, it needs to calculate the real transmission power of each terminal $i$ based on $P_{max}$ and $p_{send,i}$. Here, the real transmission power $p_{ceet,i}$ of each terminal $i$ is defined as follows:

$$p_{ceet,i} = \begin{cases} p_{send,i} & p_{send,i} < P_{max} \\ P_{max} & p_{send,i} \geq P_{max} \end{cases}$$

Based on Equation (8), the transmission power of each terminal $i$ is obtained.

Similarly, we can calculate the real transmission power of each terminal $k$ that adopts the D2D communication technique. Assume that the geographical location of the intelligent terminal $k$ is $(x_k, y_k)$, and the location of the terminal which cooperates with terminal $k$ and receives the information from the terminal $k$ is $(x_{soc,k}, y_{soc,k})$. Then using Equation (4), the distance $d_{k,i}$ between the terminal $k$ and its cooperative terminal is calculated. Terminal $k$ will use the spare channel provided by its cooperative terminal. With the cooperation of other terminals, terminal $k$ can upload its information to the power system operator, even if the equipment in the power data communication network is overload or suffer from the network failure. Based on the calculated distance $d_{k,i}$, the path loss $p_{LS,DD,k}$ and shadow fading $p_{SD,DD,k}$ between terminal $k$ and its cooperative terminal is obtained. The channel gain between terminal $k$ and its cooperative terminal is represented by a function $p_{send,DD,k} = p_{LS,DD,k} - p_{SD,DD,k}$. After calculating the channel gain $p_{send,DD,k}$ between terminal $k$ and its cooperative terminal, the interference caused by other terminals that do not use the D2D communication technique should be considered. The calculation of interference caused by other terminals that do not use the D2D communication technique is similar as $p_{SD,i}$. First, Formula (2) calculates the distance $d_{i,k}$ between each terminal $k$ and terminal $i$. Based on $d_{i,k}$, the path loss $p_{LS,DU,k,i}$ and shadow fading $p_{SD,DU,k,i}$ between terminals $i$ and $k$ can be obtained. Furthermore, assume that the path loss and shadow fading between the terminal $k$ and the base station are denoted as $p_{LS,DB,k}$ and $p_{SD,DB,k}$, respectively. The channel gain from terminal $k$ to the base station is represented by $p_{send,k,i}$

$$p_{send,k,i} = p_{Limit,k} + p_{send,k,i} + N_0 + p_{SD,DU,k,i} - p_{LS,DU,k,i}$$

where $p_{Limit,k}$ is the minimum transmission power requirement for communication. Note that $p_{send,k,i}$ considers the interference of transmission from the terminal $i$. The related interference of terminal $k$ to the communication terminal without $i$ is represented by

$$p_{cf,k,i} = p_{send,k,i} + p_{SD,DU,k} - p_{LS,DU,k}$$

The interference matrix $p_{cf}$ of $K \times M$ can be obtained. Determine whether the relationship between $K$, $M$, and $N$ satisfied the limitation in Equation (2). If satisfied, the heuristic algorithm is used to determine the D2D communication pairs that have the least impact on the base station channel in the interference matrix according to the order of the minimum channel interference. When $p_{cf,k,i}$ is lower than a given interference threshold, terminals can determine whether to adopt the D2D technique or not. Note that terminals that can adopt the D2D communication technique are selected one by one. Finally, the number of D2D terminals actually accessed to the electric power data communication network is obtained.

### 4 SIMULATION RESULT

This study proposes a D2D communication mechanism considering the service level. This proposed D2D communication mechanism is applied to reduce the burden of the communication network when the intelligent terminals collects the information and transfer it to the network. To verify the effectiveness of the proposed communication mechanism, two comparison methods are selected.

**Scenario 1:** Terminals and networks apply the traditional centralised communication mode in which the intelligent terminal only relies on the base station for communication.

**Scenario 2:** Terminals and networks apply the D2D communication technique when some uncertain cases exist (e.g. the network failure, signal blind area of the channel, or deterioration channel). However, the information transmission in scenario 2 will not consider the difference in service level.

**Scenario 3:** Scenario 3 is the proposed mechanism, which applies the D2D communication technique while enabling terminals to transmit the services with a high level first.

The related simulation parameters are taken from the realistic systems. $N_{0_{sepc}}$ range from $-150$ to $-174$ dBm/Hz.
The bandwidth of the channel $BW$ is set as 10 MHz, $\overline{PL}(d_0)$ 128.1 dBm. The parameter of path loss $\alpha$ is equal to 3.76. The radius $(d_0,r)$ of the coverage area of the network is 500 m. Parameters of shadow shading $X_\sigma, \mu_{dB}, \sigma_{dB}, \psi, \text{and } 1/\sqrt{2\pi\sigma_{\psi}}$ dB are 0, 1, 0, 0.01, and 10, respectively. The maximum transmission power of terminals is $P_{\text{max}}$ 23 dBm. $P_{\text{Limit}}$ is equal to 10 dBm.

### 4.1 Analysis of terminals under different scenarios

In this subsection, the total number of terminals under network is set as 50 ($S = 50$). First, we increase the information processed by the equipment of the communication network and compare the number of terminals that can still upload the information to the power system operator via the communication network. Obviously, when the information is increased, some equipment in the communication network will be overloaded, which can lead to parts of terminals not able to work in the normal stage and cannot upload the information. As shown in Figure 3, the number of terminals that can still upload the information in scenario 1 is much lower than that in scenarios 2 and 3. This result means that applying the proposed communication mechanism can provide an extra communication channel to terminals to improve the transmission of information. Even if some communication equipment in the network has a great burden to process information, terminals that need to upload information can use the communication link shared by other terminals. By using the shared communication link, information has more possibility to be uploaded from other equipment. Therefore, there will be more terminals that can upload the information to the network in scenarios 2 and 3. Additionally, there is not too much difference between scenarios 2 and 3. The number of terminals that can upload the information to the power system operator is almost the same in scenarios 2 and 3 during the periods.

Then, we still increase the information processed by the equipment of the communication network and analyse the effect of the proposed mechanism in communication services. It deserves noticing that terminals have different services in different time slots. Besides, services transmitted by terminals have different levels. This means that some terminals may not transmit and upload the information because of the heavy burden of network equipment, and service with high level will be affected. The proposed communication mechanism can solve this problem. Figure 4 is provided to prove the effectiveness of the proposed communication mechanism. It can be seen that the importance of total communication services in scenario 3 is much higher than in scenarios 2 and 1. The reason why scenarios 2 and 3 are higher than scenario 1 is that their D2D communication mode provides additional communication links to enable more terminals to interact. The reason why scenario 3 is higher than scenario 2 is that it gives priority to providing communicable links for terminals performing high-level services.

### 4.2 Analysis of terminals under different SINR and scale of the network

To demonstrate the performance of the proposed communication mechanism, Figures 5 and 6 are provided. In Figures 5 and 6, three scenarios are simulated under different SINR. The SINR is set as 10, 15, 20, and 25 dB, where the setting of SINR can reflect the different quality of the channel. A lower SINR means poor quality of the channel. Obviously, as the SINR decreases from 25 to 10, the total number of working terminals is reduced simultaneously. By observing Figure 5, it can be seen that the total number of working terminals in scenarios 2 and 3 is higher than in scenario 1. This means that by using the D2D communication technique, more terminals can upload their information, even if the channel quality is decreased and the equipment of the communication network is overloaded.
**Figure 4** Sum of service level of transmitted services under different scenarios

**Figure 5** The total number of working terminals under different signal to interference plus noise ratio (SINR)

**Figure 6** Sum of service level of transmitted services under different SINR
Using the D2D communication technique can improve the information transmission because the number of working terminals is increased. Furthermore, Figure 6 shows the sum of the service level of services transmitted by working terminals under different SINR. It can be seen that the sum of the service level in scenario 3 shows a special characteristic, where the sum of the service level is greater than in other scenarios. The reason behind this fact is similar to Figure 4. Because the proposed communication mechanism uses the D2D technique to share the spare communication link between each terminal, more terminals can upload their information. Also, this mechanism gives priority to transferred important services. Therefore, it can be known that the sum of service level in scenario 3 is greater than other scenarios.

In summary, Figures 5 and 6 prove that the proposed mechanism can make more important information to be uploaded to the network compared with existing work.

Figures 7 and 8 are provided to present the performance of the proposed communication mechanism under different numbers of terminals, which indicates the scale of the network. Here, the total number of terminals is set as 50, 60, and 70. Note that we increase the information processed by the equipment of the communication network. Hence, parts of terminals may not work in the normal stage and cannot upload information to the network. With the increase in the total number of terminals, the real working terminals are increased. From Figure 7, it can be seen that the number of working terminals in scenarios 2 and 3 is higher than in scenario 1. The reason for this result can be explained by the argument of Figures 4 and 5. (Due to the utilisation of the D2D technique, the number of working terminals in scenarios 2 and 3 is greater than scenario 1). Compared with scenario 1 that does not use the D2D communication technique, scenarios 2 and 3 make more terminals to transfer the information by using the D2D technique, even if the equipment of the communication network is overloaded. Also, by observing Figure 8, scenario 3 shows a better performance in transmitting important service. It can be seen that compared with scenarios 1 and 2, the sum of the service level is higher in scenario 3. This result implies that terminals give priority to transfer important services when using the D2D communication technique.
4.3  Analysis of terminals under different scenarios

Then, by fixing some parameters such as $K$, $r$, and $n$ (i.e. $K = 10$, $r = 500$, $N = 44$) we analyse the effect of different specifications, such as $M$, in the proposed communication mechanism. The first one is to simulate the number of working terminals that can upload the information to the network. In Figure 9, the horizontal axis is the interference threshold, which is applied to select the terminal that can adopt the D2D technique. The vertical axis is the number of working terminals that use the D2D technique. It can be seen that with the increase of the interference threshold, the number of working terminals increases simultaneously. When the interference threshold is $-112$ dBm, there are about 10 working terminals that can upload the information to the network by using the D2D communication technique. Furthermore, by fixing the interference threshold, the number of working terminals that use the D2D technique is decreased with the increase of $M$. The reason for this phenomenon is that the increase of $M$ will improve the channel interference of terminals. A higher $M$ means a higher interference of channel, which will lead to less terminal to access in the network by using D2D communication technique.

Then, we change the value of $r$, which is used to normalise the distance between each terminal. As shown in Figure 10, when $r$ varies from 500 to 540, the number of terminals, which can use D2D to transmit the information to the network, is increased significantly. Figure 10 reflects that with the increase in distance $r$, the interference between each terminal is decreased. Therefore, more and more terminals can share their spare communication link. The increasing terminals can use the D2D communication technique to transfer their information.

5  CONCLUSION

In this study, we proposed a novel communication mechanism based on the D2D technique to improve the access ability of terminals to the network. The proposed mechanism made terminals share their spare communication channel when some uncertain cases exist (e.g. the network failure, signal blind area of the channel, or deterioration channel).
shown the effectiveness of the proposed communication mechanism in reducing the processing burden caused by uncertain cases. Meanwhile, the proposed mechanism enables terminals to transmit high-level services first. The numerical results prove that it can make more terminals upload more important information to the network. Also, some simulation results were provided to analyse the effect of different specifications in the proposed mechanism.

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