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The Network Coding Algorithm Based on Rate Selection for Device-to-Device Communications

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ABSTRACT In this paper, we investigate the problem associated with minimizing the total energy consumption used by all devices when recovering their missing packets. It is accomplished by applying network coding based on the selection of the transmission rates in a device-to-device network. First, this paper formulates the problem as an integer nonlinear programming optimization by means of constructing a graph model with a limiting parameter to control the number of edges and thereby confirms it as an NPC. Second, this paper investigates the relationship between the energy-saving benefit and the value of the limiting parameter and thereby indicates that the benefit is maximized when the limiting parameter equals 2. Furthermore, two coding algorithms based on the selection of the maximum-weighted clique are proposed. In detail, they are selecting the best clique in terms of the weight of the vertex (SBWV) algorithm and selecting the best clique in terms of the weight of the edge (SBWE) algorithm. The former consider selecting the maximum-weighted clique on the local NC graph which is based on the weight of vertex, while the latter consider selecting the maximum-weighted cliques of the global NC graph based on the weight of the edge. Finally, the simulation results show that both the SBWV and SBWE can significantly reduce the energy of transmission and average delay when compared with COPE, content-and loss-aware IDNC, as well as TS-MIS.

INDEX TERMS Clique, device-to-device (D2D), energy consumption, multi-rate, network coding.

I. INTRODUCTION

The concept of secondary high data rate services is being studied intensively for use in the fifth generation (5G) networks. It is also referred to as D2D technology, operating as an underlay to cellular networks in a cognitive fashion [1]. D2D communications underlying a cellular network use the licensed frequency band of the cellular network, and these can increase the spectral efficiency, offload local traffic from cellular base stations and improve user experience [2]–[5]. NC (Network coding) [6], [7] is an effective way to reduce transmission time and increase network throughput. For intersession wireless network coding, COPE (Coding Opportunity Entity) [8] provides a typical scheme to improve the network throughput. TAONC (Transmission Algorithm using Opportunistic Network Coding) [9] searches coding opportunities that minimize the total power consumption between a sender and multiple receivers in wireless networks. Network coding can be applied into the data offloading [10], [11] in opportunistic vehicular networks where the social-contact patterns [12], for example, contact rate could be adopted. Classical network coding has achieved a lot in quantum environments in recent years [13]–[16]. For example, network coding also can be applied into solving the quantum multi-unicast problem [13], as well as significantly reducing the communication cost [14]. Additionally, network coding is also effective in dealing with the problem of reducing the number of exchange packets among cooperating devices [17], [18]. Some research has considered applying NC to D2D communications [19]–[22]. For example, Content-and Loss-Aware IDNC (Instantly Decodable Network Coding) [19] is proposed to minimize the completion time under the quality constraint by selecting the maximal weighted clique, the TS-MIS (Two-Stage Maximal Independent Set) [20] selection algorithm is proposed to efficiently reduce the mean video distortion by selecting

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the maximal independent set. There are two main network coding schemes: one allows the combination of all source packets using random coefficients, i.e., linear network coding [23], random network coding [24], [25], convolutional network coding [26]; the other detects coding opportunities and exploits them to combine the appropriate packets, i.e., COPE. In this paper, we are interested in the latter.

At the same time the current wireless networks support multi-rate systems. For example, IEEE 802.11g [27] supports eight transmission rates ranging from 6Mbps to 54Mbps. Some work saves energy consumption by PHY rate adaptation [28], [29] in IEEE 802.11a WLANs under the point coordination function. Other works use multi-rate to decrease transmission delay [30] as well as to reduce transmission time [31]. However, according to our research, no previous work has considered the network coding algorithm in multi-rate D2D networks to save energy consumption. This paper studies the problem of minimizing the total energy consumption while all devices are satisfied (MECDS), i.e. all devices recover their missing packets, in multi-rate D2D networks by using network coding based on transmission rate selection.

For example, let us consider Fig.1, where the base station broadcasts the set of the packets p_1, p_2, p_3, p_4 to mobile devices d_1, d_2, d_3. These devices can obtain a set of received packets, denoted by H_1, H_2, H_3, from the base station, while the sets of their missing packets are denoted by M_1, M_2, M_3, respectively. We assume that there is only one transmission in each time slot, and that all the devices are connected to each other. The maximum transmission rate (Mbps) between devices is illustrated in Fig. 1.

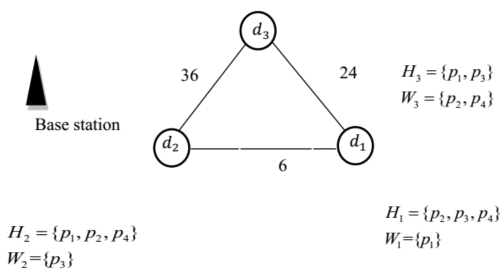


FIGURE 1. An example of D2D communications to recover the missing packets.

To enable the devices to receive their missing packets, we can adopt the COPE algorithm in a device based on the cardinality of a set of received packets in descending order as a sender. As shown in Fig.1 where the length of a packet is L and the transmission power is W. Thus, devices d_1 ($|H_1| = 3$) and d_2 ($|H_2| = 3$) are chosen as the senders. Firstly, device d_1 broadcasts $p_2 \oplus p_3$ to d_2 devices d_2 and d_3 at 6 Mbps, then devices d_2 and d_3 can recover packets p_2, p_3 by decoding the coded packet, respectively. Second, device d_2 broadcasts packet $p_1 \oplus p_4$ to devices d_1 and d_3 at 6Mbps, then devices d_1 and d_3 can recover packets p_1, p_4, respectively. Thus, the total energy consumption of COPE equals $LW/6 + LW/6 = LW/3$. In this paper, we try to choose a device associated with a higher transmission rate link as the sender to transmit encoding packets for other devices to recover their expected packets. For example, device d_2 transmits packet p_2 to device d_3, first, with the highest transmission rate of 36 Mbps. The energy consumption of the transmission equals $LW/36$. Then, device d_2 transmits packet p_4 to device d_3 with the highest transmission rate of 36 Mbps, and the energy consumption equals $LW/36$. Finally, device d_3 broadcasts an encoding packet $p_1 \oplus p_3$ to devices d_1 and d_2 with the second highest transmission rate of 24 Mbps, and the energy consumption of this transmission equals $LW/24$. Thus, the total energy consumption is $7LW/72$. Compared with COPE, our scheme can reduce the total energy consumption by 70.8%.

This paper studies the MECDS problem which is to find a coding packet with the corresponding transmission rate and the sender for each transmission, such that the total energy consumption is minimized for all devices during recovery fall missing packets. In detail, the contributions of this work are as follows:

- We propose the MECDS (minimizing the total energy consumption while all devices are satisfied) problem, then formulate the problem as an integer nonlinear programming optimization by constructing a graph model with a limiting parameter to control the number of edges, and confirms it as an NPC.
- We investigate the relationship between the energy-saving benefit and the value of the limiting parameter. Furthermore, we prove the benefit is maximized when the limiting parameter equals two.
- From considering the local NC graph and the global NC graph, we propose two heuristic encoding algorithms by selecting the maximum-weighted clique, which means selecting the best clique in terms of the weight of the vertex (SBWV) algorithm and selecting the best clique in terms of the weight of the clique (SBWE) algorithm.
- We adapt simulations to show that the proposed algorithms can significantly outperform the existing schemes in terms of reducing the energy consumption and the delay.

The rest of this paper is organized as follows. Section II presents the network model and some definitions. Section III formulates the MECDS problem and proves it as an NPC. Section IV analyzes the limiting parameter. Section V proposes two heuristic encoding algorithms based on selecting the maximum-weighted clique. Section VI evaluates the performance of the proposed algorithms. Section VII concludes the paper.

II. NETWORK MODEL AND DEFINITION

This section provides the network model and some definitions. The network consists of some cooperating mobile devices. Let $D = \{d_1, d_2, \ldots, d_n\}$ be the set of cooperating devices in the network, where n is the number of devices. These devices are within close proximity of each other; thus, they are in the same transmission range and can connect to

TABLE 1. Transmission rates and sensitivities.

Rate	Sensitivity
6 Mbps	-87dBm
9 Mbps	-86 dBm
12 Mbps	-83 dBm
18 Mbps	-82 dBm
24 Mbps	-81 dBm
36 Mbps	-80 dBm
48 Mbps	-75 dBm
54 Mbps	-74 dBm

each other via D2D links such as Wi-Fi Direct and break Bluetooth.

The cooperating mobile devices in D are interested in receiving all the packets in set $P = \{p_i | 1 \leq i \leq m\}$. Note that packets are transmitted in two stages. In the first stage, an access point or base station, broadcasts the packets in P to the mobile devices in D. Due to packet losses over the wireless broadcast link, the devices may receive only partial content. We consider that there is no error correction mechanism in the first stage. After the first stage, the set of received packets of device d_i is called H_i, referred to as the *Has* set of devices d_i. And the set of missing packets of device d_i is called M_i, referred to as the *Missing* set of devices d_i. Once the device has received packet successfully, it will send an acknowledgement to the BS. The retransmission of the packet is required only if no device receives it. Without loss of generality, we assume that for each packet $p_i \in P(p_i | 1 \leq i \leq m)$, there is at least one device on which it will be successfully received.

In the second stage, the devices cooperate to recover the missing packets via their D2D connections such as Wi-Fi Direct or Bluetooth. Furthermore, D2D resources are considered to be orthogonal to cellular resources. In this paper, we focus on fully connected D2D communications.

The receive power $W_{rec(i,j)}$ between transmitting device d_i and receiving device d_j is calculated as [32], [33]:

$$W_{rec(i,j)} = \frac{cW}{dis_{i,j}^{\alpha}}. \tag{1}$$

where c is the path loss coefficient that depends on the physical environment, and the unit size of a signal, α is constant. In general, α varies between 2 and 4. W is the transmission power, and $dis_{i,j}^{\alpha}$ is the distance between devices d_i and d_j.

In this paper, let $R = \{R_1, R_2, \ldots, R_k\}(R_1 \leq R_2 \leq \ldots \leq R_k)$ be the set of K transmission rates associated with a specific network interface. For example, in 802.11g, $R = \{6, 9, 12, 18, 24, 36, 48, 54\}Mbps$ [27], and the transmission rate as well as the corresponding sensitivity of the Cisco Aironet 1250 [34] are shown in Tab. 1. For two devices, based on the receive power by Eq. (1) and the corresponding sensitivities of transmission rates, we can obtain the maximum transmission rate between them.

We give the following definition:

Definition 1: The energy consumption between the transmitter d_i and the receiver d_j is calculated as [35]

$$E_{i,j} = \frac{LW}{R_{i,j}}, \tag{2}$$

where L is the length of the packet and is the maximum transmission rate between device d_i and device d_j.

III. PROBLEM FORMULATION

In this section, we formulate the MECDS problem and confirm it as be an NPC.

To guarantee that all devices recovered their missing packets, the devices can broadcast their received packets to each other through different transmission rates. However, the different schemes may lead to different energy consumption. Thus, the MECDS problem is as follows. Given the received and required packets of each device,and the transmission rates between devices, the task at hand is to find the coding packets with the corresponding transmission rates and senders, such that the total energy consumption is minimized under the presumption that all devices that recovered their missing packets did so by means of cooperating devices.

A trivial approach would be to exhaustively list all possible network coding candidates and corresponding transmission rates, and calculate the energy consumption for each of them to determine the best one. A more efficient approach is to use an NC (network coding) graph. An NC graph is constructed such that each clique (a clique is a subset of vertices of an undirected graph such that every two distinct vertices in the clique are adjacent) in the graph corresponding to a network code. Thus, we can find the best clique to determine the best network code, which can minimize the energy consumption.

We consider to make $G_i = (V_i, E_i)(1 \leq i \leq n)$ be an undirected local graph where v_i and E_i denote the set of vertices and edges, respectively. G_i is the graph corresponding to the case in which device d_i acted as the transmitter, and G_i is constructed as follows.

In the constructed graph, for $\forall d_j \in D \backslash d_i$, $p_l \in M_j$ and $p_l \in H_i$, there exists vertex $v_{j,l}^i \in V_i$. For edge $(v_{j,l}^i, v_{j1,l_1}^i) \in E_i$ between two vertices $v_{j,l}^i, v_{j1,l_1}^i(1 \leq i \leq n)$, we assume that $R_{i,j} = min\{R_{i,j}, R_{i,j_1}\}$, $R_{i,j_1} = max\{R_{i,j}, R_{i,j_1}\}$. We also assume that $R_{i,j} = R_x$, $R_{i,j_1} = R_{x+\mu}$, where $\mu \in \{0, 1, 2, \ldots, K-1\}$. Then, a pair of vertices $(v_{j,l}^i, v_{j1,l_1}^i)$ is connected if, and only if, the following conditions are satisfied:

(i): $l = l_1$, or $p_l \in H_{j_1}$ and $p_{l_1} \in H_j$,

(ii): $1 \leq \frac{R_{x+\mu}}{R_x} \leq \gamma$.

We define γ as the limiting parameter to control the number of edges. For example, $\gamma = 2$, if $R_{i,j} = 2Mbps$ and $2Mbps \leq R_{i,j_1} \leq 4Mbps$, then $(v_{j,l}^i, v_{j1,l_1}^i) \in E_i$.

Then, if $(v_{j,l}^i, v_{j1,l_1}^i) \in E_i$, device d_i can transmit the coding packet $p_l \oplus p_{l_1}$ for devices p_j and p_{j_1} to decode their expected packet. Similarly, if there is a clique $Q_h^i = \{v_{j,l}^i, v_{j1,l_1}^i, v_{j2,l_2}^i \ldots\}(1 \leq h \leq |V_i|)$ in G_i, device d_i can broadcast the coding packet $p_l \oplus p_{l_1} \oplus p_{l_2} \oplus \ldots$ so that all devices in Q_h^i can decode their expected packets.

Moreover, we can define a global NC graph $G = (V, E)$, where $G = \bigcup_{i=1}^{|D|} G_i$. In other words, graph G consists of $|D|$ disjoint NC local graphs. To formulate the MECDS problem, we give the definition:

Definition 2: Let

$$\omega_{i,j}^{i} = |R_{i,j}| \tag{3}$$

be the weight of vertex $v_{j,l}^{i} \in V_i$.

To describe whether vertex $v_{j,l}^{i}$ in V_i belongs to clique Q_h^i in G_i, we define an indicator variable as follows:

$$f_{j,l,h}^{i} = \begin{cases} 1, & v_{j,l}^{i} \in Q_h^i, \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

Now the MECDS problem is formulated as follows:

$$\text{Minimize} \sum_{\forall Q_h^i} E_h^i, \tag{5}$$

$$\text{subject to} \sum_{\substack{\forall 1 \le i \le |D| \\ \forall 1 \le h \le |V_i|}} f_{j,l,h}^{i} = 1, \tag{6}$$

$$f_{j,l,h}^{i} + f_{j_1,l_1,h}^{i} = 1, \tag{7}$$

$$E_h^i = \max_{\exists f_{j,l,h}^{i}=1} E_{i,n}. \tag{8}$$

where $\forall (v_{j,l}^{i}, v_{j_1,l_1}^{i}) \in E_i, 1 \le i,j \le |D|, \forall v_{j,l}^{i} \in V_i, \gamma = 1, 1 \le h \le |V_i|$.

The constraint in equation (6) indicates that a vertex is only included in one clique. In this paper, note that there are cases: $v_{j,l}^{i} \in V_i, v_{j,l}^{i} \in V_{i_1}, i \neq i_1$. Although the two vertices $v_{j,l}^{i}$ and v_{j_1,l_1}^{i} are different vertices, they are relevant, for example, when we select a clique which includes vertex $v_{j,l}^{i}$ in G_i. In other words, device d_i will send a coding packet so that device d_j can recover packet p_l. Thus, vertex does not need to be included in any clique of G_{i_1}. The constraint in (7) guarantees that, for two vertices $v_{j,l}^{i}, v_{j_1,l_1}^{i} \in V_i$, they should not be included in a clique if edge $(v_{j,l}^{i}, v_{j_1,l_1}^{i}) \notin E_i$. The constraint (8) indicates the energy consumption of clique Q_h^i.

Lemma 1: The MECDS problem is an NPC problem.

Proof: After the broadcast stage, if each device only receives partial disjoined packets from the packet set M, then we obtain $H_i \bigcap H_j = \emptyset (1 \le i,j \le n)$. Thus, the MECDS problem is equivalent to finding the maximum-weighted clique problem, which is NPC [36] in each local NC graph $G_i (1 \le i \le n)$. Therefore, the MECDS problem is an NPC.

IV. ANALYSIS OF THE PARAMETER γ

In this section, we investigate the relationship between the energy-saving benefit and the value of the limiting parameter γ. First, we present the probabilities of $R_{i,j} = R_x$ and $R_{i,j_1} = R_{x+\mu}$. Moreover, we consider the ratio of the energy-saving of the edge $(v_{j,l}^{i}, v_{j_1,l_1}^{i})$. Finally, we propose the effective ratio of the energy-saving of edge $(v_{j,l}^{i}, v_{j_1,l_1}^{i})$ and prove the energy-saving benefit reaches the maximum value when the limiting parameter γ equals two.

The limiting parameter γ is to control the number of edges by limiting the ratio of the corresponding transmission rates of an edge. Let us take edge $(v_{j,l}^{i}, v_{j_1,l_1}^{i})$ as an example, and assume that the corresponding transmission rates of vertices $v_{j,l}^{i}, v_{j_1,l_1}^{i}$ are denoted by R_x, $R_{x+\mu}$, respectively. Similarly, the corresponding energy consumption with two separate transmissions are $\frac{LW}{R_x}, \frac{LW}{R_{x+\mu}}$.

1) PROBABILITY OF $R_{I,J} = R_x$ and $R_{i,j_1} = R_{x+\mu}$

Lemma 2: For $v_{j,l}^{i} \in V_i$,we define that $P(R_{i,j} = R_x)$ asp the probability of $R_{i,j} = R_x (R_x \in R)$, and is given by

$$P(R_{i,j} = R_x) = \frac{\left(\sqrt[\alpha]{\frac{c}{Sen_x}}\right)^2 - \left(\sqrt[\alpha]{\frac{c}{Sen_{x+1}}}\right)^2}{\left(\sqrt[\alpha]{\frac{c}{Sen_1}}\right)^2}. \tag{9}$$

Proof: See APPENDIX A.

For example, in the Cisco Aironet 1250 [34], the maximum transmission rate is calculated as 12Mbps (i.e., $R_x = 12Mbps$), and the corresponding sensitivity is −83dBm. Then, according to Eq. (9), the probability of $R_{i,j} = 12Mbps$ is

$$P(R_{i,j} = 12) = \sqrt{\frac{1.99 * 10^{-9}}{2.511 * 10^{-9}}} - \sqrt{\frac{1.99 * 10^{-9}}{5.012 * 10^{-9}}} = 7\%.$$

Similarly, we obtain $P(R_{i,j} = 24) = 24\%$.

Therefore, let $P(R_x, R_{x+\mu})$ be the probability of $R_{i,j} = R_x$ and $R_{i,j_1} = R_{x+\mu}$, and is obtained as:

$$P(R_x, R_{x+\mu}) = P(R_{i,j} = R_x) P(R_{i,j_1} = R_{x+\mu}). \tag{10}$$

2) RATIO OF ENERGY-SAVING OF EDGE $(V_{J,L}^{I}, v_{j_1,l_1}^{i})$

For vertex $v_{j,l}^{i}$ and vertex v_{j_1,l_1}^{i}, if device d_i separately transmits packets p_l and p_{l_1}, respectively, the corresponding energy consumption of the two transmissions are $\frac{LW}{R_x}, \frac{LW}{R_{x+\mu}}$, respectively.

Thus, some definitions are given by:

Definition 3: Let $E_{(v_{j,l}^{i}, v_{j_1,l_1}^{i})}$ be the corresponding energy consumption of edge $(v_{j,l}^{i}, v_{j_1,l_1}^{i})$. According to Eq. (2), is$E_{(v_{j,l}^{i}, v_{j_1,l_1}^{i})}$ given by:

$$E_{(v_{j,l}^{i}, v_{j_1,l_1}^{i})} = \frac{LW}{R_x}. \tag{11}$$

Definition 4: Let $E_{save(x,x+\mu)}$ be the energy-saving of the edge $(v_{j,l}^{i}, v_{j_1,l_1}^{i})$ corresponding with sending coding packet $p_l \oplus p_{l_1}$ from device d_i instead of two separate transmissions with sending packets p_l and p_{l_1}, and is given by:

$$\begin{aligned} E_{save(x,x+\mu)} &= (E_{i,j} + E_{i,j_1}) - E_{(v_{j,l}^{i}, v_{j_1,l_1}^{i})} \\ &= (\frac{LW}{R_x} + \frac{LW}{R_{x+\mu}}) - \frac{LW}{R_x} = \frac{LW}{R_{x+\mu}}. \end{aligned} \tag{12}$$

Thus, we obtain the ratio of energy-saving of edge $(v_{j,l}^{i}, v_{j_1,l_1}^{i})$ in Def. 5.

Definition 5: We define $\beta_{x,x+\mu}$ as the ratio of energy-saving of edge $(v^i_{j,l}, v^i_{j_1,l_1})$, and it is given by

$$\begin{aligned}\beta_{x,x+\mu} &= \frac{E_{save(x,x+\mu)}}{E_{i,j}+E_{i,j_1}} \\ &= \frac{(\frac{LW}{R_x}+\frac{LW}{R_{x+\mu}})-\frac{LW}{R_x}}{\frac{LW}{R_x}+\frac{LW}{R_{x+\mu}}} \\ &= \frac{R_x}{R_x+R_{x+\mu}} \end{aligned} \tag{13}$$

Combining Eq. (10) and Eq. (13), we obtain the expectation of $\beta_{x,x+\mu}$ as follows

$$Exp(\beta_{x,x+\mu}) = \sum_{\substack{x=1 \\ 1\le x+\mu\le K}}^{K} \beta_{x,x+\mu} P(R_x, R_{x,x+\mu}). \tag{14}$$

In this way, we can get theorem 1.

Theorem 1: $Exp(\beta_{x,x+\mu})$ increases with μ, and reaches the maximum value when $\mu = K-1$.

Proof: See APPENDIX B.

3) EFFECTIVE RATIO OF ENERGY-SAVING OF EDGE $(V^I_{J,L}, v^i_{j_1,l_1})$

From Th. 1, we know the expectation of the ratio of energy-saving of edge $(v^i_{j,l}, v^i_{j_1,l_1})$, is increasing with the limiting parameter γ. Thus, the bigger γ is, the greater number of edges are. However, in the result we choose some edges with high ratio of energy-saving.

For example, in Fig. 2, there are three vertices in G_i, as shown in Fig. 2(a). For the transmission rates $R_{1,2} = 6Mbps, R_{1,3} = 12Mbps, R_{1,4} = 18Mbps$. If $\gamma = 2$, we assume that there is only one edge $(v^i_{j,l}, v^i_{j_1,l_1})$, as shown in Fig. 2(b). If $\gamma = 3$, we assume that there are two edges $(v^1_{2,1}, v^1_{3,2})$ and $(v^1_{2,1}, v^1_{4,3})$, as shown in Fig. 2(c). In Fig. 2 (b), there is only one edge, so the transmission scheme is deterministic. First, based on $(v^1_{2,1}, v^1_{3,2}) \in E_1$, device d_1 sends $p_l \oplus p_2$ to devices d_2, d_3, then d_2, d_3 can recover p_1, p_2 by decoding, respectively. This transmission consumes energy $\frac{LW}{6}$. Next, device d_1 sends p_3 to device d_4, then device d_4 receives p_3. This transmission consumes energy $\frac{LW}{18}$. Thus, the total energy consumption is $\frac{4LW}{18}$. However, in Fig. 2(c), there are two edges $(v^1_{2,1}, v^1_{3,2})$ and $(v^1_{2,1}, v^1_{4,3})$ such that there are two transmission schemes. One is the same as the above scheme. The other scheme is as follows. First, based on $(v^1_{2,1}, v^1_{4,3})$, device d_1 sends $p_1 \oplus p_3$ to d_2 and d_4. Second, device d_1 sends p_2 to device d_3. In this way, the total energy consumption is γ. Obviously, the bigger limiting parameter may cause greater energy consumption.

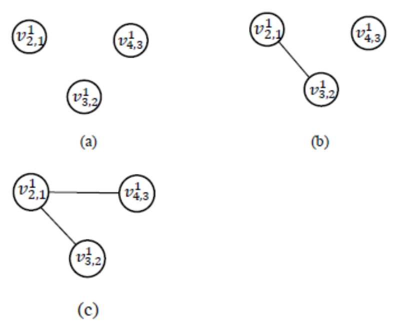


FIGURE 2. Using the limiting parameter to control the number of edges γ.

Obviously, the bigger limiting parameter when γ equals 3 result in choosing the edge where the corresponding energy consumption is higher than the corresponding consumption if γ equals 2.

Next, for the edge $(v^i_{j,l}, v^i_{j_1,l_1})$, the corresponding energy consumption $E_{(v^i_{j,l}, v^i_{j_1,l_1})} = \frac{LW}{R_x}$. We assume that the average energy consumption of each vertex of the edge equals $\frac{LW}{2R_x}$. On the one hand, for vertex $v^i_{j,l}$, its corresponding energy consumption $E_{i,j} = \frac{LW}{R_x}$ is more than the average energy consumption. On the other hand, the corresponding energy consumption for vertex $v^i_{j_1,l_1}$ is $E_{i,j_1} = \frac{LW}{R_{x+\mu}}$. However, we are uncertain whether E_{i,j_1} is bigger than the corresponding average energy consumption. Thus, we define their difference as $E_{differ(x,x+\mu)}$:

$$E_{differ(x,x+\mu)} = \frac{LW}{R_{x+\mu}} - \frac{LW}{2R_x}. \tag{15}$$

On the one hand, we want the expectation of the ratio of energy-saving of edge $(v^i_{j,l}, v^i_{j_1,l_1})$ to be great enough. On the other hand, we don't want $E_{differ(x,x+\mu)}$ to be negative. Thus, we define $\psi_{x,x+\mu}$ to be the effective ratio of energy saving of the edge $(v^i_{j,l}, v^i_{j_1,l_1})$:

$$\begin{aligned}\psi_{x,x+\mu} &= \frac{E_{differ(x,x+\mu)}}{E_{save(x,x+\mu)}} \\ &= \frac{\frac{LW}{R_{x+\mu}}-\frac{LW}{2R_x}}{\frac{LW}{R_{x+\mu}}} = 1-\frac{LW}{2R_x}. \end{aligned} \tag{16}$$

Obviously, the effect of is $\psi_{x,x+\mu} \ge 0$ more efficient than that of $\psi_{x,x+\mu} < 0$.

Next, we let $Exp(\psi_{x,x+\mu})$ be the expectation of the effective ratio of the energy-saving of the edge $(v^i_{j,l}, v^i_{j_1,l_1})$, and is given by

$$Exp(\psi_{x,x+\mu}) = \sum_{\substack{x=1 \\ 0\le x+\mu\le K}}^{K} \psi_{x,x+\mu} P(R_x, R_{x+\mu}) \tag{17}$$

We can obtain the following theorem:

Theorem 2: $Exp(\psi_{x,x+\mu})$ reaches the maximum when $\gamma = 2$.

Proof: See APPENDIX C.

Thus, if $\gamma = 2$, then an edge will have reached maximum efficiency in energy-saving.

V. TWO HEURISTIC CODING ALGORITHMS

Due to the fact that the MECDS problem is an NPC, this section presents two heuristic coding algorithms. In particular, they are selecting the best clique in terms of the weight of the vertex (SBWV) algorithm and selecting the best clique in terms of the weight of the edge (SBWE) algorithm. The former considers selecting the maximum-weighted clique with the local NC graph based on the weight of the vertex, while the latter considers selecting the maximum-weighted cliques of the global NC graph based on the weight of the edge. Note that, the clique is a complete sub-graph, but for simplicity, this section focuses on its vertices. In fact, its edges can be determined by its vertices.

A. SELECTING THE BEST CLIQUE IN TERMS OF THE WEIGHT OF THE VERTEX

The basic idea behind Algorithm 1 is to greedily construct a maximal-weighted clique by adding the current maximum-weighted vertex connected with the vertices iteratively chosen from a particular local NC graph.

Algorithm 1 Selecting the Best Clique in Terms of the Weight of the Vertex

Require: NC graph G.
Ensure: Clique Q as the set of maximum-weighted clique.

1: Initialization: G' is set to G. Clique $Q_i' = \emptyset (1 \leq i \leq n)$, and clique set $Q = \emptyset$.
2: **While** $G' \neq \emptyset$
3: Find the maximum-weighted vertex in G'. Let it be $v_{\max}$ in G_i. Add v_{max} to Q_i', and delete it from G_i.
4: Construct N_{max} as the set of all vertices that are connected to v_{max} in G_i.
5: **If** $N_{\max} = \emptyset$
6: **Return** Q_i' as the maximum-weighted clique, and add Q_i' to Q.
7: **Else**
8: **While** $N_{\max} \neq \emptyset$
9: Find the maximum-weighted vertex in N_{max}, and let it be v_{max}'. Add v_{max}' to Q_i', and delete it from $N_{\max}$.
10: **Update** N_{max}: delete all vertices which are disjoint to v_{max}'.
11: **Return** Q_i' as the maximum-weighted clique, and add it to Q.
12: **Return** Q as the set of maximum-weighted clique.

In Algorithm 1, we first define G', which is initially set to the original graph G. We also initialize clique Q_i' and clique set Q as empty (line 1). Note that Q_i' is the current maximum-weighted clique. While G' is not empty, then we do the loop to construct clique Q_i' added to Q (lines 3-12). The vertex with the maximum weight, denoted by v_{max} in G_i, is selected to be added to clique Q_i' and deleted from G' (line 3). And we construct N_{max} as the set of all vertices that are connected to vertex v_{max} (line 5). If N_{max} is empty, then clique Q_i' is the maximum-weighted clique and is added to Q (lines 5-6). Otherwise, we find the maximum-weighted clique among all vertices in N_{max} (lines 8-11). Find the maximum-weighted vertex, called v_{max}' in N_{max}, add it to Q_i', delete it from N_{max} and update N_{max} (lines 9-10) until $N_{max} = \emptyset$. Line 12 returns Q_i' as the maximum-weighted clique, and adds it to Q. When $G' = \emptyset$, then return clique set Q as the set of the maximum-weighted clique (line 12), which corresponds to the transmission schemes.

For example, in Fig. 1, $V_1 = \{v_{3,2}^1, v_{3,4}^1, v_{2,3}^1\}$, $V_2 = \{v_{3,2}^2, v_{3,4}^2, v_{1,1}^2\}$, $V_3 = \{v_{1,1}^3, v_{2,3}^3\}$, $E_1 = E_2 = \emptyset$, $E_3 = (v_{1,1}^3, v_{2,3}^3)$. In line 1, p$G' = G$, $\forall V_i' = V_i$, $E_i' = E_i$, $i = 1, 2, 3$. In this way, $G' \neq \emptyset$, we can obtain the maximum-weighted vertices as $v_{3,4}^2$, $v_{3,2}^2$,and $v_{2,3}^3$, all with weights of 36 (line 3). Suppose that we randomly choose vertex $v_{3,4}^2$, add it to Q_i', and obtain $N_{max} = \emptyset$ (lines 3-4). In lines 5-6 $N_{max} = \emptyset$, because, we add clique $Q_i' = \{v_{3,4}^2\}$ to clique set in line 6, i.e., based on Q, there is a transmission where device d_2 send packet p_4 to device d_3 with a transmission rate of 36Mbps. Similarly, we obtain the maximum-weighted clique $Q_i' = \{v_{3,2}^2\}$ and $Q_i' = \{(v_{1,1}^3, v_{2,3}^3)\}$. Thus, obtain the set of maximum-weighted clique $Q = \{(v_{3,4}^2), (v_{3,2}^2), (v_{1,1}^3, v_{2,3}^3)\}$.

B. SELECTING THE BEST CLIQUE IN TERMS OF THE WEIGHT OF THE EDGE

The basic idea behind Algorithm 2 is to greedily create the maximal-weighted clique based on the weight of the edge in each local NC graph, and choose the maximum-weighted clique among them.

We first give some definitions:

Definition 6: Let

$$\omega_{(v_{j,l}^i, v_{j_1,l_1}^i)} = CN_{j,j_1} * (\omega_{j,l}^i + \omega_{j_1,l_1}^i). \tag{18}$$

be the weight of the edge $(v_{j,l}^i, v_{j_1,l_1}^i)$, where CN_{j,j_1} is the number of common neighbor of vertex $v_{j,l}^i$ and vertex v_{j_1,l_1}^i.

Definition 7: Let

$$\omega_{Q_h^i} = \sum_{\forall v_{j,l}^i \in Q_h^i} \omega_{j,l}^i. \tag{19}$$

be the weight of the clique Q_h^i.

In line 2 of Algorithm 2, we first define G', which is initially set to the global NC graph G, $G_i' = G_i$ in G', and initialize clique set Q, where each clique is corresponding to an empty transmission. If G' has a vertex, then alg. 2 runs the loop from line 3 to line12. In the loop, first, for local graph $G_i'(1 \leq i \leq n)$ in G', we find the maximum weighted clique and set it as Q_i' (lines 4-12). We then find the maximum-weighted clique, called Q_{max}' among all cliques in $\{Q_i' | 1 \leq i \leq n\}$, and add it to Q. The following introduces how to find the maximum-weighted clique. If $E_i'' \neq \emptyset$ and $V_i'' \neq \emptyset$, we choose a vertex with the maximum weight, called $v_{j,l}^i$, and set $V_i'' = \{v_{j,l}^i\}$ (lines 5-6). If $E_i'' \neq \emptyset$, we do the loop to construct clique Q_i' (line 9-12) until $E_i'' \neq \emptyset$. In line 10, find the maximum-weighted edge, denoted by $(v_{j,l}^i, v_{j_1,l_1}^i)$, let *Nset* be the set of the common neighbors. To update V_i'', we delete the other vertices except vertices in *Nset* because these vertices cannot be in a clique with vertices $v_{j,l}^i, v_{j_1,l_1}^i$. In line 11, we also update E_i'' by deleting edge $(v_{j,l}^i, v_{j_1,l_1}^i)$ because the two vertices are reduced to a new vertex $\{v_{j,l}^i, v_{j_1,l_1}^i\}$ in V_i''

Algorithm 2 Selecting the Best Clique in Terms of the Weight of the Edge

Require: NC graph G.
Ensure: Clique Q as the set of maximum-weighted clique.
1: Initialization: G'_i is set to G. G'_i is set to G_i, Clique $Q'_i = \emptyset(1 \le i \le n)$, and clique set $Q = \emptyset$.
2: **While** G'_i has vertices do
3: **For** each $G'_i(1 \le i \le n)$ do
4: Let $G''_i = G'_i$
5: **If** $E''_i = \emptyset$ and $V''_i = \emptyset$
6: Choose a vertex with the maximum weight, called $v^i_{i,j}$,$V''_i = \{v^i_{i,j}\}$.
7: **Else**
8: **While** $E''_i \neq \emptyset$
9: Find the edge with the maximum weight in E''_i, called $(v^i_{i,j}, v^i_{i_1,j_1})$. Let *Nset* be the set of the common neighbors of the edge ends. Delete the other vertices except vertices in *Nset* in V''_i.
10: Delete edge $(v^i_{i,j}, v^i_{i_1,j_1})$ and the edges which connected to vertices $v_{i,j}, v_{i_1,j_1}$ in E''_i.
11: Create a new vertex, called $\{v^i_{i,j}, v^i_{i_1,j_1}\}$. Its weight is the sum of the weight of the two vertices and add it to V''_i and add new edges between it and each vertex in *Nset* to E''_i.
12: Add the set of vertices of representation of V''_i to Q'_i, delete all vertices from Q'_i in V'_i and the edges associated with any vertex from Q'_i in E''_i.
13: Find the clique with the maximum weight among all cliques $\{Q'_i | 1 \le i \le n\}$, called Q'_{max}. Add Q'_{max} to Q.
14: **Return** Q as the set of maximum-weighted clique.

(line 11), and the edges which disjoint with vertices $v^i_{j,l}, v^i_{j_1,l_1}$ in E''_i. Note that the new vertex $\{v^i_{j,l}, v^i_{j_1,l_1}\}$ represents two vertices which can form a clique, and its weight is the sum of the weight of the vertices $v^i_{j,l}, v^i_{j_1,l_1}$. At the same time, line 11 adds new edges between the new vertex and each vertex in *Nset* to E''_i. After line 4-11, for local graph G'_i, we can obtain a maximum-weighted clique Q'_i, whose vertices are in V''_i. Thus, we add the set of vertices of representation of V''_i to Q'_i (line 12). At the same time, we delete the vertices from Q'_i in V'_i and all the vertices associated with any vertices from Q'_i in E''_i. Finally, line 14 returns clique set Q as the set of the maximum-weighted clique, which corresponds to the transmission schemes.

We consider Fig. 1 as an example again. $V_1 = \{v^1_{3,2} v^1_{3,4}, v^1_{2,3}\}$, $V_2 = \{v^2_{3,2}, v^2_{3,4}, v^2_{1,1}\}$, $V_3 = \{v^3_{1,1}, v^3_{2,3}\}$, $E_1 = E_2 = \emptyset$, $E_3 = (v^3_{1,1}, v^3_{2,3})$, $\forall G_i \neq \emptyset$. For $G'_i = G_i(1 \le i \le 3)$, we can obtain $Q'_1 = \{v^1_{3,4}\}$, $Q'_2 = \{v^2_{3,2}\}$ (lines 5-6, 12), and $Q'_3 = \{(v^3_{1,1}, v^3_{2,3})\}$ (lines 8-12). The weights of these cliques are 24, 36, 60. Thus, in line 13, we choose Q'_3 as the current maximum weighted clique, and add it to Q (line 13). Q'_3 is corresponding to a transmission, i.e. device d_3 sending packet $p_1 \oplus p_3$ to devices d_1 and d_2 with transmission rate of 36 Mbps. Similarly, we can obtain the set of maximum-weighted clique $Q = \{(v^3_{1,1}, v^3_{2,3})\}$.

VI. SIMULATION RESULTS

In this section, performance of the proposed SBWV and SBWE are compared with that of COPE [8], Content-and Loss-Aware IDNC [19] and TS-MIS [20]. We adopt the COPE in a device based on the cardinality of the set of received packets in descending order as a sender. A simulation is developed in C++ language. The devices are randomly placed in a square area. The IEEE 802.11g [27] is used in all the simulations. The length of the packet is 1Mb, and the transmission power is 2dBm. The following performance metrics are included: (1) the energy consumption represents the total energy consumption for all devices recovering their missing packets; (2) the number of transmissions is the total account of transmissions by devices until all devices receive all their expected packets; (3) the average delay is the average time in which a device recovers its missing packets.

To investigate the impact of the varying number of devices to our algorithms, we vary the number of devices from 4 to 11. The number of packets is 10 and the network size is 800m $*$ 800m. The simulation results are shown in Fig. 3. As shown in Fig. 3(a), by increasing the number of devices, the energy consumption of the algorithms almost increases. Moreover, the energy consumption of the proposed SBWV and SBWE are always lower than that of COPE, Content-and Loss-Aware IDNC, and TS-MIS. In detail, compared with COPE, Content-and Loss-Aware IDNC and TS-MIS, SBWE decreases the energy consumption by up to 43%, 32%, and 24%, respectively, and SBWV decrease the energy consumption by up to 40%, 28%, and 16%, respectively. The SBWE is able to decrease the energy consumption by an average of 4% compared with the SBWV. As shown in Fig. 3(b), compared with COPE, Content-and Loss-Aware IDNC, and TS-MIS, SBWV decreases the average delay by an average of 22%, 14%, and 12%, respectively, and SBWE decreases the average delay by an average of 24%, 20%, and 16%, respectively. The reason is that the proposed algorithms try to select the link with the higher transmission rate to transmit packets. Additionally, the SBWE is able to decrease the average delay by up to 8% compared with SBWV. The reason is that the former tries to search more coding opportunities with higher transmission rates in the global graph, which could reduce the transmission time, while the latter considers selecting transmissions in the local graph. As shown in Fig.3(c), compared with COPE, Content-and Loss-Aware IDNC and TS-MIS, SBWV increases the number of transmissions by 38%, 30%, and 25% on average, respectively. And SBWE increases the number of transmissions by an average of 30%, 22%, and 20%, respectively.

We then vary the number of packets from 8 to 22. The number of devices is increased to 5, and the network size remains 800m $*$ 800m. The results of the experiments are

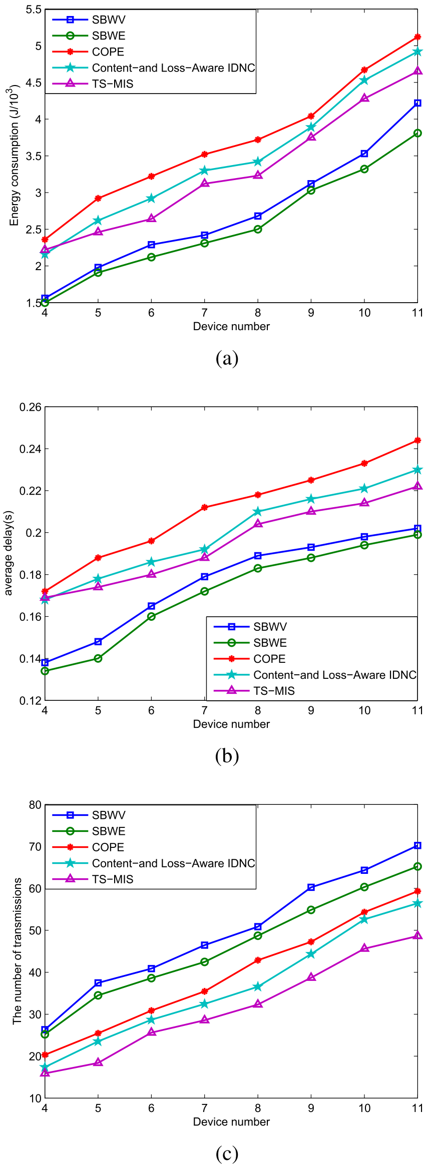


FIGURE 3. Performance comparison under different number of devices. (a) Energy consumption. (b) Average delay. (c) The number of transmissions.

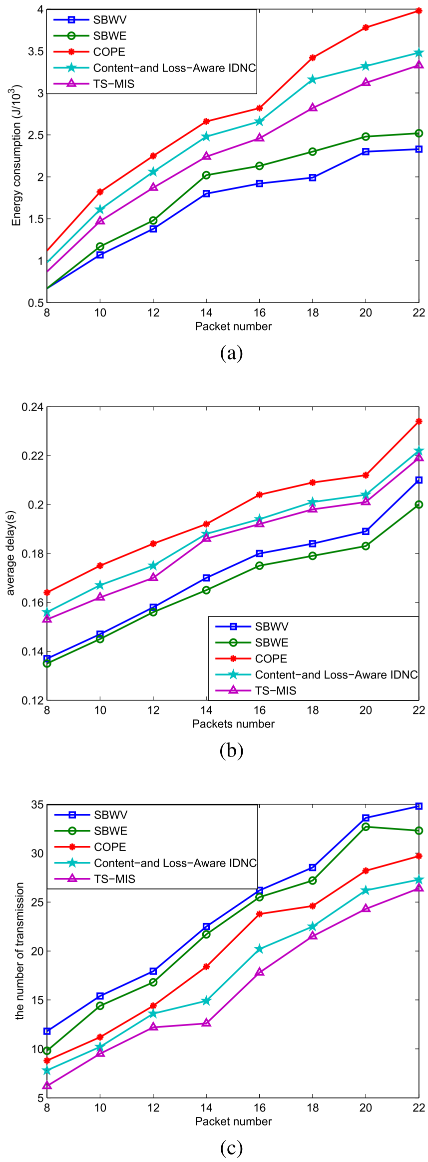
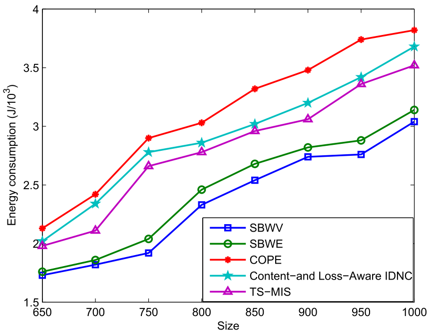


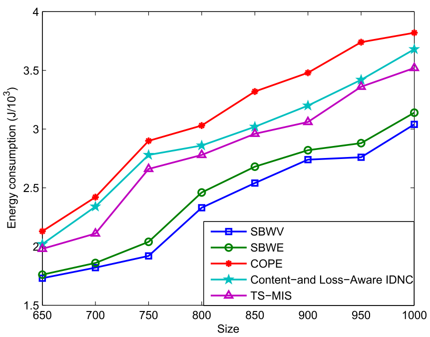
FIGURE 4. Performance comparison under different number of packets. (a) Energy consumption. (b) Average delay. (c) The number of transmissions.

plotted in Fig. 4. With an increase in the number of packets, the energy consumptions of all algorithms increase rapidly, as shown in Fig. 4(a). Compared with COPE, Content-and Loss-Aware IDNC and TS-MIS, SBWV decreases the energy consumption by 42%, 30%, and 22%, on average, respectively, and SBWE decreases the energy consumption by 30%, 26%, and 20%, on average, respectively. Compared with COPE, Content-and Loss-Aware IDNC, and TS-MIS, the SBWV decreases the average delay by 25%, 22%, and 20%, on average, respectively, and SBWE by 28%, 26%, and 21%, on average, respectively, as shown in Fig. 4(b). The SBWE is able to decrease the average delay by 4% compared with the SBWV on average. Finally, as shown in Fig.4(c), compared with COPE, Content-and Loss-Aware IDNC and TS-MIS, the SBWV takes less than 31%, 22%, and 18% extra transmission numbers, respectively. Moreover, compared with COPE, Content-and Loss-Aware IDNC, and TS-MIS, the SBWE takes less than 34%, 25%, and 19% extra transmission numbers, respectively.

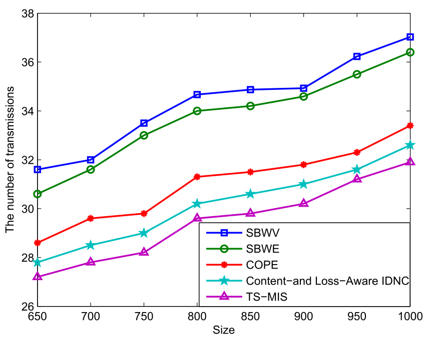
Finally, we vary the network size from 650m$*$650m to 1000m$*$1000m. Thus, the diversity of the transmission rates increases with the increase of the network area. Additionally, there are 10 packets and 5 devices. Fig. 5 illustrates the experimental results. As shown in Fig. 5(a), compared with COPE, Content-and Loss-Aware IDNC, and TS-MIS, SBWV saves 47%, 32%, and 26% extra energy on average, respectively, and the SBWE saves energy 42%, 30%, and 23% on average, respectively. As shown in Fig. 5(b), compared with COPE, Content-and Loss-Aware IDNC, and TS-MIS, the SBWV



(a)



(b)



(c)

FIGURE 5. Performance comparison under different network size. (a) Energy consumption. (b) Average delay. (c) The number of transmissions.

decreases the average delay by 29%, 22%, and 17%, on average, respectively. Similarly, the SBWE decreases the metric by an average of 35%, 24%, and 20%, respectively. The SBWE is able to decrease the average delay by 6%, on average, compared with the SBWV. Moreover, similar to Fig. 3(b) and 4(b), Fig. 5(b) shows that the average delay of the SBWE is the lowest. As shown in Fig.5(c), the SBWV consumes 42%, 31%, and 27% extra transmission numbers compared with COPE, Content-and Loss-Aware IDNC, and TS-MIS, respectively. And the SBWE increases 40%, 25%, and 20% extra transmission numbers, respectively. Like Fig. 3(c) and Fig. 4(c), Fig. 5(c) shows that the number of transmissions of the SBWE is less than SBWV.

VII. CONCLUSIONS

This paper had studied the problem of minimizing total energy consumption of all devices during recovery of their missing packets by applying coding algorithms based on the selection of the transmission rates in a D2D network. We formulated the problem as an integer nonlinear programming optimization and confirmed it as an NPC. Next, this paper analyzed the energy-saving benefit of the limiting parameter to control the edge number in the graph model. Furthermore, we proved the limiting parameter equals two when achieving the maximum benefit. Additionally, we presented two heuristic coding algorithms, which select the best clique in terms of the weight of the vertex (SBWV) and the best clique in terms of the weight of the edge (SBWE). Finally, the simulation results showed that the SBWV and SBWE both outperform existing coding schemes, with less energy consumption and lower average delays. Moreover, the SBWV consumed less energy than the SBWE, while the SBWE had a small number of transmissions than the SBWV. Future research and development will focus on increasing the coding opportunities in D2D networks and decreasing the number of transmissions in rate selection in order to improve the performance of the proposed algorithms.

APPENDIX

A. PROOF OF LEMMA 2

Proof: For $v^i_{j,l} \in V_i$, if $R_{i,j} = R_x$, then there is a corresponding sensitivity, denoted by Sen_x. And the corresponding received power $W^x_{rec(i,j)}$ should satisfy the following inequality:

$$Sen_x \leq W^x_{rec(i,j)} \leq Sen_{x+1}. \tag{20}$$

Therefore, based on Eq. (1), the distance between device d_i and device d_j is obtained as:

$$\sqrt[\alpha]{\frac{c \cdot W}{Sen_{x+1}}} \leq dis_{i,j} \leq \sqrt[\alpha]{\frac{c \cdot W}{Sen_x}}. \tag{21}$$

where c is a path loss coefficient that depends on the physical environment and the unit size of a signal, and is a constant and W is transmission power.

To ensure the transmission of the packet at least at the lowest rate R_1, the maximum distance dis_{max} between the sender and the receiver is obtained as:

$$dis_{max} = \sqrt[\alpha]{\frac{c \cdot W}{Sen_1}}. \tag{22}$$

Thus, according to the value range of $dis_{i,j}$ as shown in Eq. (23) and the geometric probability model, the probability of $R_{i,j} = R_x$ can be expressed as

$$P(R_{i,j} = R_x) = \frac{\pi \cdot (\sqrt[\alpha]{\frac{c \cdot W}{Sen_{x+1}}})^2 - \pi \cdot (\sqrt[\alpha]{\frac{c \cdot W}{Sen_x}})^2}{\cdot dis^2_{max}} = \frac{(\sqrt[\alpha]{\frac{c}{Sen_x}})^2 - (\sqrt[\alpha]{\frac{c}{Sen_{x+1}}})^2}{(\sqrt[\alpha]{\frac{c}{Sen_1}})^2}. \tag{23}$$

If $c = 1$ and $\alpha = 4$, then Eq. (23) becomes

$$P(R_{i,j} = R_x) = \sqrt{\frac{Sen_1}{Sen_x}} - \sqrt{\frac{Sen_1}{Sen_{x+1}}}. \quad (24)$$

B. PROOF OF THEOREM 1

Proof: For $\forall \mu, \mu + 1 \in \{0, 1, .., K - 1\}$. We define a function $f(\mu)$ as

$$\begin{aligned} f(\mu) &= Exp(\beta_{x,x+\mu}) \\ &= \beta_{1,1+0}P(R_{1,1+0}) + \ldots + \beta_{1,1+\mu}P(R_{1,1+\mu}) + \ldots \\ &\quad + \beta_{K,K+0}P(R_{K,K+0} + .. + \beta_{K,K+\mu}P(R_{K,K+\mu}). \end{aligned} \quad (25)$$

Then,

$$\begin{aligned} f(\mu+1) &= Exp(\beta_{x,x+\mu+1}) \\ &= \beta_{1,1+0}P(R_{1,1+0}) + \ldots + \beta_{1,1+\mu+1}P(R_{1,1+\mu+1}) \\ &\quad + \ldots + \beta_{K,K+0}P(R_{k,K+0}) + .. \\ &\quad + \beta_{K,K+\mu+1}P(R_{K,K+\mu+1}). \end{aligned} \quad (26)$$

Obviously,

$$\begin{aligned} f(\mu+1) - f(\mu) = \beta_{1,1+\mu+1}P(R_{1,1+\mu+1}) + \ldots \\ + \beta_{K,K+\mu+1}P(R_{K,K+\mu+1}) > 0. \end{aligned}$$

Thus, it is clear that know that $f(\mu)$ is an increasing function. Hence, $f(K - 1)$ is the maximum value, and the corresponding expectation $Exp(\beta_{x,x+K-1})$ is the maximum.

C. PROOF OF THEOREM 2

Proof: For $\forall \mu, \mu + 1 \in \{0, 1, .., K - 1\}$. We define a function $g(\mu)$ as

$$\begin{aligned} g(\mu) &= \sum_{\substack{x=1 \\ 0 \le x+\mu \le K}}^{K} \psi_{x,x+\mu}P(R_x, R_{x+\mu}) \\ &= \sum_{\substack{x=1 \\ 0 \le x+\mu \le K}}^{K} (1 - \frac{R_{x+\mu}}{2R_x})P(R_x, R_{x+\mu}). \end{aligned} \quad (27)$$

According to Eq. (17), and $P(R_x, R_{x+\mu}) > 0$. We can find that if $\frac{R_{x+\mu}}{R_x} < 2$, then $\psi_{x,x+\mu} > 0$, and $g(\mu)$ is an increasing function. If $\frac{R_{x+\mu}}{R_x} > 2$, then $\psi_{x,x+\mu} < 0$, and $g(\mu)$ is a decreasing function. If $\frac{R_{x+\mu}}{R_x} = 2$, then $\psi_{x,x+\mu} = 0$. Thus, $g(\mu)$ reaches the maximum value when $\frac{R_{x+\mu}}{R_x} = 2$. At the same time, reaches the maximum value.

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Authors' photographs and biographies not available at the time of publication.