Privacy and Social Aware Hybrid Successive Relaying with Mixed Trustworthy Untrustworthy D2D Helpers

Jie Wei*, Jianjing Wei†, Shaoling Hu‡, and Wei Chen‡, *Senior Member, IEEE*
*School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing 100044, China
Email: jwei@bjtu.edu.cn
†Beijing Jiaoda Signal Technology Co., Ltd., Beijing 102206, China
Email: weijianjing@jd-signal.com
‡Beijing National Research Center for Information Science and Technology (BNRist)
Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
Email: husl16@tsinghua.org.cn, wchen@tsinghua.edu.cn

***Abstract*— Social networks play a pivot role in people's daily life for allowing people to be connected with their relationships anytime and anywhere. Especially during the coronavirus pandemic, since the social distancing is practiced, the role of social networks become more important than ever. In this paper, we consider a social network based on device-to-device (D2D) relay communications, in which devices working as relays are divided into two sets. One is trustworthy for the source node, while the other is untrustworthy. To ensure the information security, those trustworthy nodes are allowed to decode signals from the source, while those untrustworthy nodes are forbidden. As a result, decode-and-forward (DF) relaying model can be applied by trustworthy nodes, however, untrustworthy nodes can adopt amplify-and-forward (AF) relaying model only. A successive relaying scheme is further applied to improve the transmission efficiency. In our scheme, digital and analog signal process methods are adopted to reduce the incurred inter-relay interference, respectively, for those trustworthy and untrustworthy relays. The analytical result of the maximum diversity gain is acquired for our scheme. Numerical results show that our scheme outperforms those schemes with two-timeslot relays, or only the trustworthy relays.**

I. Introduction

The social networks become a major technique for people to keep in touch with their relationships. Social networks have witnessed a rapid growth in traffic demand over the past year. Although 5G networks can help to improve the transmission efficiency, it is still an urgent demand to increase the capacity of social networks, while maintaining the privacy and security of users information [1] [2].To meet the challenge of the rapid growth of data exchanges over social network, device-to-device (D2D) communication as a promising technology can be applied into social network by allowing devices directly communicate with each other in close proximity. Moreover, the social ties between users are of great importance for D2D communications by providing those trusted neighbor peers as possible relays [3], which enhances the performance of D2D network.

For these reasons, social-aware D2D communications have drawn lots of attention recently. Particularly, social relationships of users act as decisive factors for selecting relays that are trusted by source or destination nodes in [4]- [6]. More specifically, relays are selected by jointly considering physical layer and social layer in [4]. A trustworthy D2D relay communication was developed based on methods of dynamic social trust management in [5]. A kinship trust model is established for the mobile social network (MSN) to screen out those trusted active strong relationship relay nodes in [6].

Furthermore, social ties of users can also offer important instructions for resource allocation within D2D communication networks [7] [8]. Specifically, recent advances of computing, caching, and communications were incorporated into social networks to share resources among users based on their social relationship in [7]. Both the one-hop-based and relay-based social-aware incentive mechanisms were proposed for a D2D network to instruct the resource sharing among those social-trustworthy and locality-adjacent devices in [8]. Additionally, the maximum capacity of fractal D2D social networks was investigated in [9], within both direct and hierarchical communications.

In this paper, we are interested in improving the throughput of a social-aware D2D communication network, while ensuring the users privacy and information security. Specifically, social connections of users are exploited to divided devices that can serve as relays into two disjoint sets, i.e., trustworthy nodes and untrustworthy nodes. Unlike those conventional social-aware D2D communication schemes in which only trustworthy nodes are used, both trustworthy and untrustworthy nodes participate in forwarding signals from the source node to the destination node. Furthermore, to maintain users privacy and information security, those trustworthy nodes are allowed to decode the received signals, while those untrustworthy nodes are forbidden. As a result, decode-and-forward (DF) mode can be adopted by trustworthy nodes, while untrustworthy nodes can only use amplify-and-forward (AF) mode. Moreover, to improve transmission efficiency, a successive relaying scheme is applied to schedule all these relay nodes. Through this scheme, the severe multiplexing loss due to half-duplex constraints of relays can be recovered by allowing the concurrent transmission of the source and a relay. Digital and analog signal processing methods are, respectively, used at trustworthy and untrustworthy nodes. Moreover, the maximum diversity gain of our scheme is given. Numerical results show that our scheme performs better than two-timeslot relaying and those schemes with only trustworthy relays in terms of throughput and outage probability.

II. System model

We consider a social-aware D2D communication network in which a source node S transmits to its destination node D with the aid of other devices, as shown in Fig. 1. Assume that all the devices are equipped with both the DF and AF relaying protocols and can work in half-duplex mode. However, not all devices that can cooperate with the node S are trustworthy. According to the social ties of source node, these devices working as relays are divided into two sets. One includes all the trustworthy nodes, which is denoted by $\mathcal{M}$. The untrustworthy nodes are classified into the other set denoted by $\mathcal{N}$.

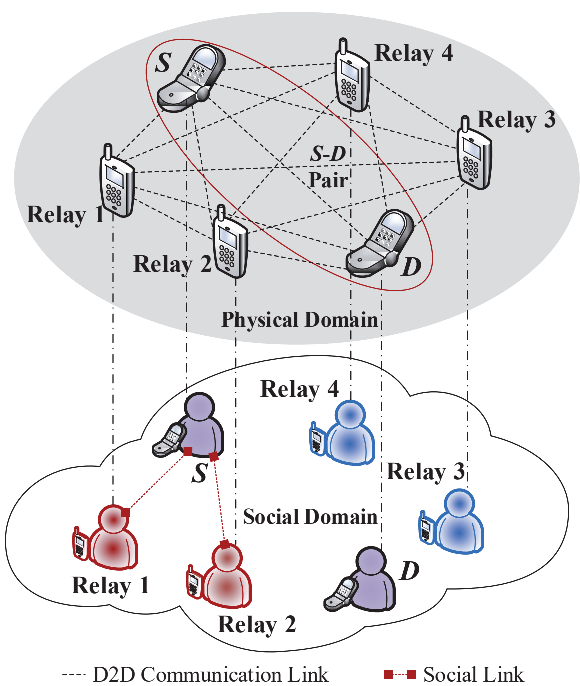

Fig. 1. System model (Take an example of four relays, two trustworthy relays and two untrustworthy relays).

Cooperative communication schemes are used to schedule the transmissions of the node S and the relay nodes. Additionally, the slow-fading channel model is assumed. Let $h_{i,j}$ denote the channel coefficient between the node i and the node j, where, $i \neq j$, $i \in \{S\} \cup \mathcal{M} \cup \mathcal{N}$, and $j \in \{D\} \cup \mathcal{M} \cup \mathcal{N}$. Time is divided into timeslots of equal length. We denote by $X_i[k]$ the signal transmitted by node i in the kth timeslot. Due to the half-duplex mode, the receiving node j can not transmit its signals simultaneously. The received signal by node j in the kth timeslot is given by

$$Y_j[k] = \sum_{i \in \mathcal{J}[k]} h_{i,j} X_i[k] + Z_j[k], \tag{1}$$

in which $\mathcal{J}[k]$ is the set of nodes transmitting in the kth timeslot. We use $Z_j[k]$ to denote the Additive White Gaussian Noise (AWGN) at node j. This AWGN is assumed to be subject to normal distribution with zero mean and variance σ^2, i.e., $Z_j[k] \sim \mathcal{CN}(0, \sigma^2)$.

Additionally, pilot-based channel estimation is applied. Channel State Informations (CSIs) of all links are broadcast and shared by each node participating in the communication between nodes S and D.

III. Successive Relaying in Social Network

In this section, we present a successive relaying algorithm for social networks, through which relay nodes are coordinated to transmit the source's signals. Particularly, different signal processing methods are introduced, respectively, for the trustworthy relays and untrustworthy relays.

Letting other devices in the network work as relays is an effective scheme to enhance the transmission reliability from node S to node D. However, because of the half-duplex constraint of relays, two timeslots must be consumed to send one message, resulting in severe multiplexing loss. An efficient method to recover the multiplexing loss is successive relaying, the idea of which is based on the concurrent transmission of node S and its relays. More specifically, when node S transmits its signals to a relay, there is another relay transmitting to the node D simultaneously. Through this way, one message can be sent within less than two timeslots in average, improving the multiplexing gain greater than $\frac{1}{2}$ even under the half-duplex constraint of relaying. However, as a result, heavy inter-relay interference (IRI) will be incurred by this successive relaying protocol. This inter-relay interference may significantly reduce the reliability of transmission unless it is canceled or effectively mitigated. In our previous work [10]-[12], the interference cancellation or mitigation methods have been developed for the successive relaying schemes based on DF mode or AF mode, respectively. In the following, we show how to use the successive relaying scheme into a social network to improve both its diversity gain and multiplexing gain.

Since relay nodes in set $\mathcal{M}$ are trustworthy for the node S, any relay node in set $\mathcal{M}$ is enabled to decode the messages received from node S. Thus, the DF relaying protocol can be applied by those relay nodes in set $\mathcal{M}$. Furthermore, it has been proved in [10], the IRI can be canceled thoroughly for the DF-based successive relaying once the relay nodes in $\mathcal{M}$ are carefully reordered. An equivalent parallel relay model is thus established in this way, achieving the optimal performance of successive relaying.

Let $\mathcal{M} = \{1, 2, \ldots, M\}$, where M is the number of relay nodes in $\mathcal{M}$. Any $i \in \mathcal{M}$ is the label of relay node in $\mathcal{M}$. Define $g_{i,j} = |h_{i,j}|^2$, which denotes the channel gain between node i and node j. Assume that the transmission power P

at each node is all the same, i.e., $P = \mathbb{E}\{|X_i[k]|^2\}$ for any $i \in \{S\} \cup \mathcal{M} \cup \mathcal{N}$, where $\mathbb{E}\{\bullet\}$ is the expectation operator. Then, based on Eq. (2) in [10], the relay nodes in $\mathcal{M}$ should be reordered according to

$$g_{S,(1)} \leq g_{S,(2)} \leq \cdots \leq g_{S,(M)}. \tag{2}$$

Correspondingly, the relay set $\mathcal{M}$ can be rewritten to be $\mathcal{M} = \{(1), (2), \ldots, (M)\}$. Eq. (2) implies that the relay labeled by (m) has the mth smallest channel gain to node S. Scheduled based on a successive relaying scheme, the received signals at relay (m), $(m) \in \mathcal{M}$, are given by

$$Y_{(m)}[1] = h_{S,(m)} X_S[1] + Z_{(m)}[1], \tag{3}$$

$$Y_{(m)}[k] = h_{S,(m)} X_S[k] + h_{(k-1),(m)} X_{(k-1)}[k] + Z_{(m)}[k], 2 \leq k \leq m, \tag{4}$$

where $X_S[k]$ and $X_{(k-1)}[k]$ are transmission signals at node S and relay $(k-1)$, respectively.

For a DF relay, its transmission rate cannot exceed the channel capacity of the link from the source node to itself. Having been ordered following Eq. (2), relay (m), $m > 1$, is thus capable of decoding $X_S[1]$, which is the forwarded signal of relay (1). Then, the decoded signal $X_S[1]$ can be used by relay (m) to cancel the interference from relay (1) in $Y_{(m)}[2]$. After canceling the interference, relay (m) can decode source signal $X_S[2]$ which will be used to cancel the interference from relay (2) in $Y_{(m)}[3]$. In this way, the interference from other relays can be always canceled before relay (m) decodes its source signal $X_S[m]$. This process is presented by

$$Y_{(m)}[k] - h_{(k-1),(m)} X_{(k-1)}[k] = h_{S,(m)} X_S[k] + Z_{(m)}[k]. \tag{5}$$

An equivalent parallel AWGN channel model without any inter-relay interference is thus established between node S and its relays.

As a contrast, relay nodes in set $\mathcal{N}$ are not trustworthy for node S. As a result, these relay nodes are not allowed to decode the received signals from node S to avoid privacy leakage. All the relays in $\mathcal{N}$ will work in AF relaying mode. To fully exploit these relay, an AF-based successive relaying scheme that has been developed in [11] can be applied. Through this AF-based successive relaying scheme, the inter-relay interference can be effectively mitigated. However, after the interference mitigation, there may exist residual interference that will be forwarded with desired signals by the relay. To avoid the impact of this residual interference on relays in set $\mathcal{M}$, these AF relays in $\mathcal{N}$ are arranged to transmit after the transmission of DF relays in $\mathcal{M}$.

Let $\mathcal{N} = \{M+1, M+2, \cdots, M+N\}$, where N is the number of relay nodes in set $\mathcal{N}$. Any $n \in \mathcal{N}$ is the label of relay node in $\mathcal{N}$. The received signals at relay n, $n \in \mathcal{N}$, are presented by

$$Y_n[1] = h_{S,n} X_S[1] + Z_n[1], \tag{6}$$

$$Y_n[k] = h_{S,n} X_S[k] + h_{(k-1),n} X_{(k-1)}[k] + Z_n[k], \quad 2 \leq k \leq M+1, \tag{7}$$

$$Y_n[k] = h_{S,n} X_S[k] + h_{k-1,n} X_{k-1}[k] + Z_n[k], \quad M+2 \leq k \leq n, \tag{8}$$

where $X_{(k-1)}[k]$ and $X_{k-1}[k]$ are, respectively, forwarded signals of DF relays and AF relays. Additionally, it is not necessary to reorder the AF relay nodes. A linear weighted sum with low complexity is applied to mitigate the inter-relay interference at AF relay nodes. Received signals $Y_n[k]$, $1 \leq k \leq n-1$, will work as the prior knowledge for AF relay n to get the desired signal $X_S[n]$. More specifically, these signals will be subtracted with different weights from $Y_n[n]$ by AF relay n. Let $\omega_n[k]$ denote the weight of $Y_n[k]$, $k \in \{1, 2, \ldots, n-1\}$. Define $\boldsymbol{\omega}_n = [\omega_n[1], \omega_n[2], \ldots, \omega_n[n-1]]$ and $\boldsymbol{y}_n = [Y_n[1], Y_n[2], \ldots, Y_n[n-1]]$. The processed signal after IRI mitigation at relay n is given by

$$Y_n^{AC} = Y_n[n] - \boldsymbol{\omega}_n \boldsymbol{y}_n^{\mathsf{T}}, \ \forall n \in \mathcal{N}. \tag{9}$$

Then relay n amplifies and forwards signal Y_n^{AC} to node D. The forwarded signal denoted by $X_n[n+1]$ is thus obtained by

$$X_n[n+1] = b_n Y_n^{AC}, \ \forall n \in \mathcal{N}, \tag{10}$$

where b_n is the amplify factor of relay n. After this IRI mitigation at AF relay n, it is clear that there exists residual interference, which is presented by $h_{n-1,n} X_{n-1}[n] - \boldsymbol{\omega}_n \boldsymbol{y}_n^{\mathsf{T}}$. The power of residual interference at relay n is given by

$$\Theta_n = \mathbb{E}\left\{ |h_{n-1,n} X_{n-1}[n] - \boldsymbol{\omega}_n \boldsymbol{y}_n^{\mathsf{T}}|^2 \right\}, \ \forall n \in \mathcal{N}. \tag{11}$$

Since the transmission power is P, i.e., $P = \mathbb{E}\{|X_n[n+1]|^2\}$, the amplifier factor is obtained by

$$b_n = \sqrt{\frac{P}{|h_{S,n}|^2 P + \Theta_n + \sigma^2}}, \ \forall n \in \mathcal{N}. \tag{12}$$

To minimize the power of residual interference Θ_n, the optimal weights $\boldsymbol{\omega}_n^*$ can be obtained. Some definitions should be introduced first before we show how to obtain the optimal weights $\boldsymbol{\omega}_n^*$. Define $\boldsymbol{z}_k = [Z_k[1], Z_k[2], \ldots, Z_k[k]]$ for $1 \leq k \leq M+N$, $\hat{\boldsymbol{z}}_n = [Z_n[1], Z_n[2], \ldots, Z_n[n-1]]$, and $\boldsymbol{x}_n = [X_S[1], X_S[2], \ldots, X_S[n]]$, for $n \in \mathcal{N}$. Then, we get

$$\boldsymbol{y}_n^{\mathsf{T}} = \boldsymbol{F}_n^H \boldsymbol{x}_{n-1}^{\mathsf{T}} + \sum_{k=M+1}^{n-2} \boldsymbol{D}_{n,k}^H \boldsymbol{z}_k^{\mathsf{T}} + \hat{\boldsymbol{z}}_n^{\mathsf{T}}, \tag{13}$$

where $\boldsymbol{F}_n^H$ and $\boldsymbol{D}_{n,k}^H$ are, respectively, the coefficient matrices of vectors $\boldsymbol{x}_{n-1}^{\mathsf{T}}$ and $\boldsymbol{z}_k^{\mathsf{T}}$ in $\boldsymbol{y}_n^{\mathsf{T}}$. Notations H and T denote Hermitian transpose and matrix transpose, respectively. Furthermore, we rewrite Y_n^{AC} by

$$Y_n^{AC} = \boldsymbol{\alpha}_n \boldsymbol{x}_{M+N}^{\mathsf{T}} + \sum_{k=M+1}^{n} \boldsymbol{\beta}_{n,k} \boldsymbol{z}_k^{\mathsf{T}}, \tag{14}$$

where $\boldsymbol{\alpha}_n$ and $\boldsymbol{\beta}_{n,k}$ are, respectively, the coefficient vectors of vectors $\boldsymbol{x}_{M+N}^{\mathsf{T}}$ and $\boldsymbol{z}_k^{\mathsf{T}}$ in Y_n^{AC}. In more detail, we get

$$\boldsymbol{\alpha}_n = \left[b_{n-1} h_{n-1,n} \boldsymbol{\alpha}_{n-1}(1 : n-1) - \boldsymbol{\omega}_n \boldsymbol{F}_n^H, h_{S,n}, \mathbf{0}_{1,M+N-n} \right], \tag{15}$$

$$\boldsymbol{\beta}_{n,k} = b_{n-1} h_{n-1,n} \boldsymbol{\beta}_{n-1,k} - \boldsymbol{\omega}_n \boldsymbol{F}_{n,k}^H, M+1 \leq k \leq n-2, \tag{16}$$

$$\boldsymbol{\beta}_{n,n-1} = b_{n-1} h_{n-1,n} \boldsymbol{\beta}_{n-1,n-1}, \tag{17}$$

$$\boldsymbol{\beta}_{n,n} = \left[-\boldsymbol{\omega}_n, 1 \right], \tag{18}$$

where $n \in \mathcal{N}$, $h_{M,M+1} = h_{(M),M+1}$, b_M=1, $\boldsymbol{\alpha}_M$=$\boldsymbol{e}_M$, and $\boldsymbol{e}_k$=$[\mathbf{0}_{1,k-1}, 1, \mathbf{0}_{1,M+N-k}]$. We use $\mathbf{0}_{i,j}$ to denote a $i \times j$ matrix whose components are all zeros. It is seen that matrices

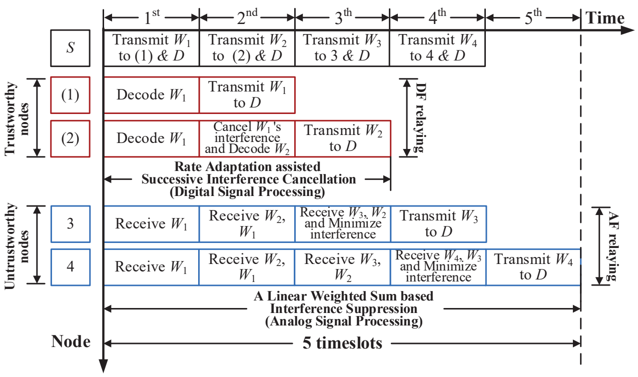

Fig. 2. Time-slotted scheduling for $M = 2$ and $N = 2$. (W_k is the message encoded into $X_S[k]$.)

$\boldsymbol{F}_n^H$ and $\boldsymbol{D}_{n,k}^H$ can also be expressed as functions of $\{\boldsymbol{\alpha}_k\}$ and $\{\boldsymbol{\beta}_{n,k}\}$, given by

$$\begin{aligned}\boldsymbol{F}_n &= \bar{h}_{S,n}\boldsymbol{I}_{n-1} + [\boldsymbol{0}_{n-1,1}, \bar{h}_{(1),n}\boldsymbol{e}_1(1:n-1), \ldots,\\ &\quad \bar{h}_{(M),n}\boldsymbol{e}_M(1:n-1), \bar{b}_{M+1}\bar{h}_{M+1,n}\boldsymbol{\alpha}_{M+1}^H(1:n-1),\\ &\quad ,\ldots, \bar{b}_{n-1}\bar{h}_{n-1,n}\boldsymbol{\alpha}_{n-1}^H(1:n-1)], \end{aligned} \tag{19}$$

$$\begin{aligned}\boldsymbol{D}_{n,k} &= [\boldsymbol{0}_{k,k}, \bar{b}_k\bar{h}_{k,n}\boldsymbol{\beta}_{k,k}^H, \bar{b}_{k+1}\bar{h}_{k+1,n}\boldsymbol{\beta}_{k+1,k}^H, \cdots,\\ &\quad \bar{b}_{n-2}\bar{h}_{n-2,n}\boldsymbol{\beta}_{n-2,k}^H], M+1 \le k \le n-2, \end{aligned} \tag{20}$$

where $\boldsymbol{I}_{n-1}$ is $(n-1)\times(n-1)$ identity matrix. Next, we arrive at the optimal weight vector $\boldsymbol{\omega}_n^*$.

***Theorem** 1:* The optimal weight vector $\boldsymbol{\omega}_n^*$ that minimizes the power of residual interference is given by

$$\boldsymbol{\omega}_n^* = b_{n-1}h_{n-1,n}\boldsymbol{a}_n\boldsymbol{B}_n^{-1}, \forall n \in \mathcal{N}, \tag{21}$$

in which

$$\boldsymbol{a}_n = P\boldsymbol{\alpha}_{n-1}(1:n-1)\boldsymbol{F}_n + \sigma^2\sum_{k=M+1}^{n-2}\boldsymbol{\beta}_{n-1,k}\boldsymbol{D}_{n,k}, \tag{22}$$

$$\boldsymbol{B}_n = P\boldsymbol{F}_n^H\boldsymbol{F}_n + \sigma^2\left(\sum_{k=M+1}^{n-2}\boldsymbol{D}_{n,k}^H\boldsymbol{D}_{n,k} + \boldsymbol{I}_{n-1}\right). \tag{23}$$

Proof: Substituting Eqs. (13), (15)-(18) into Eq. (11), the power of residual interference is reformulated by

$$\Theta_n = P\boldsymbol{\alpha}_n(1:n-1)\boldsymbol{\alpha}_n^H(1:n-1) + \sigma^2\left(\sum_{k=1}^{n}\boldsymbol{\beta}_{n,k}\boldsymbol{\beta}_{n,k}^H - 1\right). \tag{24}$$

Notice that both $\boldsymbol{\alpha}_n(1:n-1)$ and $\boldsymbol{\beta}_{n,k}$, $k \in \{M+1,\ldots,n-2,n\}$ are functions of $\boldsymbol{\omega}_n$. Based on the principle of orthogonality, the optimal weight vector $\boldsymbol{\omega}_n^*$ is obtained by $\frac{\partial\Theta_n}{\partial\boldsymbol{\omega}_n} = 0$. By substituting Eqs. (24) into this equation, we get Eq. (21), which completes the proof. ■

***Lemma** 1:* The minimum power of residual interference is obtained by

$$\Theta_n = g_{n-1,n}\left(P - g_{n-1}\boldsymbol{a}_n\boldsymbol{B}_n^{-1}\boldsymbol{a}_n^H\right). \tag{25}$$

Proof: The minimum power of residual interference is obtained by directly substituting Eq. (21) into Eq. (24). ■

An example of this scheduling strategy is shown in Fig. 2. Having presented the signal processes at relay nodes, we next introduce how to get the desired signals at node D. The received signals at node D are given by

$$\begin{aligned} Y_D[k] &= h_{S,D}X_S[k] + h_{(k-1),D}X_{(k-1)}[k] + Z_D[k], \\ &\qquad 1 \le k \le M+1, \end{aligned} \tag{26}$$

$$\begin{aligned} Y_D[k] &= h_{S,D}X_S[k] + h_{k-1,D}X_{k-1}[k] + Z_D[k], \\ &\qquad M+2 \le k \le M+N, \end{aligned} \tag{27}$$

$$\begin{aligned} Y_D[M+N+1] &= h_{M+N,D}X_{M+N}[M+N+1] \\ &\quad + Z_D[M+N+1], \end{aligned} \tag{28}$$

where $h_{(0),D} = 0$ and $X_{(0)}[1] = 0$.

A reverse successive decoding scheme is adopted by node D to cancel the interference from node S. More specifically, node D first decodes W_{M+N} from its last received signal $Y_D[M+N+1]$ in which there is no interference from S. By re-encoding W_{M+N}, node D reconstructs the signal $X_S[M+N]$. Signal $h_{S,D}X_S[M+N]$ can be reconstructed at node D with obtained CSI $h_{S,D}$. By subtracting the signal $h_{S,D}X_S[M+N]$ from $Y_D[M+N]$, node D can completely cancel the interference caused by S in $Y_D[M+N]$. Node D can decode W_{M+N-1} from the residual signal $h_{M+N-1,D}X_{M+N-1}[M+N] + Z_D[M+N]$. In this way, for $k = 2, \cdots, M+N+1$, node D can reconstruct $X_S[k]$ by re-encoding W_k. Using this prior knowledge $X_S[k]$ and local CSI $h_{S,D}$, node D can thoroughly cancel the interference from S by

$$\begin{aligned} Y_D[k] - h_{S,D}X_S[k] &= h_{(k-1),D}X_{(k-1)}[k] + Z_D[k] \\ &\qquad 2 \le k \le M+1, \end{aligned} \tag{29}$$

$$\begin{aligned} Y_D[k] - h_{S,D}X_S[k] &= h_{k-1,D}X_{k-1}[k] + Z_D[k], \\ &\qquad M+2 \le k \le M+N. \end{aligned} \tag{30}$$

Node D can decode message W_{k-1} from the residual signal $h_{k-1,D}X_{k-1}[k] + Z_D[k]$. This process makes no differences between the signals from DF relays and AF relays.

IV. Performance Analysis

In the above, we have presented the successive relaying scheme to enhance the links of a social network. We next analyze the average throughput in the following context. Based on the analysis of average throughput, we give the achievable diversity gain of this successive relaying scheme.

A. Average Throughput

Based on the baseband model in above section, we present the average throughput in the following theorem.

***Theorem** 2:* The average throughput of this successive relaying scheme is obtained by

$$\bar{C} = \frac{\sum_{k=1}^{M+N} C_k}{M+N+1}, \tag{31}$$

in which C_k is given by

$$C_k = \begin{cases} \log\left(1 + \min\{g_{S,(k)}, g_{(k),D}\}\frac{P}{\sigma^2}\right), \\ \qquad k = 1, 2, \cdots, M, \\ \log\left(1 + \frac{g_{S,k}g_{k,D}P^2}{Pg_{k,D}(\Theta_k+\sigma^2)+\sigma^2(\Theta_k+\sigma^2)+Pg_{S,k}\sigma^2}\right), \\ \qquad k = M+1, M+2, \cdots, M+N. \end{cases} \tag{32}$$

Proof: We shall first obtain the capacities of links through DF relays and AF relays, respectively. Then, the average throughput is given by Eq. (31).

Since the IRI is completely canceled by DF relay nodes, the equivalent SNR of $S-(k)-D$ link is obtained by $\gamma_{(k)} = \min\left\{g_{S,(k)}, g_{(k),D}\right\}\frac{P}{\sigma^2}$. The capacity is then acquired by $C_k = \log\left(1+\min\{g_{S,(k)}, g_{(k),D}\}\frac{P}{\sigma^2}\right)$ for $k = 1, 2, \ldots, M$. Due to the residual IRI for AF relays, the equivalent SNR of $S-k-D$ links is given by

$$\gamma_k = \frac{g_{S,k}g_{k,D}P^2}{Pg_{k,D}(\Theta_k+\sigma^2)+\sigma^2(\Theta_k+\sigma^2)+Pg_{S,k}\sigma^2}, \quad (33)$$

where $k = M+1, \ldots, M+N$. Then, the capacity of this AF relay link is obtained by

$$C_k = \log\left(1+\frac{g_{S,k}g_{k,D}P^2}{Pg_{k,D}(\Theta_k+\sigma^2)+\sigma^2(\Theta_k+\sigma^2)+Pg_{S,k}\sigma^2}\right). \quad (34)$$

Finally, the capacity of each relay link is given by Eq. (32). ∎

B. Outage Probability and Diversity Gain

In this part, we first present the analysis of outage performance of this successive relaying scheme. Finally, we analyze the achievable diversity gain of this scheme.

Let $p_o(\gamma)$ denote the outage probability given by

$$p_o(\gamma) = \Pr\left\{\frac{\sum_{k=1}^{M+N} C_k}{M+N+1} \leq R\right\}, \quad (35)$$

in which R, $R > 0$, and γ are the target rate and the transmitter side SNR, respectively. The diversity gain d is defined by

$$d = -\lim_{\gamma\to\infty}\frac{\log p_o(\gamma)}{\log\gamma}, \quad (36)$$

in which $\gamma = \frac{P}{\sigma^2}$. Assume that each of the channel gains $g_{i,j}$ submits to an exponential distribution with parameter $\frac{1}{\bar{g}_{i,j}}$. Additionally, the target rate R is set to be a constant. Then, we can acquire the achievable maximum diversity gain of this scheme.

***Theorem** 3:* The maximum diversity gain of this successive relaying scheme is given by

$$d_{\max} = M + \frac{N}{M+1}. \quad (37)$$

Proof: The proof is to use the method of large deviation. Define $v_{i,j} = -\frac{\log g_{i,j}}{\log\gamma}$ and $t_k = -\frac{\log\tau_k}{\log\gamma}$, where $\tau_k = \frac{\Theta_k+\sigma^2}{\sigma^2}$, $v_{i,j} \geq 0$, $v_{(i),D} = v_{i,D}$ and $v_{S,(i)} = v_{S,i}$ for $i = 1, \ldots, M$. It can be shown that t_k is a function of $\{v_{i,j}\}$. By substituting $\{v_{i,j}\}$ and $\{t_k\}$ into Eq. (35), we get

$$\begin{aligned}
&\lim_{\gamma\to\infty} p_o(\gamma) \\
&= \lim_{\gamma\to\infty}\Pr\Bigg\{\sum_{k=1}^{M}\log\left(1+\min\{\gamma^{1-v_{S,k}}, \gamma^{1-v_{k,D}}\}\right) + \\
&\sum_{k=M+1}^{M+N}\log\left(1+\frac{\gamma^{1-v_{S,k}-v_{k,D}}}{\gamma^{t_k-v_{k,D}}+\gamma^{-v_{S,k}}}\right) \leq (M+N+1)R\Bigg\} \\
&\overset{(1)}{=} \lim_{\gamma\to\infty}\Pr\Bigg\{\sum_{k=1}^{M}(1-\max\{v_{S,k}, v_{k,D}\})^+ + \\
&\sum_{k=M+1}^{M+N}(1-\max\{t_k+v_{S,k}, v_{k,D}\})^+ \leq 0\Bigg\}, \quad (38)
\end{aligned}$$

where $(a)^+ = \max\{a, 0\}$. Step (1) is due to that R is a constant and $\lim_{\gamma\to\infty}\frac{(M+N+1)R}{\log\gamma} = 0$. From Eq. (38), we get the feasible region of $\{v_{i,j}\}$ by

$$\begin{aligned}
&\mathcal{O} = \{v_{i,j} \in \mathbb{R}, i \in \{S\}\cup\mathcal{M}\cup\mathcal{N}, j \in \{D\}\cup\mathcal{M}\cup\mathcal{N} | \\
&v_{i,j} \geq 0, \max\{v_{S,k}, v_{k,D}\} = 1, \max\{t_k+v_{S,k}, v_{k,D}\} = 1\}.
\end{aligned} \quad (39)$$

Based on Eq. (38), the diversity gain is obtained by

$$d = \min_{v_{i,j}\in\mathcal{O}} \sum_{i\in\{S\}\cup\mathcal{M}\cup\mathcal{N}, j\in\{D\}\cup\mathcal{M}\cup\mathcal{N}} v_{i,j}. \quad (40)$$

The explanation of this transition can be found in the appendix of [13]. Thus, we get $v_{S,k} = 0$, $v_{k,D} = 1$ or $v_{S,k} = 1$, $v_{k,D} = 0$ for $k = 1, 2, \ldots, M$. Furthermore, we get $\sum_{k\in\mathcal{M}}(v_{S,k} + v_{k,D}) = M$. Additionally, from appendix C in [11], we can get $t_{M+1} = Mv_{S,M+1}$. To minimize the sum of $\{v_{i,j}\}$, we obtain from Eq. (39) that $t_k + v_{S,k} = 1$ and $v_{k,D} = 0$, otherwise, if $t_k + v_{S,k} = 0$ and $v_{k,D} = 1$, the sum of $\{v_{i,j}\}$ will be greater. Thus, we get $v_{S,M+1} = \frac{1}{M+1}$.

What's more, it is important to note that to achieve the maximum diversity gain, all of the AF relay nodes should be reordered as well. Different from the DF relays, reordering is not necessary for AF relays. However, by reordering of AF relays, the maximum capacity can be achieved, which leads to the maximum diversity gain. After this reordering, we acquire that $v_{S,(k)} = \frac{1}{M+1}$ for $k = M+1, M+2, \ldots, M+N$ from the proof of Theorem 6 in [11].

As a summary, we get $v_{S,k} = 0$, $v_{k,D} = 1$ or $v_{S,k} = 1$, $v_{k,D} = 0$ for $k = 1, 2, \ldots, M$, $v_{S,(k)} = \frac{1}{M+1}$ for $k = M+1, M+2, \ldots, M+N$. The remaining variables in $\{v_{i,j}\}$ can be set to be zeros based on Eqs. (39)-(40). Finally, we have the maximum diversity gain by Eq. (37). ∎

From Theorem 3, it is seen that both the trustworthy and the untrustworthy relays contribute to the diversity gain. However, the number of DF relay nodes has an impact on the diversity gain obtained by AF relays.

V. Numerical results

In this section, we present the numerical results to validate the theoretical analysis and show the potential of the proposed successive relaying scheme for social networks. Specifically, we discuss two cases, one includes one trustworthy node and two untrustworthy nodes, while the other includes two trustworthy nodes and one untrustworthy node. Consider independent and identically distributed ($i.i.d.$) Rayleigh fading channels with $\frac{1}{\bar{g}_{i,j}} = \frac{1}{4}$ for each node pair (i, j). To give more insights, our scheme is compared with conventional two-timeslot relaying scheme with two DF relays and those schemes with only trustworthy relays or untrustworthy relays.

Fig. 3 shows the curves of average throughput versus transmitter side SNR. We use r to denote the slope of curves in the high SNR region. There are three different values to these slopes, i.e., $\frac{3}{4}$, $\frac{2}{3}$, and $\frac{1}{2}$, corresponding to successive relaying schemes with three or two relays, and two-timeslot relaying schemes, respectively. From Fig. 3, more DF relays can improve the average throughput with the same total number of relay nodes for our scheme. Specifically, to reach 3 bit/s/Hz,

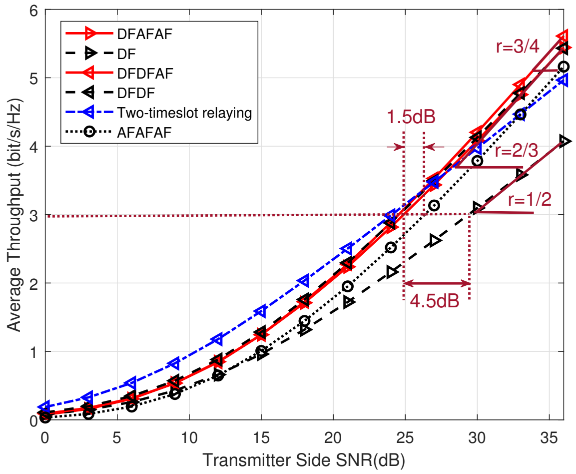

Fig. 3. The Average Throughput.

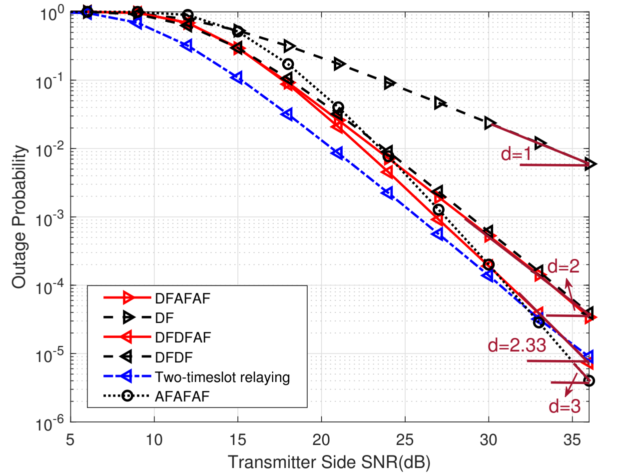

Fig. 4. The Outage Probability. The target rate and multiplexing gain are set to be $R = 1$ and $r = 0$, respectively.

the scheme with three untrustworthy nodes consumes more 1.5 dB than that with one trustworthy node and two untrustworthy nodes. Moreover, exploiting both trustworthy and untrustworthy relays achieves higher throughput than those schemes with only trustworthy or untrustworthy relays. Specifically, to reach 3 bit/s/Hz, the scheme with one trustworthy node and two untrustworthy node saves 4.5 dB than that with only one trustworthy node. Additionally, our scheme outperforms those two-timeslot relaying schemes in the high SNR region.

Fig. 4 shows the curves of outage probability versus transmitter side SNR for $R = 1$bit/s/Hz. Moreover, the diversity gains can be estimated from the slopes of the curves. For our schemes, the theoretical diversity gains can be obtained by Eq. (37). Simulation results show that diversity gains are, respectively, 2 and 2.33 for the case of one DF relay and two AF relays, and the case of two DF relays and one AF relay, which validates the theoretical analysis. Additionally, the schemes using both trustworthy and untrustworthy relays outperform those with only trustworthy relays and two-timeslot relaying scheme. Moreover, under the same total number of relays, more trustworthy relays can improve this achievable diversity gain. The diversity gain of our scheme with three untrustworthy relays is 3, which further validates Theorem 3.

VI. Conclusion

In this paper, we have investigated the social-aware D2D communications, in which a privacy-aware successive relaying scheme is applied to improve the transmission efficiency. Specifically, both the trustworthy and untrustworthy relay nodes are exploited to enhance the transmission link. Moreover, DF and AF modes are respectively, applied at trustworthy and untrustworthy nodes. As a result, digital and analog signal processing methods are, respectively, adopted by trustworthy and untrustworthy nodes to cancel or mitigate the IRI incurred by the successive relaying. Furthermore, we have given the closed-form expression of the maximum diversity gain of our scheme. Additionally, the users privacy and security of information are maintained by only allowing trustworthy nodes to decode signals from the source. What's more, it has been shown through our scheme that those untrustworthy nodes can also be used to improve the network in terms of throughput and outage performance without any risk of privacy leakage and security threats.

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