Social-Oriented Adaptive Transmission in Opportunistic Internet of Smartphones

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***Abstract*—Stable and reliable wireless communication is one of the critical demands for smart cities to connect people and devices. Although intelligent terminals can be leveraged to deliver and exchange data through Internet, poor network coverage and expensive network access challenge the deployment of network infrastructure. In this paper, we propose a social-oriented smartphone-based adaptive transmission mechanism to improve the network connectivity and throughput in Internet of Things (IoTs) for smart cities. First, a social-oriented double-auction-based relay selection scheme is investigated to stimulate the relay smartphones to forward packets for others so that the network connectivity can be strengthened. Furthermore, for the sake of achieving high throughput in smartphone-based IoTs, the relay method selection is determined by integrating various kinds of transmission schemes in an optimal fashion to make full use of wireless spectrum resource. Due to its high computational complexity, a firefly-algorithm-based scheme is investigated, by which the formulated NP-complete problem can be solved effectively. Simulation results demonstrate the superiority of our proposed method.**

***Index Terms*—Firefly algorithm, Internet of smartphones, relay selection, smart cities, social selfishness.**

I. Introduction

SMART cities require ubiquitous urban sensing and communication so that the advanced and innovative services can be provided to improve the overall quality of citizens' life. Although some work can be fulfilled by connecting to the Internet directly or via multihop wireless networks, it is probably impossible to provide reliable connection under some circumstances due to the high cost or low communication coverage [1]. For example, cellular communication is costly for data transmission with large volume and free Wi-Fi connections are not invariably usable. On the contrary, opportunistic networks [2] provide a new way to collect and share data in the regions with poor or no network coverage by low-cost transmissions, whose core idea is to leverage the intermittent connections with short-range radio communications among mobile individuals. The advantages of opportunistic networks are twofold: 1) their infrastructure is more flexible than the cellular network, and the workload of the cellular network can be alleviated by opportunistic transmissions; and 2) the corresponding transmissions are high energy efficiency and low cost.

Since it is difficult for decision making at different terminals due to the insufficient or overload of the available information in Internet of Things (IoTs), a consensus decision-making method has been studied for data processing [3]. However, one challenge inside is that all the individuals have to wait for the slowest one during each iteration for synchronization, which decelerates the convergence speed. One promising alternative for ubiquitous urban sensing and communication is to employ the prevalence of smartphones to construct the opportunistic communication paradigm. Crowdsensing has gained comprehensive attention due to the extensive utilization of mobile equipment in IoTs. Its objective is to involve participants from public to contribute sensing data from their mobile terminals (such as smartphones) in a collaborative method [4]. It is deemed that smartphones equipped with increasingly powerful sensors will play a critical role for applications in smart cities because they are able to collect accurate location-aware information to feed new services [5]. Smartphones can perform as relays to bridge the connections between sensors and base stations by utilizing low-cost short-range communications (such as Zigbee, Wi-Fi, and Bluetooth) and human mobility [6]. The mentioned low-cost communication methods are suitable for the delay-tolerant sensing applications, take urban traffic monitoring as an example.

Although cooperative transmissions in smartphone-based IoTs (i.e., Internet of smartphones) are advocated for smart cities, three key issues have to be addressed.

1) A fundamental assumption in the relay-selection-based social networks is that individuals are generally viewed as fully cooperative. However, the Internet of smartphones is both opportunistic and human centric. Thus, some

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smartphones may either refuse to forward information for others to save their limited resources (e.g., bandwidth or energy) or prefer forwarding for the smartphones with strong social relationship. Therefore, the selfish behavior of smartphones is a nontrivial issue, which would cause link disconnection and performance deterioration.

2) Although various incentive schemes have been investigated to stimulate selfish nodes in packet forwarding, user aspiration, selfish variability, and node diversity have not been fully discussed yet. One common solution is to suppress node selfish behavior. However, it is an intrinsic feature changing with time and network situations.
3) An ocean of transmission schemes coexists in Internet of smartphones; how to integrate these techniques optimally to make full use of wireless spectrum is challenging.

The authors in [7] presented a credit-based incentive method to encourage packet forwarding by selfish nodes in community-based networks. A truthful auction scheme for cooperative communication (TASC) has been investigated in [8]. Its main idea is to enforce both sellers and buyers submitting true valuations to suppress node selfishness and eliminate market manipulation. A selfish-tailored routing protocol has been studied in [4] according to smartphones' contacts and willingness for cooperation. Node's social selfishness is modeled as differentiated relay cost, which demonstrates that not only the available bandwidths but also nodes' social relationships determine the transmission rates at the destination nodes. Therefore, social selfishness is an essential part of high-efficiency transmission for smart cities.

In this paper, a social-oriented adaptive transmission mechanism is proposed to improve the network connectivity and throughput in Internet of smartphones. First, a social-aware double-auction-based relay selection is studied, by which the relays are stimulated for packet forwarding so that the network connectivity can be strengthened. Then, the relay method selection is determined by integrating various kinds of transmission schemes in an optimal fashion to maximize network throughput. Due to the high computational complexity of the formulated problem, a firefly-algorithm-based method is investigated to solve this problem with a heuristic approach. Our main contributions are stated as follows.

1) We investigate a social-oriented double-auction-based relay selection scheme according to both social relationship and trust of smartphones, by which the network connectivity can be enhanced. Our method is market oriented and selfishness tolerant so that source and relay nodes bid or ask according to their network resources and social relationships.
2) We present an optimal relay method selection scheme to make full use of wireless spectrum resource in Internet of smartphones. By stimulating smartphones to take part in the cooperative communications, more opportunities can be generated to take advantage of the cooperative communication techniques for throughput improvement.
3) Since the formulated optimization problem is NP-complete, a firefly-algorithm-based scheme is modeled to solve this problem, by which the formulated problem can be solved effectively with a heuristic approach. To the best of our knowledge, the application of the firefly algorithm has not been studied in the corresponding research area yet.
4) Extensive experiments are conducted using both synthetic- and real-trace-based simulations, which demonstrate that our optimal scheme outperforms other methods in delivery ratio, throughput gain, link capacity, and power consumption. Furthermore, the firefly-algorithm-based scheme is effective to obtain the network performance gained by the optimal method.

The remainder of this paper is organized as follows. Section II illustrates the related works. Section III describes the social-oriented next-hop node selection for smartphones. The optimal relay method selection scheme in Internet of smartphones is investigated in Section IV, and the firefly-algorithm-based heuristic approach is studied in Section V. Performance evaluations are demonstrated in Section VI. Finally, some concluding remarks are presented in Section VII.

II. Related Works

The advantages brought by smartphones in mobile sensing and communication facilitate the applications in smart cities, such as the monitoring of traffic congestion and air pollution. The corresponding adaptive technologies have been investigated by researchers from both industry and academia. Since the connections between human and smartphones are inherently integrated, the corresponding studies are becoming hot topics, which can be generally classified as effective packet delivery and security transmissions in Internet of smartphones.

The concept of multihop device-to-device communication networks has been utilized for a multitude of applications. For example, the smartphone-based transmission schemes for emergency message delivery in disconnected areas have been investigated in [5]. Due to the spontaneous of the smartphone-based networks, ambiguous transmission opportunities and short message lifetime become obstacles for efficient data delivery. The authors in [9] have studied a transient delivery method based on the Markov predictor, which makes the forwarding decisions according to the quantified regularity of small-time-scale movement of smartphones. By employing the sensors to capture surrounding information, a cloud-centric cyber-physical system has been constructed according to the returned service sharing or computation information by smartphones [10].

The studies of security and privacy transmissions in Internet of smartphones also become research hotspot. Although crowdsensing by smartphones is advocated, how to guarantee the trustworthiness of the crowd sensed data is challenging. A vote-based crowdsensing framework has been presented in [11], which concentrates on trustworthiness assurance by the voting of the involved smartphone users. Since the traditional mobile communication paradigm is being changed by the spread of mobile cloud computing infrastructure, new privacy risks arise because the personal information of the smartphone users is spread among different terminals. A communication protocol for smartphone users in cloud computing environments has been presented in [12], which supports anonymous communication so that node security can be guaranteed. Since smartphones with particular applications are likely to be the carriers of IoTs with various services, the application's trustworthiness is quantified by the similarity between the application's behavior and the behavior expected by the user [13]. Part of this work has been proposed in [14]. This paper differs from the previous one in the following aspects.

1) The original double-auction-based scheme is extended to a more general model for diverse situations by investigating node trust.
2) A firefly-algorithm-based scheme is designed to solve the NP-complete problem brought by the optimization model.
3) The environment awareness and forwarding strategy of the presented scheme are enhanced in Internet of smartphones for smart cities.
4) Both synthetic- and real-trace-based simulations are conducted to demonstrate the superiority of our method.

III. Social-Oriented Next-Hop Selection

For the sake of providing both effective and security transmissions in Internet of smartphones, a trust-based social-aware user assignment scheme is studied in this section, which is from the aspects of social relationship evaluation and node trust evaluation.

A. Social-Based Metrics

In order to evaluate node relationship, the social-based metrics are employed, which consider network density, quality, and community by analyzing the information exchange with their surrounding nodes. The network is modeled as a directed graph $G = (V, E)$, where V is a set of nodes and E is a collection of links between the nodes. If a node pair $j - j'$ can communicate with each other directly, it is defined as one session. If the packets are conveyed from nodes j to j' with the aid of an intermediate node i, the node group $j - i - j'$ is denoted as one session. Three complementary social-based metrics are presented as follows.

1) Friendship of Neighboring Nodes: In order to evaluate the degree that one node impacts its neighboring nodes during one scheduling period, this metric calculates the percentage of the number of the packets transmitted from one source node to the total number of the packets received by the destination node. The friendship of neighboring nodes for node j, denoted as FN_j, is shown as $FN_j = \frac{1}{|Q_j|}\sum_{j' \in V}\frac{b_{j,j'}}{\sum_{h \in V-j} b_{h,j'}}$, where $b_{j,j'}$ is the number of packets intended to be transmitted from source node j to destination node j', and $\sum_{h \in V-j} b_{h,j'}$ represents the total number of packets that are from other nodes in the network community received by node j'. The number of neighboring nodes of node j is denoted by $|Q_j|$.

2) Friendship of Associated Nodes: In order to describe the friendship between one node and its associated nodes, this metric normalizes the signal-to-interference plus noise ratio (SINR) value over associated links to reflect link state. The friendship of associated nodes for node j is defined as FA_j, that is, $FA_j = \frac{1}{|A_j|}\sum_{j' \in V}\frac{\gamma_{j,j'}}{1+\gamma_{j,j'}}$, where $|A_j|$ is the number of nodes that node j has connected with. $\gamma_{j,j'}$ is the SINR value at destination node j'; it can be calculated by $\gamma_{j,j'} = \frac{P_{j,j'}G_{j,j'}}{\eta+\sum_{h \in V-\{j\}} P_{h,j'}G_{h,j'}} \geq \Gamma$, where $P_{j,j'}$ and $G_{j,j'}$ are the transmission power and channel gain from nodes j to j', respectively, and η represents the thermal noise. The neighboring nodes represent the nodes within the transmission range of each other and can be connected by one hop. The associated nodes illustrate the nodes that are connected and have packets for transmission. Because not all the neighboring nodes are able to be associated, the number of the associated nodes is less than that of neighboring nodes (i.e., $|A_j| \leq |Q_j|$).

3) Friendship of Community Nodes: The community in this paper means a group of nodes that are associated directly or via a multihop transmission. The friendship of community for node j, denoted by FC_j, is computed by $\frac{|A_j|}{|V|}$, where $|V|$ is the total number of network nodes. The idea is to evaluate the communication ability of each node in the community. The social relationship of node j is expressed by φ_j, which is a weighted sum of the three above-mentioned complementary metrics. The corresponding weights can be set up deterministically or by experimental data.

B. Node Trust Evaluation

Since opportunistic networks are frequently deployed in harsh or uncontrolled environment, the main focus of recommendation is to compensate for the lack of monitoring capabilities caused by the distributed characters of networks. Therefore, describing and quantifying node trust is important to guarantee the operation of self-organizing networks, especially where highly heterogeneous individuals and tight degree of collaborations exist in large-scale networks.

Node trust can be evaluated by analyzing the behaviors of other nodes with the interaction of the source node. It is understood that node reputation can be reflected by other nodes. Three factors for node-trust-based evaluation are considered, i.e., node centrality, direct experience (obtained by the node itself), and indirect experience (the opinion from other nodes). Node trustworthiness level is calculated according to the feedback stored by other nodes to avoid single-node failure. Define $T_{j,j'}$ as the trustworthiness between nodes j and j', and it can be represented by

$$T_{j,j'} = \mu Q_{j,j'} + \phi Q^{\rm dir}_{j,j'} + \chi Q^{\rm ind}_{j,j'} \tag{1}$$

where the summation of weighting factors in (1) is equal to 1. $Q_{j,j'}$ is the node centrality, and $Q^{\rm dir}_{j,j'}$ and $Q^{\rm ind}_{j,j'}$ illustrate the direct and indirect experiences of node j from its neighboring nodes. These three aspects of relationships can reflect node trustworthiness from the perspectives of the network structure, the node itself, and the other nodes. The corresponding weighting values can be preset or defined according to the empirical value.

The centrality of node j can be represented by $Q_{j,j'} = \frac{K_{j,j'}}{|N_j|}$, where the denominator is the number of friends of node j, and the numerator represents the common number of friends between nodes j and j'. The target of this metric is to prevent malicious nodes gaining a high centrality value by constructing relationships continuously.

If two nodes have an army of friends in common, their evaluation parameters for relationship construction are similar. When trustworthiness information is required from nodes j to j', node j checks the last direct transactions and determines its own opinion according to

$$O_{j,j'}^{\mathrm{dir}} = \frac{\log(N_{j,j'}+1)}{1+\log(N_{j,j'}+1)} O_{j,j'}^{\mathrm{sho}} + \frac{1}{1+\log(N_{j,j'}+1)} O_{j,j'}^{\mathrm{lon}} \quad (2)$$

where $O_{j,j'}^{\mathrm{sho}}$ and $O_{j,j'}^{\mathrm{lon}}$ are the short-term and long-term opinions. The reason for weighting factor setting is that the relationship factor starts to lose its importance, and the feedback returned by the last transaction is stressed. The short-term and long-term opinions in (2) can be calculated by $O_{j,j'}^{\mathrm{sho}} = \frac{\sum_{l=1}^{L^{\mathrm{sho}}} f_{j,j'}^l \pi_{j,j'}^l}{\sum_{l=1}^{L^{\mathrm{sho}}} \pi_{j,j'}^l}$, and $O_{j,j'}^{\mathrm{lon}} = \frac{\sum_{l=1}^{L^{\mathrm{lon}}} f_{j,j'}^l \pi_{j,j'}^l}{\sum_{l=1}^{L^{\mathrm{lon}}} \pi_{j,j'}^l}$, respectively, where l is denoted as the latest transaction. The feedback is weighted by $\pi_{j,j'}^l$ to distinguish paramount transactions from insignificant ones, where $\pi_{j,j'}^l$ illustrates the relevance of transaction between nodes j and j'. The short-term opinion is crucial, which can prevent the node from acting maliciously after building up its reputation.

The indirect opinion is calculated by $O_{j,j'}^{\mathrm{ind}} = \sum_{k=1}^{|K_{j,j'}|} (C_{j,k} O_{k,j'}^{\mathrm{dir}}) / \sum_{k=1}^{|K_{j,j'}|} C_{j,k}$. $C_{j,k}$ is the credibility from nodes i to k and can be computed by $C_{j,k} = \eta O_{j,k}^{\mathrm{dir}} + \mu Q_{j,k}^{\mathrm{ind}}$, where $\eta + \mu = 1$. It should be noted that $C_{j,k}$ depends on the direct experience between nodes. Thus, the trust of node j can be calculated by $T_j = \frac{1}{|N_j|} \sum_{j \in N_j'} T_{j,j'}$.

C. Trust-Based Social-Aware User Assignment Scheme

The double-auction mechanism is commonly leveraged to handle the multibuyer and multiseller problem in economics, which is frequently encountered in the real market. The auction scheme includes bidding and asking from buyers and sellers. It is mapped by a controller to a payment for each agent. In the relay-based Internet of smartphones, if the relay service is regarded as a commodity, the source and relay nodes are viewed as buyer and seller, respectively, the social-oriented next-hop node selection problem can be modeled by the double-auction mechanism.

On the one hand, the intermediate nodes are social selfish, and they are reluctant to serve as relays only if their resource expenditure (e.g., energy consumption) can be compensated. On the other hand, with the objective of achieving high transmission rate, it is feasible for source nodes to purchase relay service from intermediate nodes. Following economic terminology, the prices submitted by source and relay nodes are named as bidding and asking, respectively. At the beginning of the new round auction, the relay nodes start to receive different bidding prices from the source nodes. Meanwhile, the source nodes obtain various asking prices from potential relay nodes. The auction proceeds periodically, and one-round double-auction procedure can be described as follows.

According to the Shannon formula, the data rate in one-time slot for direct transmission is $C_{j,j'} = W\log_2(1+\frac{P_{j,j'}G_{j,j'}}{\eta+\sum_{h\in V-\{j\}} P_{h,j'}G_{h,j'}})$, where W is the link bandwidth. Without loss of generality, the bandwidth of each link is assumed to be the same. If node i wins out for relay node selection between nodes j and j', a relay-based session is constructed. Two links are included in the session, that is, $j \to i$ and $i \to j'$, and the corresponding link rates are $C_{j,i} = W\log_2(1+\frac{P_{j,i}G_{j,i}}{\eta+\sum_{h\in V-\{j\}} P_{h,i}G_{h,i}})$ and $C_{i,j'} = W\log_2(1+\frac{P_{i,j'}G_{i,j'}}{\eta+\sum_{h\in V-\{i\}} P_{h,j'}G_{h,j'}})$, respectively. Thus, the required time for fulfilling one-unit data transmission in the relay-based session is $T = \frac{1}{C_{j,i}} + \frac{1}{C_{i,j'}}$, and the corresponding transmission rate is $C_{j,i,j'} = \frac{1}{T} = \frac{C_{j,i}C_{i,j'}}{C_{j,i}+C_{i,j'}}$. The idle nodes can be employed as potential relaying nodes in the double-auction scheme.

From the aspect of source nodes (buyers), the achieved rate enhanced by relay-based transmission is $C_j^i = C_{j,i,j'} - C_{j,j'}$, where C_j^i is the benefit that buyer (source) j gains from the seller (relay) i. It is obvious that no buyer would like to purchase the commodity only if the gained transmission rate by the relay-based transmission is higher than that obtained by the direct transmission. From the view of sellers, they are ready to help source nodes for packet relaying unless satisfied reward can be acquired to compensate their resource consumption. The utility function evaluates the relationship between the transmission rate and gained network utility. For any $C \geq 0$, the utility function can be manifested as

$$F(C) = \alpha(1 - e^{-\beta C}) \quad (3)$$

where α is the upper limitation of the utility function, and β determines the curve shape of the function.

If packets are forwarded from source node j to destination node j' with the help of relay node i, compared with the direct transmission, the increased utility I_j is calculated by

$$I_j = F(C_{j,i,j'}) - F(C_{j,j'}) \quad (4)$$

where $F(C_{j,i,j'})$ and $F(C_{j,j'})$ are the utilities gained by the relay-based and direct transmissions, respectively.

For relay node i, after providing relay service, its lost ability L_i in contributing utility improvement can be worked out by

$$L_i = F(C_{i,j'}(P_{i,j'})) - F(C_{i,j'}(P_{i,j'} - P_{i,j'}^{\mathrm{con}})) \quad (5)$$

where $P_{i,j'}$ and $(P_{i,j'} - P_{i,j'}^{\mathrm{con}})$ are the usable transmission powers of relay node i before and after forwarding packets to node j', respectively. $P_{i,j'}^{\mathrm{con}}$ is the consumed power for packet relay, which can be calculated by $Q_j(\delta_j \sum_{j'\in V-\{j\}} W_{j,j'})$. Herein, δ_j is the required percent of energy for transmission, and $W_{j,j'}$ represents the number of sessions for transmission on node j. $C_{i,j'}(P_{i,j'})$ and $C_{i,j'}(P_{i,j'} - P_{i,j'}^{\mathrm{con}})$ are the achievable data rates before and after providing relay service, respectively. The utilities of node i's ability before and after to contribute providing relay service are represented by $F(C_{i,j'}(P_{i,j'}))$ and $F(C_{i,j'}(P_{i,j'} - P_{i,j'}^{\mathrm{con}}))$, respectively.

Driven by economic profit, traders in real market are unwilling to reveal the actual value (cost) of the commodity. Generally speaking, buyer j would bid lower than the actual value of the commodity, and seller i prefers to ask higher than its actual cost. This extra part deviated from the actual value is named "mark-up" in economic terminology. Due to the greedy character of traders in the double-auction-based market, the source node j bids as

$$I_j^{\text{bid}} = I_j(1 - m_j) \tag{6}$$

where $m_j \in [0, 1]$ is the mark-up of buyer j, and the relay node i asks as

$$L_i^{\text{ask}} = L_i(1 + m_i) \tag{7}$$

where $m_i \in [0, 1]$ denotes the markup of seller i.

Different from [15], which assumes that the mark-up of all the nodes is the same, we take node social relationship, trust, and residual energy into account during mark-up calculation. The reason behind is that for one thing, network individuals in the real world are often socially selfish, that is, they would like to forward packets for others with strong social relationship. For another reason, if the residual resource of the source node is plenty, it will not be so positive to purchase the relay service for money saving. Furthermore, individuals would like to trade with the node with the high trust value. Therefore, the lower price is bid by the source node under these situations. On the contrary, the relatively truthful price is bid by the source node to seek more transaction opportunities at the cost of economic expenses. The mark-up of the source node is defined as

$$m_j = A_1\varphi_j + A_2\frac{\text{AE}_j}{\text{TE}_j} + A_3T_j \tag{8}$$

where AE_j and TE_j denote the available (residual) and total energies of node j, respectively, φ_j represents the social relationship value of node j, and T_j is the node trust between node j and the corresponding node in the market.

From the perspective of the relay node, its mark-up computation is quite different. If the energy of the potential relay node is not sufficient, it will be reluctant to provide service for other nodes, since the requirement of its own communication should be satisfied before earning extra profit. Furthermore, if this relay node has strong social relationship and trust, a host of source nodes would like to purchase the relay service by bidding. Therefore, the relay node tends to ask a higher price than the actual value under these situations. Otherwise, a relatively reasonable price would be submitted to fulfill the transaction for economic profit. The mark-up of the relay node can be expressed as

$$m_i = A_1\varphi_i + A_2\left(1 - \frac{\text{AE}_i}{\text{TE}_i}\right) + A_3T_i \tag{9}$$

where AE_i and TE_i are the available (residual) and total energies of relay node i, respectively, φ_i is the social relationship value of relay node i, and T_i is the node trust between node i and the corresponding node in the market.

A central-bank-based model is assumed, and an account of each individual is kept in the time-division multiple-access (TDMA)-based network system. This assumption is reasonable since an army of mainstream access networks, such as IEEE 802.11 wireless local area network, and IEEE 802.16 wireless metropolitan area networks, utilize TDMA to guarantee the quality of services among individuals. The access channel can be further decomposed into control subchannel and data subchannel. The former not only contains the information of channel condition measurement but also message exchange in the central bank. When the packets of source node have been forwarded successfully, a sum of virtual money will be paid to the relay node through the central bank. And some virtual money will be received via the central bank by the relay node if it wins out during the double auction. Virtual money recorded in the central bank can be leveraged to purchase relay service from other nodes. If source node j wins out, the PayOff (PO) is

$$\text{PO}_j = I_j - \text{Pay}_j \tag{10}$$

where Pay_j is the actual payment of node j. If relay node i wins out, the payoff can be calculated by

$$\text{PO}_i = \text{Rec}_i - L_i \tag{11}$$

where Rec_i is the actual income of node i.

It is assumed that the economic profit of the intermediary agency is zero during the double auction. According to [16], the corresponding payment Pay_j and receive Rec_i are

$$\text{Pay}_j = \text{Rec}_i = \frac{I_j^{\text{bid}} + L_i^{\text{ask}}}{2} \tag{12}$$

and node virtual money in the central bank changes according to (10) and (11) after the double-auction process finishes.

Similar to the process in [15], the following theorem can be obtained.

Theorem 1: The double-auction-based scheme would proceed unless the gained profits by the source and relay nodes are nonnegative, which should satisfy: $I_j^{\text{bid}} \geq L_i^{\text{ask}}$.

Proof: As $I_j^{\text{bid}} \geq L_i^{\text{ask}}$, by (6) and (7), it is obvious that

$$I_j(1 - m_j) \geq L_i(1 + m_i). \tag{13}$$

Thus, it is apparent that

$$I_j - L_i \geq I_j \times m_j + L_i \times m_i. \tag{14}$$

By (6), (7), and (12), we can find that

$$\begin{aligned}\text{Pay}_j &= I_j - \frac{I_j^{\text{bid}} + L_i^{\text{ask}}}{2} = I_j - \frac{I_j(1 - m_j) \geq L_i(1 + m_i)}{2} \\ &= \frac{I_j - L_i + I_j \times m_j - L_i \times m_i}{2}.\end{aligned} \tag{15}$$

According to (13), it is obvious that

$$\begin{aligned}\text{Pay}_j &= \frac{I_j - L_i + I_j \times m_j - L_i \times m_i}{2} \\ &\geq \frac{I_j \times m_j + L_i \times m_i + I_j \times m_j - L_i \times m_i}{2} \geq 0.\end{aligned} \tag{16}$$

Similarly, the conclusion for node i is

$$\text{Rec}_i \geq I_i \times m_i \geq 0. \tag{17}$$

■

When the packet from the source node is delivered successfully with the assist of the relay node, the capacity of the source node is increased, and the relay node obtains satisfying payment to compensate the network resource consumption. Therefore, it is a "win–win" situation, and both sides can gain profit. From the economic point of view, if the participants are able to obtain satisfying income, they are inclined to participate in the trades, and the market will be prosperous. Therefore, the target of the DASA scheme is to maximize the value of social welfare (SW), that is,

$$\mathrm{SW} = \sum_{i\in V}\sum_{j\in V}(\mathrm{PO}_i + \mathrm{PO}_j). \tag{18}$$

After finishing one round of the DASA scheme, the next-hop node for packet relaying is able to be determined. If the next hop node is not the final destination, the packet forwarding will continue until it can be delivered to the destination node successfully. Therefore, multihop transmissions can be fulfilled by the aid of relay nodes, so that network connectivity and coverage can be enlarged.

IV. Optimal Relay Method Selection

A brief introduction of the involved relay methods (i.e., physical-layer network coding (PNC), conventional network coding (CNC), spatial reuse, and plain routing) has been stated in [17]. After conducting the presented DASA scheme, long-range transmissions are decomposed into multihop transmissions by stimulating nodes to take part in the cooperative communication. Thus, more opportunities to perform network coding (NC) and spatial reuse are brought, which can increase the spectrum utilization so that network throughput can be enhanced. In this section, a comprehensive relay method selection scheme is studied based on link scheduling, by which links are activated concurrently in an optimal method. The denoise-and-forward (DNF) method of PNC is considered in this paper owing to its better antinoise property than the analog NC method of PNC.

Define S as the set of all feasible configurations containing link sessions in the network. ω_s is an integer variable representing the required number of time slots for a certain configuration $s \in S$ to fulfill the transmission task. Denote $x^s_{i,j}$ as a binary variable, which is 1 if link $i \to j$ is activated in Configuration s, and 0 otherwise. Let u^s_i, c^s_i, and d^s_i be the binary transmission variables to indicate whether relay node i performs unicast, CNC, or DNF. V_i is defined as a set of associated nodes of relay node i. Node j is an outgoing or incoming node with respect to relay node i for $j \in V^+_i$ or $j \in V^-_i$. Y^j_i is the quantity of unicast traffic conveyed by node i on link $i \to j$, $\sum_{j'\in V^-_i-\{j\}} Y^{j,j'}_i$ stands for the amount of traffic conveyed by links $j \to i$ and $j' \to i$ in the multiple access (MA) phase of DNF, and $\sum_{j'\in V^+_i-\{j\}} Y^{j,j'}_i$ is the amount of traffic broadcasted by relay node i on links $i \to j$ and $i \to j'$ during the BC phase of CNC and DNF. $W^s_{i,j}$ illustrates the number of packets intended to be transmitted on link $i \to j$ during one scheduling period. The optimal relay method selection scheme can be modeled as

$$\min \sum_{s\in S}\omega_s \tag{19}$$

subject to

$$x^s_{i,j} + x^s_{j,i} \le 1 \tag{20}$$

$$u^s_i + c^s_i + d^s_i \le 1 \tag{21}$$

$$\sum_{j\in V-\{i\}} x^s_{i,j} \le 1 + (1 - u^s_i) \tag{22}$$

$$\sum_{s\in S}(u^s_i + c^s_i + d^s_i)x^s_{i,j}\omega_s W^s_{i,j} \ge u^s_i Y^j_i + d^s_i \sum_{j'\in V^-_i-\{j\}} Y^{j,j'}_i + (c^s_i + d^s_i)\sum_{j'\in V^+_i-\{j\}} Y^{j,j'}_i. \tag{23}$$

In order to maximize network throughput, the totally required activating time $\sum_{s\in S}\omega_s$ for fulfilling the entire transmission task should be minimized by selecting the proper relay method comprehensively. The half-duplex property is stated in (20), which means any node cannot transmit and receive at the same time. During one scheduling period, at most one transmission mode can be selected by relay node i, which is constrained in (21). Constraint (22) ensures that at most one transmission link is activated during one scheduling period if node i is in the unicast mode. In order to fulfill all the transmission sessions, each link should be activated for enough time, as demonstrated in (23).

The transmission mode supported by relay node i can be determined by constraints (24)–(28). If more than one outgoing flow is from node i, it will choose either CNC or DNF, as shown in (24). If more than one incoming flow is to node i, this node will select the DNF method, as demonstrated in (25). If there is only one incoming flow to node i (i.e., $u^s_i = 1$ or $c^s_i = 1$), d^s_i is forced to 0, as shown in (26). Constraint (27) restricts the maximum number of incoming links to two in DNF to guarantee the decodability. If the relay node broadcasts the coded packets ($c^s_i = 1$ or $d^s_i = 1$), more than one outgoing link is activated as shown in (28):

$$c^s_i + d^s_i \ge \sum_{j\in V^+_i} x^s_{i,j} - 1 \tag{24}$$

$$d^s_i \ge \sum_{j\in V^-_i} x^s_{i,j} - 1 \tag{25}$$

$$d^s_i \le \sum_{j\in V^-_i} x^s_{i,j} - u^s_i - c^s_i \tag{26}$$

$$\sum_{j\in V^-_i} x^s_{i,j} \le 1 + d^s_i \tag{27}$$

$$1 + \sum_{j'\in V^+_i-\{j\}} x^s_{i,j'} \ge x^s_{i,j} + c^s_i + d^s_i. \tag{28}$$

The SINR constraint of the unicast transmission is

$$P_{j,j'}G_{j,j'} + M^s_{j,j'}(1 - x^s_{j,j'}) + M^s_{j,j'}(1 - u^s_j) \ge \Gamma[\eta + \sum_{h\in V-\{j\}} P_{h,j'}G_{h,j'}u^s_h + \sum_{h\in V-\{j\}} P_{h,\mathrm{BC}}G_{h,j'}(c^s_h + d^s_h)] \tag{29}$$

where $P_{h,\mathrm{BC}}$ is the broadcasting power when node h is in the broadcast (BC) phase of CNC or DNF. Because the BC stages of DNF and CNC are essentially the same, the broadcasting power of relay node i ($P_{i,\mathrm{BC}}$) is equal to the maximum power of $P_{i,j}$ and $P_{i,j'}$ to guarantee that the intended receiver with worse channel status can decode the broadcasted packet successfully. $M^s_{j,j'}$ is a constant value, which satisfies $M^s_{j,j'} \geq \Gamma[\eta + \sum_{h \in V-\{j\}} P_{h,j'} G_{h,j'} u^s_h + \sum_{h \in V-\{j\}} P_{h,\mathrm{BC}} G_{h,j'} (c^s_h + d^s_h)]$. The cumulative interference on receiving node j' caused by other concurrent transmission links corresponds to the right-side summation in (29).

In the MA phase of the DNF method, the minimum received power (min $(P_{j,i}G_{j,i}, P_{j',i}G_{j',i})$) is utilized for SINR calculation. Without loss of generality, by assuming $P_{j,i}G_{j,i} < P_{j',i}G_{j',i}$, the corresponding SINR constraint becomes

$$P_{j,i}G_{j,i} + M^s_{j,i}(1 - x^s_{j,i}) + M^s_{j,i}(1 - d^s_j) \geq \Gamma[\eta + \sum_{h \in V-\{j\}} P_{h,i} G_{h,i} u^s_h + \sum_{h \in V-\{j\}} P_{h,\mathrm{BC}} G_{h,i} (c^s_h + d^s_h)] \quad (30)$$

where $M^s_{j,i} \geq \Gamma[\eta + \sum_{h \in V-\{j\}} P_{h,i} G_{h,i} u^s_h + \sum_{h \in V-\{j\}} P_{h,\mathrm{BC}} G_{h,i} (c^s_h + d^s_h)]$.

In the BC phase for both CNC and DNF methods, the SINR constraint in node j (similar for node j') can be computed by

$$P_{i,BC}G_{i,j} + M^s_{i,j}(1 - x^s_{i,j}) + M^s_{i,j}(1 - c^s_i - d^s_i) \geq \Gamma[\eta + \sum_{h \in V-\{i\}} P_{h,j} G_{h,j} u^s_h + \sum_{h \in V-\{i\}} P_{h,\mathrm{BC}} G_{h,j} (c^s_h + d^s_h)] \quad (31)$$

where $M^s_{i,j} \geq \Gamma[\eta + \sum_{h \in V-\{i\}} P_{h,j} G_{h,j} u^s_h + \sum_{h \in V-\{i\}} P_{h,\mathrm{BC}} G_{h,j} (c^s_h + d^s_h)]$.

Therefore, configuration s is identified by binary variables $x^s_{i,j}, u^s_i, c^s_i, d^s_i$, and the transmission power, and one schedule S is a set of such configurations, i.e., $s \in S$.

Since the direct transmissions have been separated into multihop transmissions by the DASA scheme in Section III, the available relay methods can be determined according to constraints (24)–(31). Finally, the optimal relay method is determined by minimizing the activation time slot while satisfying constraints (20)–(23).

The link-scheduling scheme with fixed transmission rate has been modeled as an edge coloring problem, known as an NP-complete problem, which relies on the enumeration of all the feasible configurations. In the next section, a firefly-algorithm-based relay method selection scheme will be presented to decrease the computational complexity, while approaching the performance gained by the optimal method.

V. Firefly-Algorithm-Based Relay Method Selection

Various kinds of heuristic methods have been studied to solve the integer linear programming (ILP) or mixed ILP problems, which include the branch and bound method, the Lagrangian relaxation, and so on. However, these methods either have high computational complexity or converge slowly as network size expands. Some researchers have investigated artificial intelligent algorithms to approach the optimal solution. Unfortunately, these solutions have been demonstrated to only search for the local optimal solutions effectively. Inspired by biological sciences, the firefly algorithm was first proposed in [18]. This algorithm has been leveraged to solve the economic dispatch problem further. However, the previous studies cannot be employed directly in our formulated problem, since they focused on real number encoding instead of integer variable. In this section, the firefly-algorithm-based scheme is innovatively modeled to solve the optimization problem formulated in Section IV.

A. Brief Introduction of the Firefly Algorithm

There are more than 2000 kinds of fireflies in the world. Most of them can produce rhythmic light within short range. The main functions of the produced light can be summarized as follows: attracting isomerism to match and luring potential prey. The rhythmic shining light can bring different fireflies together and synchronize their shining behaviors. This is one kind of self-organization behavior in biological science.

Since the optical density from illuminant is inversely proportional to distance and the light is absorbed by air, the visible light becomes weak as distance increases. Therefore, the light generated by the firefly can be seen only within a certain range, by which the firefly can utilize for communication.

In the firefly algorithm, the attraction function θ is a monotone decreasing function, denoted as

$$\theta(d_{i,j}) = \theta_0 e^{-\tau d^{\nu}_{i,j}}, \nu > 1. \quad (32)$$

The attraction function is codetermined by the selection of θ_0 and τ. $d_{i,j}$ is the straight-line distance between fireflies i and j, $d_{i,j} = ||D_i - D_j||$, and ν is the path loss factor. Generally speaking, $\theta_0 \in [0, 1]$. If $\theta_0 = 0$, it means the noncooperative mechanism, and random individual selection is utilized. If $\theta_0 = 1$, the flight paths of different fireflies are determined by the luminance only. The variation trend is decided by τ. If $\tau = 0$, the attraction of firefly keeps constant. If $\tau = +\infty$, it becomes a random individual selection. τ is usually set between 0 and 10.

The trace of firefly i is affected by the luminance (attraction) of firefly j, and the corresponding movement trend is

$$D'_i = D_i + \theta(D_i - D_j) + \kappa(\mathrm{rand} - 0.5) \quad (33)$$

where D'_i and D_i are the positions of firefly i during the current and next time slots. The second item in (33) represents the effect brought from the interactive attraction of fireflies to the movement direction of the next time slot. The third part adds movement randomness, where κ is a randomized parameter, and rand is a value distributed uniformly between 0 and 1.

B. Firefly-Algorithm-Based Scheme

In this subsection, the firefly-algorithm-based heuristic algorithm is presented to solve the formulated NP-complete problem. It can be seen that the high computational complexity in the joint scheduling and relay method selection problem is mainly brought by the scheduling factor $x_{i,j}$ and relay method selection indexes since they are integer variables. Denote X_i and X_j equal to 1 and 0, respectively, to represent whether nodes i and j can be activated for transmission, $X_{i,j} = X_i - X_j$, so that the range of $d_{i,j}$ varies between -1 and 1. The next iteration state of X_i can be expressed as

$$X_i^{'} = X_i + \theta(X_i - X_j) + \kappa(\text{rand} - 0.5). \quad (34)$$

For the sake of determining the state of the next time slot, the node function value needs to be calculated. In order to guarantee the function value between 0 and 1, a tanh function is utilized, which can be demonstrated as

$$f(X_i^{'}) = \tanh(|X_i^{'}|) = \frac{e^{2|X_i^{'}|} - 1}{e^{2|X_i^{'}|} + 1}. \quad (35)$$

If $X_i^{'}$ is larger than the threshold, this node is activated and set to 1; otherwise, it is equal to 0 for sleep.

In order to judge node transmission state and relay method, the firefly-algorithm-based relay selection scheme contains the following seven steps.

Step 1: Initialize the parameters of the firefly algorithm, which include θ_0, τ, and the maximum number of iteration times.

Step 2: Initialize the state of fireflies. The initial state of half number of the links is randomly set to 1, and the initial state of the other links is set to 0.

Step 3: Update the information of fireflies. One firefly adjusts its position according to the luminance of other fireflies, and the new state information can be calculated by (34).

Step 4: Repair the firefly algorithm according to network constraints. When the position of one firefly has been determined after the iteration process (e.g., whether this node is activated for transmission), check the constraints in (20) and (23). If the obtained position information of firefly satisfies these constraints, go to Step 5; otherwise, the next subsection will present the node repair strategy.

Step 5: Solve the relay method selection problem according to the fitness function. The fitness function corresponds to the luminance of firefly. A large value of fitness function corresponds to high transmission rate, as manifested in (3). Therefore, a transmission-rate-based relay method selection metric is presented, which can be demonstrated as

$$\Omega_i^s = \begin{cases} c_i \times C_{i,\text{BC}} \times \frac{2n_i^C}{2n_i^C - 1} \times \frac{n_i^C \times L}{n_i^C \times L_C + L}, & \text{CNC is adopted} \\ d_i \times C_{i,\text{BC}} \times \frac{n_i^D}{n_i^D - 1} \times \frac{n_i^D \times L}{n_i^D \times L_D + L}, & \text{DNF is adopted} \\ d_i \times C_{i,j} \times \Psi_i, & \text{otherwise} \end{cases} \quad (36)$$

where $C_{i,\text{BC}}$ and $C_{i,j}$ correspond to the transmission rates of node i in broadcast and unicast transmissions, respectively. $\frac{2n_i^D}{2n_i^C - 1}$ and $\frac{n_i^D}{n_i^D - 1}$ are the NC gains by utilizing CNC and DNF, respectively, where n_i^C and n_i^D are the number of transmission nodes for different relay methods. Ψ_i is the number of concurrent transmission packets by spatial reuse; if $\Psi_i = 1$, it becomes the unicast transmission model. L_C and L_D are the extra network costs for CNC and DNF, respectively, and L is the packet length for transmission. The summation of these three parts in (36) represents the performance improvement of the transmission rate (fitness function).

Step 6: Record the maximum value of the utility function up to now, and the iteration time is increased by 1.

Step 7: Repeat Steps 3–6 until the terminal condition is satisfied, which is defined as network performance does not improve for five times of iterations or the iteration number reaches the predefined upper value.

C. Repair Strategy for the Firefly-Algorithm-Based Scheme

If the individual state is updated according to (34), the constraints in (20) and (23) may not be concurrently satisfied; the repaired strategy for the firefly-algorithm-based heuristic approach is illustrated as follows.

Step 1: If (20) is satisfied, go to Step 3. Otherwise, go to Step 2.

Step 2: If (20) is not satisfied, it indicates the half-duplex condition is violated, that is, one node has both incoming and outcoming information flows. In this situation, it is demonstrated that this node is activated for both packets receiving and transmitting during one time slot. Then, the values of firefly with both incoming and outcoming flows are calculated according to the fitness function, and the firefly state with the low computed value (weak luminance) is set to 0.

Step 3: If (23) is not met, it means the number of transmission links to be activated is large while the time for link activation is not enough, then the node whose fitness function value is closest to the threshold is changed from 0 to 1.

Step 4: Step 3 may have an impact on Step 2. If Step 2 is satisfied, finish; otherwise, return to Step 2 and continue until the constraints have been satisfied.

VI. Performance Evaluation

Two objectives are intended to be achieved in this section. First, the efficiency of DASA needs to be evaluated with respect to different evaluation metrics. Second, the effectiveness of both the optimal and the firefly-algorithm-based DASA methods should be demonstrated by both synthetic- and real-trace-based simulations. The experiment setup is introduced first, followed by the simulation results and discussions.

A. Experiment Setup

The setups of both synthetic- and real-trace-based simulations are described first. Then, the performance metrics and benchmark mechanisms are stated.

1) *Synthetic Simulation Setup*: The random network topology with 100 nodes is considered, where some nodes are selected to generate sessions to random destinations. These nodes are arbitrarily distributed in a square region, where each side is 1 km. The considered network scenario can be viewed as a part of the campus environment, where all the smartphones held by students belong to the same community. Due to the high repeatability of students' activity in the campus, the considered time-slot-based model is reasonable since the scope and duration of students' activity are relatively fixed. The SINR threshold is set to 2.5, and bandwidth W is set to 56 MHz. The residual energy (in Joule) of each node before packet transmission is randomly selected between $(0, 1]$,

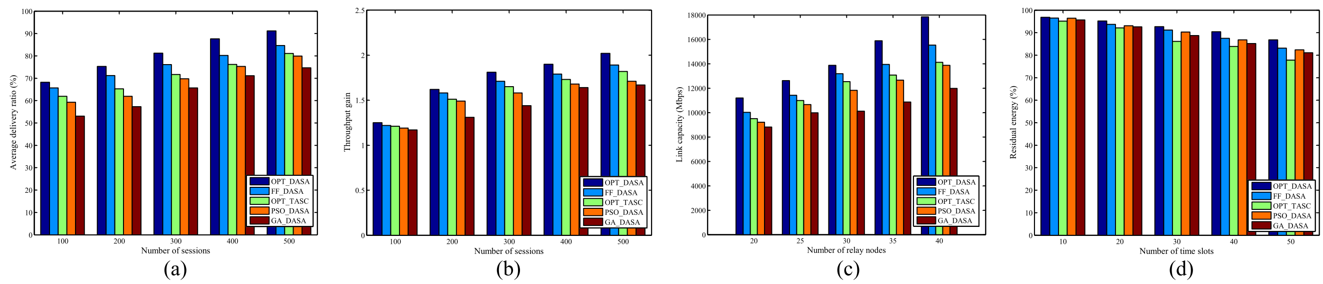

Fig. 1. Performance comparisons in synthetic-based simulations. (a) Delivery ratio. (b) Throughput gain. (c) Link capacity. (d) Residual energy.

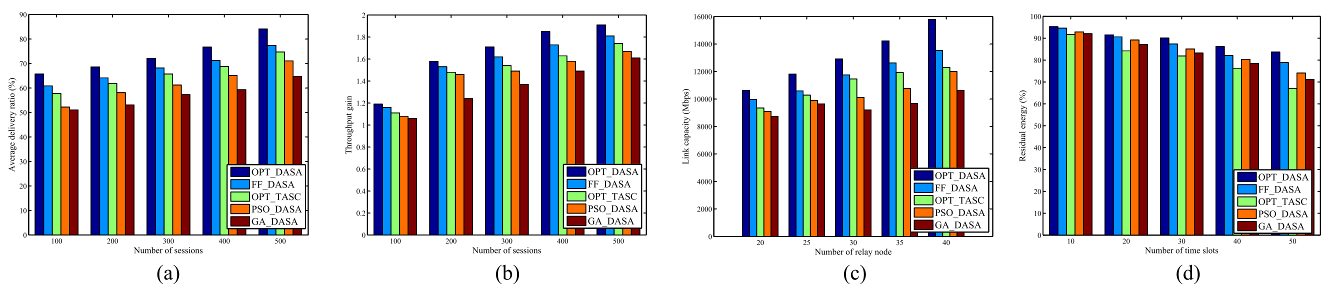

Fig. 2. Performance comparisons in real-trace-based simulations (a) Delivery ratio. (b) Throughput gain. (c) Link capacity. (d) Residual energy.

and the total energy of each node equals to 1 J. According to [19], the energy cost function $Q_j(\delta_j \sum_{j' \in V-\{j\}} W_{j,j'})$ is defined as $\zeta_j(\delta_j \sum_{j' \in V-\{j\}} W_{j,j'})^2$, where ζ_j is distributed uniformly between 0.2 and 0.5, and δ_j is set as the 0.018% of the node total energy based on preliminary experiments. $\alpha = 1$, $\beta = \frac{\ln(0.1)}{12.5}$, and the thermal noise is 10^{-6} mW, set as in [20]. The weights of the three complementary social-based metrics are all set to $\frac{1}{3}$. θ_0 is set according to the social relationship value of each node, $\tau = 0.5$, and the iteration number is 500. The random walk model is considered, and the moving speed of each smartphone is randomly set between 1 m/s and 10 m/s.

2) *Real-Trace-Based Simulation Setup*: In addition to the synthetic simulations, the social evolution dataset [21] is studied. This dataset includes the traces of 80 students carrying their mobile phones for eight months. The corresponding contacts and social features of users between January and June 2009 are leveraged for our experiments. Among them, six features are selected for relationship measurement: Bluetooth contact frequency, user interests (e.g., music, politic), living sector, year in school, phone calls, and SMS logs.

Four metrics are considered in our work:

1) average delivery ratio, which is the ratio between the number of delivered messages to the total number of generated messages;
2) average throughput gain is defined as the ratio between ω_u to ω_s. The former is the scheduling length by considering unicast only, and the latter is the scheduling length by jointly considering NC and spatial reuse;
3) link capacity, which is directly proportional to the data rate involved in the transmission;
4) power consumption for packet forwarding.

In order to demonstrate the effectiveness of the optimal and firefly-algorithm-based methods, three mechanisms are compared, that is: TASC [8], which guarantees truthful auctions between buyers and sellers; particle swarm optimization (PSO)-based DASA; and genetic algorithm (GA)-based DASA, where the probabilities of crossover and mutation are set as 0.85 and 0.05, respectively. The optimal relay methods under DASA and TASC schemes are denoted as OPT_DASA and OPT_TASC, respectively. The firefly-algorithm-, PSO-, and GA-based methods are expressed by FF_DASA, PSO_DASA, and GA_DASA, respectively. More details for PSO and GA can be found in [22].

B. Simulation Results

The percentages of the average delivery ratio in synthetic- and real-trace-based simulations are illustrated in Figs. 1(a) and 2(a). As the number of sessions increases, the curves for different schemes augment since the opportunity to select a suitable relay method adds so that network connectivity is enhanced. It can be observed that the gap between FF_DASA and OPT_DASA becomes larger as the number of sessions increases due to the searching space of the heuristic algorithm is not large enough. It is noted that the performance gained by FF_DASA is even better than OPT_TASC. The reason behind is that more users in DASA would like to be involved in the double-auction scheme for social welfare improvement; thus, link connectivity can be largely improved. Compared with GA, the high efficiency of PSO is also demonstrated in our work.

Figs. 1(b) and 2(b) demonstrate network throughput gain under different schemes. It is obvious that the performance gained by the FF_DASA scheme can approach the optimal network performance effectively. The OPT_DASA performs much better than OPT_TASC, since the former stimulates the

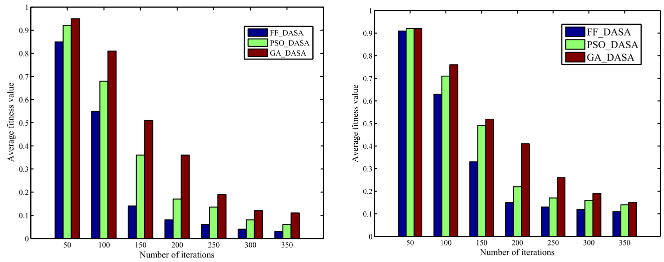

Fig. 3. Comparison of average fitness values among different schemes. (a) Synthetic-based simulation. (b) Real-trace-based simulation.

cooperation among network nodes, which results in that more direct transmissions are separated into multihop transmissions aided by relay nodes. Therefore, more links can be activated for packet transmission during one scheduling period. Link capacity comparisons among different algorithms are demonstrated in Figs. 1(c) and 2(c). It is noted that link capacity enhances as the number of relay nodes increases. This is because on the one hand, more opportunities exist for packet forwarding; on the other hand, it is not indispensable for source nodes to compete with each other for relay node selection because the number of relay nodes is adequate.

The percentages of the residual energy of the total network are demonstrated in Figs. 1(d) and 2(d). We can observe that as the number of time slots increases, the residual energy of OPT_DASA declines gently, while the corresponding residual energy curves of other methods lower rapidly. Among them, the performances achieved by OPT_TASC are the worst. The reason behind is that TASC has to discard some trading opportunities to guarantee the truthful transactions, which will decrease the number of trades. Therefore, relay forwarding is restrained and long transmission links have to be conducted, which is energy consuming. DASA is market oriented and selfish tolerant, where source and relay nodes bid or ask according to their network resource. Compared with bionics algorithms, the superiority of OPT_DASA is demonstrated, since the interplay between different transmission schemes has been fully considered.

The comparisons among different bionics methods are shown in Fig. 3, which illustrate the convergence character of each algorithm in both synthetic- and real-trace-based simulations. The average fitness function in our work is defined as the variance of Ω_i^s in (36). The fitness values demonstrate that the FF_DASA can converge faster than the other two algorithms. The reason behind is that the improved firefly algorithm can effectively avoid obtaining suboptimal solutions. It can be seen that our method converges when the number of iterations is between 150 and 200.

VII. Conclusion

In this paper, we have studied the social-oriented adaptive transmission in opportunistic Internet of smartphones. Our method has two steps. First, the social attributes of smartphones are modeled by their friendships, and the social-aware double-auction-based relay selection method has been presented by considering node trust to stimulate the cooperation among smartphones. After that, a spectrum spatial reuse-aware relay method selection scheme is investigated to study the interplay between NC and spatial reuse by concurrently activating links in an optimal way. Because the formulated problem is NP-complete, a firefly-algorithm-based heuristic approach is presented to approach the optimal network performance with low computational complexity. Simulation results have demonstrated that our proposed scheme outperforms other methods in delivery ratio, throughput gain, link capacity, and power consumption. The firefly-algorithm-based scheme is effective to acquire the network performance gained by the optimal method. Due to the hardware limitations of smartphones, how to integrate our method with cloud-assisted opportunistic networks is part of our future work.

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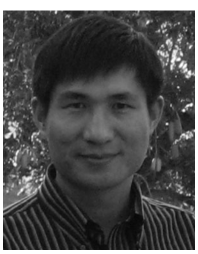

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