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Throughput in A Cooperative Network and Channel State Information

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Abstract Cooperative communications greatly enhance the point-to-point link capability to against channel fading, and such performance gain is expected to large wireless ad hoc networks. However, current cooperative networking is based on ideal assumptions of completely known network information and centralized optimization, which is practically infeasible to large ad hoc networks requiring unscalable control signaling overhead. In this paper, the exact throughput of practical cooperative ad hoc network is provided, in which users make autonomous decisions with regard to their network usage based on the current network conditions and their individual preferences. Since preference of each node is shown by the achievable data rate estimated from the channel state information (CSI) of links of each source-destination pair, the cost of acquiring CSI is considered in the throughput analysis. Furthermore, the cooperation beneficial condition and the operation algorithm of each node to guarantee the network operating at the highest throughput are proposed. The proposed algorithm provides a way to control network-level performance by local operations among nodes.

Keywords Ad hoc network · Game theory · Interference · Cooperative networks · Channel state information · Stochastic geometry

1 Introduction

Recently, Cooperative communication (CC) has attracted much attention as an effective technique to combat multi-path fading and enhance reliability for a single transmission pair [1–6]. However, for wireless networks in which lots of users transmit simultaneously, the

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gain with cooperation may be reduced due to the increase of interference among nodes (i.e., network interference), as shown in Fig. 1. Since performing cooperation may be costly in terms of interference, energy, and bandwidth, in wireless networks, whether CC still outperform direct transmissions (DT) is questionable [7–14].

On the way to the development of CC, the practical benefits and limitations is needed to be understood. Especially, it becomes critically important to study how the performance gain of cooperative diversity at the physical layer can be reflected at the network layer, thus ultimately improving application performance [15–19]. The throughput of wireless cooperative networks in a regular linear network scenario is discussed in [20]. By introducing stochastic geometry [21, 22], the performance of cooperative ad hoc networks are discussed in [17, 23–27], which has insights about the performance for fixed densities of nodes. However, these works still did not capture the operation of practical ad hoc networks—each heterogeneous autonomous node only can choose its transmission strategy based on its own transmission performance. Since optimally and centrally deciding the transmission strategy (i.e., DT or CC) of each source is not practically available, in practice, each node performs individual decision on whether conducting CC solely based on its achievable transmission data rate. In this paper, the exact throughput of practical distributed wireless cooperative ad hoc networks is proposed, and the similar computations can be extended to other decentralized wireless networks.

To calculate the exact throughput of practical cooperative ad hoc networks, the gains and costs for conducting CC have to be specified, which is the basis for each source to choose transmission strategy.

- In this paper, the gain of CC refers to the increased data rate than DT. For a source, the achievable data rate can be estimated by the channel gains (i.e., fading and power decay with distance) of links from the source to its destination, the source to its selected relay, and its selected relay to its destination, which is referred to channel state information (CSI) of each source in the rest of paper. Particularly, each source only can acquire the CSI of links between the source, its selected relay and its destination, but not the CSI of other source-destination pairs. The CSI can be measured by estimating the received probing packets [28–31].
- The cost of CC refers to the time a source spent to select the best relay and to measure and collect CSI.

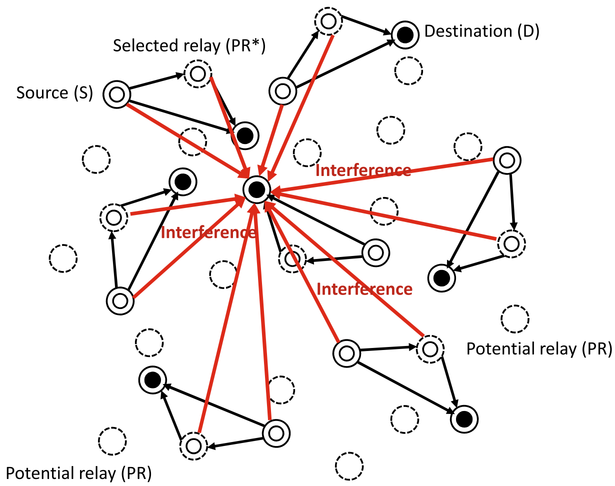


Fig. 1 Cooperative communication (CC) in wireless ad hoc networks. The node *S* represents source, the node *PR** represents the selected relay (if the source could have one after the relay selection process), and the node *D* represents destination. The *red arrow* represents the interference from other sources and selected relays. (Color figure online)

If a source makes the strategy choice only based on less CSI (i.e., only based on the channel gain of link from the source to its destination), it saves the time to measure and collect CSI of other links (i.e., the channel gains of links from the source to its selected relay and from its selected relay to its destination) thus has more time for data transmission. However, the achievable data rate may decrease if the inaccurate transmission strategy choice is made due to the insufficient CSI. Thus, a source has to trade-off between more sufficient information to choose strategy and the higher time cost to measure and collect the more CSI. To investigate the impacts from gains and costs for conducting CC to the strategy choice of each source and thus the throughput, the following two classified scenarios are discussed:

(1) The cost of acquiring CSI can be ignored: Each source can collect all CSI (the channel gains of links from the source to its destination, from the source to its selected relay, and from its selected relay to its destination), and then estimate the transmission data rate by DT and CC, respectively. Network optimization is not available due to unable to analyze interaction of heterogeneous autonomous users [15, 32]. These interaction can be modeled by game-theoretic approaches [15, 33–35], and the equilibrium, in which individual users cannot achieve better performance through individual actions, is analyzed.

(2) The cost of acquiring CSI can not be ignored: At beginning, a destination only has the CSI of link from its source to the destination. Based on the information, the destination should decide to do DT or to spend time cost to select relay and collect the CSI of links from its source to its selected relay, and from its selected relay to the destination. This situation corresponds to a two-level decision [36], and the throughput under randomized decision is analyzed.

The major contributions of the paper can be summarized as follows:

- We provide the first work for the exact throughput of practical cooperative ad hoc networks in which users choose transmission strategy independently and distributively. Moreover, the cooperation beneficial criteria of maximum transmission range and traffic load and the throughput improvement are identified, which show the system performance benefits by CC based on each user's voluntary.
- After the system performance benefits by cooperation is derived, the distributive procedure of each node to achieve the system performance benefits is more concerned. We propose an operation algorithm which guarantees the largest throughput of both the node and the network to be achieved. The proposed algorithm provides a way to control the global network performance distributively and independently by controlling the operation of the local transmission pairs.

The remainder of this paper is organized as follows. In Sect. 2, we present the network model. The game-theoretic formulation, decision problem formulation and analysis of the wireless ad hoc networks are discussed in Sect. 3. The performance evaluation results are provided in Sect. 5. We summarize and draw a conclusion in Sect. 6.

2 Network Model and Relay Selection Protocol

2.1 Network Topology and Channel Model

We consider an ad hoc network which is time-slotted with the slot duration of t seconds and all nodes can transmit and receive packet simultaneously. The spatial distributions of all nodes follow homogeneous Poisson point processes (PPPs) Φ with density λ [9, 37, 38]. The probability that a node has packets to transmit in a time slot is p, called "active probability". In each time slot, a node accesses medium when it has packets to transmit, so the active probability is also the medium access probability. From the thinning property of PPP [21], the spatial distributions of active nodes (source; the nodes which have packet to transmit in this time slot) follow homogeneous PPP Φ_A with density $p\lambda$, and the spatial distributions of idle nodes (the nodes which do not have packet to transmit in this time slot) follow homogeneous PPP Φ_I with density $(1-p)\lambda$. Each source is associated with a target destination at a fixed distance of d away with an arbitrary direction.

Each node is assumed to use the same power P_t for transmission. Due to the stationary characteristics of PPP, the interference received by a typical destination could represent the interference seen by other receivers. Figure 1 shows a transmission pair and its parameters, where S represents source of typical transmission pair, PR represents potential relays, r represents the selected relay, and D represents destination.

Throughout this paper, we consider slow-flat Rayleigh fading and path-loss for channel model. For a source, the random variables $h_{S,D}$, $h_{S,r}$, $h_{r,D}$ represents empirical fading gains of link from the source to its destination, from the source to its selected relay and from its selected relay to its destination, respectively. Without loss of generality, let d be the expected distance from the source to its destination, $d_{S,r}$ from the source to its selected relay, and $d_{r,D}$ from its selected relay to its destination. From [39], the value of $d_{S,r}$ and $d_{r,D}$ decreases when the node density λ increases. In this paper, the CSI for a source is defined as follows:

Definition 1 For a source, the CSI of link from the source to its destination $\gamma_{S,D}$ is defined as the channel gain (i.e., fading and power decay with distance)

$$\gamma_{S,D} = h_{S,D} d^{-\alpha}.$$

Similarly, the CSI of link from the source to its selected relay $\gamma_{S,r}$ and the CSI of link from its selected relay to its destination $\gamma_{r,D}$ are defined as

$$\begin{aligned} \gamma_{S,r} &= h_{S,r} d_{S,r}^{-\alpha}, \\ \gamma_{r,D} &= h_{r,D} d_{r,D}^{-\alpha}, \end{aligned}$$

respectively. The parameter α is the path-loss exponent.

2.2 Relay Selection Protocol

Relay selection protocols of ad hoc networks are designed to maximizing capacity or/and minimizing outage probability. The max-min criterion [40–42], which maximizes the minimum of signal-to-noise ratios (SNRs) of the source-relay link and relay-destination link, has been proven optimal, which is defined as follows:

$$l^* = \arg\max_{l} \min\{\gamma_{S,l}, \gamma_{l,D}\}, \tag{1}$$

where l is the index of the idle node which could receive both data from S and D, l^* is the selected relay index and $\gamma_{i,j}$ is the channel gain between nodes i and j. Because all sources conduct CC and thus relay selection process simultaneously, it is difficult to calculate the probability that a source could obtain a selected relay after the relay selection. We define this probability as follows:

$$P_{hr} := \text{Theprobabilitythatanactivenodecould obtainaselectedrelayafterrelayselection}$$

The value of P_{hr} is evaluated by simulations. Figure 2 shows that P_{hr} only depends on the active probability p. For simplicity of calculations, we assume that the set of locations of selected relays Φ_r follows PPP with density $P_{hr}p\lambda$. The PPP assumption is valid when the uncoordinated transmitting nodes are independently and uniformly distributed over the network arena, which is often reasonable for networks with indiscriminate node placement or substantial mobility [43]. If intelligent transmission scheduling is performed, the resulting transmitter locations will most certainly not form a PPP. This framework has been extended to CSMA, and the gains are not that large over Aloha [44, 45]. In this Sect. 5, we will discuss the conditions when this assumption is valid by compared with simulation results.

2.3 Interference, Signal, and Successful Access Probability

Consider a typical transmission pair, the interference from the sources to the typical destination is

$$I_S = \sum_{X_j \in \Phi_A} h_{X_j} P_t \|X_j\|^{-\alpha},$$

and from the selected relay to the typical destination is

$$I_r = \sum_{Y_j \in \Phi_r} h_{Y_j} P_t \|Y_j\|^{-\alpha},$$

where h_{X_j} and h_{Y_j} denote fading gains from node $x \in \Phi_A$ and $y \in \Phi_r$ to the typical destination, respectively, $\|x\|$ is the distance from node x to the typical destination, and α is the path-loss exponent. For a typical transmission pair conducting DT, the received SINR is

$$\mathsf{SINR}_{\mathsf{DT}} = \frac{P_t h_{S,D} d^{-\alpha}}{I_S + I_r + \sigma^2}, \tag{2}$$

where σ^2 is the noise power level. For a typical transmission pair using cooperative relay, we assume that relay protocol is Decode-and-Forward, and thus the received SINR is [1]

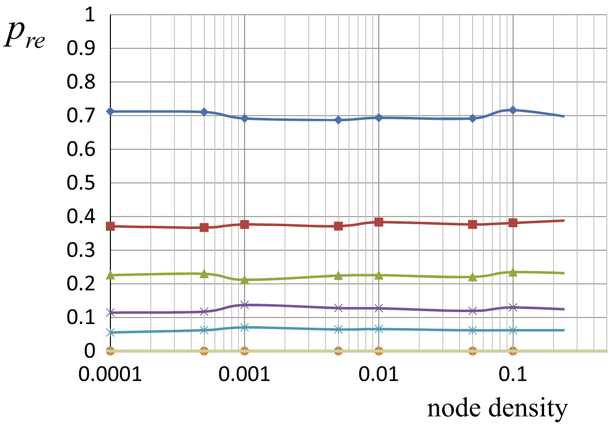


Fig. 2 The probability P_{hr} that a source could have a selected relay after relay selection versus node density λ under different active probability p

$$\mathsf{SINR_{CC}} = \min\left\{\frac{h_{S,r}}{d_{S,r}^{\alpha}}, \frac{h_{S,D}}{d^{\alpha}} + \frac{h_{r,D}}{d_{r,D}^{\alpha}}\right\} \frac{P_t}{I_S + I_r + \sigma^2}. \tag{3}$$

Without loss of generality, the noise power σ^2 is set to be zero. We assume that each selected relay knows the data that the source transmits to destination. This scenario exists under the situation that when the source transmits data to destination but the destination does not receive data, then the source needs to retransmit, and the source would decide whether to conduct CC in aid of the selected relay.

The following lemmas show the successful transmission probability (equal to the complement of outage probability) achieved by DT and cooperative transmission, respectively, for a source in ad hoc networks. These successful transmission probabilities could be derived from the derivation of outage probability similar to [21] and [46]. Each node is assumed to know the necessary parameters of the wireless network like node density λ, active probability p, the expected distance d from source to destination, $d_{S,r}$ from source to selected relay, and $d_{r,D}$ from selected relay to destination.

To derive the success probability, we define a criterion to distinguish the strength of the received SINR at the selected relay of typical transmission pair, which is also important to the analysis of strategy choice and thus throughput.

Definition 2 For a typical source-destination pair, define that if the CSI of the link from the source to its destination (i.e., $\gamma_{S,D}$), from the source to its selected relay (i.e., $\gamma_{S,r}$) and from its selected relay to its destination (i.e., $\gamma_{r,D}$) satisfy

$$\gamma_{S,r} > \gamma_{S,D} + \gamma_{r,D}, \tag{4}$$

then the situation is defined as "strong relay received power" (SRRP). Otherwise, the situation is defined as "weak relay received power" (WRRP).

Transmissions success occurs if the received SINR is larger than the threshold $\beta = 2^{2R} - 1$, where R is the desired information rate. The success probability (SP) of DT and CC are derived as below:

Lemma 1 *For a source using direct link transmission, the success probability (SP) of transmission is denoted as*

$$P_{SP}^{DT}(\beta) = \exp\left(-(1 + P_{hr}\phi)p\lambda \frac{\pi^2\delta}{\sin(\pi\delta)} d^2\beta^{\delta}\right), \tag{5}$$

where ϕ is the probability that a source transmits with the aid of the selected relay, δ is defined as $\frac{2}{\alpha}$, and α is the path-loss exponent.

Proof The proof is presented in Appendix. □

Lemma 2 *For a source using cooperative transmission, the success probability (SP) is denoted as*

$$\begin{aligned} P_{SP}^{CC}(\beta) =& (1 - P_S)\exp\left(-\epsilon d_{S,r}^2\right) + \frac{P_S}{1 - \left(\frac{d}{d_{r,D}}\right)^{\alpha}} \\ & \times \left[\exp\left(-\epsilon d^2\right) - \left(\frac{d}{d_{r,D}}\right)^{\alpha} \exp\left(-\epsilon d_{r,D}^2\right)\right], \end{aligned} \tag{6}$$

where $\epsilon = (1 + P_{hr}\phi)p\lambda \frac{\pi^2\delta}{\sin(\pi\delta)}\beta^{\delta}$, P_S *is the occurring probability of situation SRRP.*

Proof The proof is presented in Appendix. □

Lemmas 1 and 2 shows the success transmission probability for a typical receiver using DT and CC, respectively. In the following sections, we calculate the data rate and throughput by Lemmas 1 and 2.

3 Problem Formulation

In practice, a node makes choice of transmission strategy (DT or CC) based on the possible achievable data rate. To calculate the exact throughput of practical cooperative ad hoc networks, the gains and costs for conducting CC have to be specified, which is the basis for each source to choose transmission strategy.

In this paper, the gain of CC is the increased data rate than DT, which can be estimated by the CSI (fading and power decay with distance) of links from the source to destination ($\gamma_{S,D}$), source to selected relay ($\gamma_{S,r}$), and selected relay to destination ($\gamma_{r,D}$). The CSI can be measured distributively by estimating the received probing packets [28–31], as shown in Fig. 3. Particularly, each source only can acquire the CSI of links between the source, its selected relay and its destination, but not the CSI of other source-destination pairs.

The cost of CC refers to the time a source spent to select the best relay and to measure and collect $\gamma_{S,D}$, $\gamma_{S,r}$, and $\gamma_{r,D}$. If a source makes the strategy choice based on less CSI (i.e., only based on $\gamma_{S,D}$), it saves the time to measure and collect CSI of other links (i.e., $\gamma_{S,r}$, $\gamma_{r,D}$) thus it has more time for data transmission. However, the total data which can be transmitted in a time slot may decrease if the inaccurate transmission strategy choice is made due to the insufficient CSI. Thus, a source has to trade-off between more sufficient information to choose strategy and the higher time cost to measure and collect the more CSI.

To investigate the impacts from gains and costs for conducting CC to the strategy choice of each source and thus the throughput, the following two scenarios are discussed:

- The cost of acquiring CSI can be ignored: Each source can collect the CSI of all links of its source-destination pair (i.e., $\gamma_{S,D}$, $\gamma_{S,r}$, $\gamma_{r,D}$) by similar methods proposed in [40–42], and then estimate the transmission data rate by DT and CC, respectively. The decision of transmission strategy is made based on the amounts of data (bits/Hz/s) which can be transmitted in a time slot.
- The cost of acquiring CSI can not be ignored: At beginning of each time slot, each destination only can have $\gamma_{S,D}$, which is measured by the probing packet sent from source [40–42]. Based on $\gamma_{S,D}$, the destination should decide to do DT or to spend time selecting the best relay and collecting more CSI (i.e., $\gamma_{S,r}$, $\gamma_{r,D}$) by sending probing packet to potential relays and the selected relay reporting $\gamma_{S,r}$ and $\gamma_{r,D}$ to the destination [31]. If the destination choose to acquire $\gamma_{S,r}$ and $\gamma_{r,D}$, then it decides whether to conduct CC based on achievable data rate and thus the amounts of data (bits/Hz/s) estimated by $\gamma_{S,D}$, $\gamma_{S,r}$ and $\gamma_{r,D}$.

In the following subsections, the details of two scenarios are described and the corresponding problem are formulated.

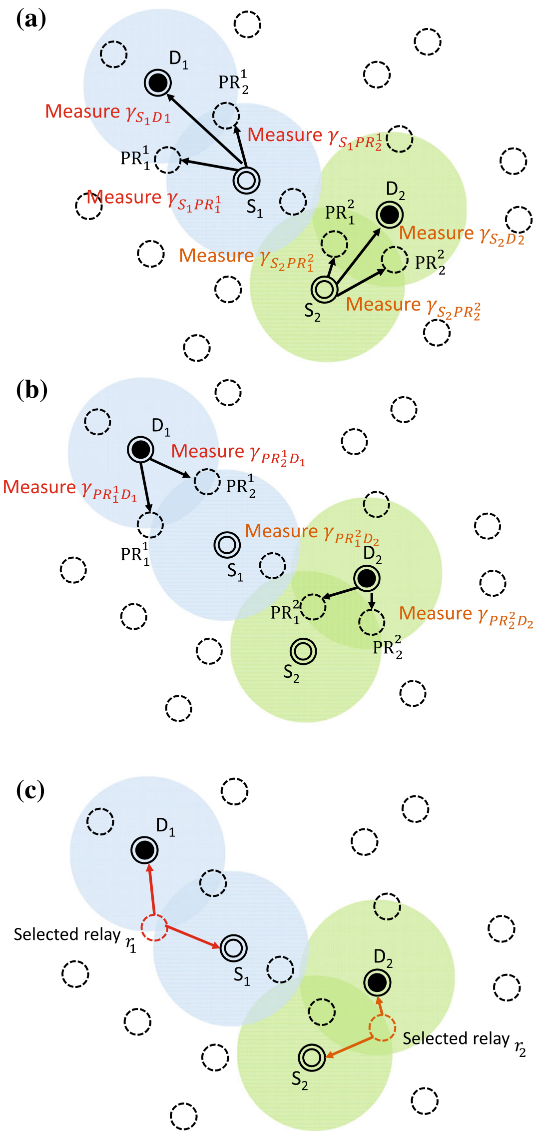
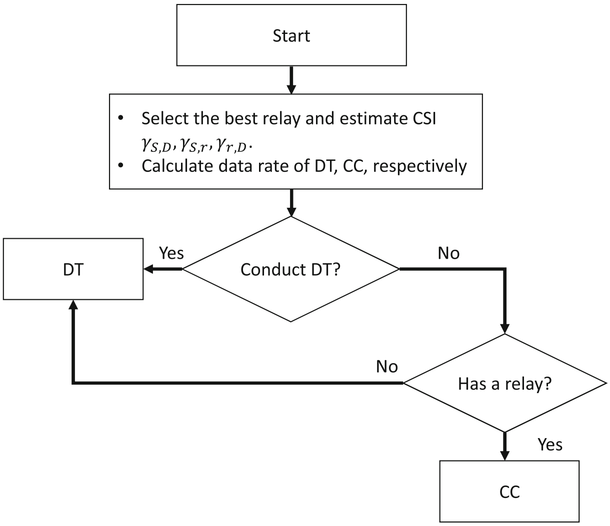


Fig. 3 An example of the CSI acquisition. **a** The source S_1 and S_2 broadcasts their probing packets, respectively. The destination D_1, D_2 estimate CSI γ_{S_1,D_1}, γ_{S_2,D_2}. And the potential relays of S_1 and S_2 can measure γ_{S_1,PR_i^1} and γ_{S_2,PR_i^2} for all i, respectively, which is the CSI of link from each source to their ith potential relay. **b** Then the destination D_1, D_2 broadcasts their probing packets, which is received by their potential relays and the CSI $\gamma_{PR_i^1,D_1}$ and $\gamma_{PR_i^2,D_1}$ for all i are measured. **c** Based on the relay selection algorithm [40–42], the best relays r_1, r_2 of S_1, S_2 are chosen respectively. The selected relay r_1 reports the CSI γ_{S_1,r_1}, γ_{r_1,D_1} to S_1, D_1, and the selected relay r_2 reports the CSI γ_{S_2,r_2}, γ_{r_2,D_2} to S_2, D_2

3.1 The Cost of Acquiring CSI can be Ignored

In this scenario, each source can collects the CSI of all links of its source-destination pair (i.e., $\gamma_{S,D}$, $\gamma_{S,r}$, $\gamma_{r,D}$) without spending any time cost. Based on $\gamma_{S,D}$, $\gamma_{S,r}$ and $\gamma_{r,D}$, the achievable data rate by conducting DT and CC precisely estimated by each source, which the basis for a source to choose transmission strategy. Since the time cost to select relay r and probe CSI $\gamma_{S,r}$, $\gamma_{r,D}$ can be ignored, the time for data transmission is the whole time slot t. If a source does not have a selected relay after relay selection process (no idle nodes in the intersection of its transmission range and its destination's transmission range), it

Fig. 4 The flow diagram of a source when the cost of collecting CSI and selecting the best relay can be ignored



conducts DT. Figure 4 shows the flow diagram of a source to decide whether to do cooperative transmission.

In practical cooperative ad hoc networks, since the global information of the entire network is unavailable due to huge overhead, users make autonomous decisions based on the current network conditions and individual preferences, and the achievable data rate of each user is affected by the strategies chosen of others in the form of interference. Game theory naturally addresses competition among users for limited network resources, models the interaction between multiple devices, and the equilibrium, where individual users cannot achieve better performance through individual actions, is analyzed [35, 47, 48].

Since a source only measures and collects CSI from links of its source-destination pair, it can not estimate other sources' data rate accurately due to have no knowledge about the CSI of links of other source-destination pairs. In other words, a player (source) can not accurately know other players' preferences (achievable data rate) about their transmission strategies. In game theory, this situation of at least one player has incomplete information about others usually adopted by Bayesian game [33, 34, 49]. Basesian game assumes that each player has its own type representing the private information of this player, and each player only knows its own type but not others'. We may therefore obtain an equilibrium of the game such as a Bayesian Nash Equilibrium (BNE), which is defined as operating points where a player's unilateral deviation from the equilibrium would bring less payoff to itself, thereby motivating players to stay at equilibrium points. Consequently, these equilibria can be used as robust operating points for decentralized wireless networks.

From the above discussion, our problem can be modeled as a Bayesian game as follows:

Definition 3 (***Static Bayesian Game***) The static Bayesian game is defined by $G = \{\Phi_A, \mathcal{A}, \Gamma, s, R\}$.

- A source in the wireless network is a player. The set of players is the set of sources Φ_A in the network.
- The set of actions $\mathcal{A}$ for player $i \in \Phi_A$ is $\mathcal{A} = \mathcal{DT}, \mathcal{CC}$. Strategy "*DT*" represents *DT*, and strategy "*CC*" represents that the player executes a relay selection process and does cooperative transmission.

- The *CSI* of the link from source i to its destination ($\gamma_{S,D}$), from source i to its selected relay ($\gamma_{S,r}$) and from its selected relay to its destination ($\gamma_{r,D}$) can be classified into two category:

  (1) If $\gamma = (\gamma_{S,D}, \gamma_{S,r}, \gamma_{r,D})$ satisfies $\gamma_{S,r} > \gamma_{S,D} + \gamma_{r,D}$, then γ is classified to a set called strong relay received power (*SRRP*) type.

  (2) If $\gamma = (\gamma_{S,D}, \gamma_{S,r}, \gamma_{r,D})$ satisfies $\gamma_{S,r} < \gamma_{S,D} + \gamma_{r,D}$, then γ is classified to a set called weak relay received power (*WRRP*) type.

  Defined the set of type as $\Gamma = SRRP, WRRP$. Each player knows the exact values of its type, but only the probability distribution of others'.
- The strategy function is $s : \Gamma \rightarrow \mathcal{A}$, where $s(\gamma) \in \mathcal{A}$ is the action of a typical player.
- For player $i \in \Phi_A$, the payoff R_i associated with an action is the maximum data could be transmitted in a time slot by the action, which can be estimated from *CSI*.
  For the strategy *DT*,

$$R_i(\text{ DT }, \mathbf{s_{-i}}) = t\log(1 + \mathsf{SINR}_{\mathsf{DT}}) \tag{7}$$

For the strategy *CC*,

$$R_i(\text{ CC }, \mathbf{s_{-i}}) = t\log(1 + \mathsf{SINR}_{\mathsf{CC}}), \tag{8}$$

where $\mathbf{s_{-i}}$ denotes the collective strategies of all players expect player i.

In our definition, fundamental operation of a distributed ad hoc network are involved in our Bayesian game model. Types of users capture the effects of asymmetry and uncertainty information of channel conditions. Strategy stands for the possible decisions made by each node.

3.2 The Cost of Acquiring CSI can Not be Ignored

At the beginning of each time slot, each source broadcasts a probing packet, which is received by its destination and its potential relays. The term of "potential relays" is defined as follows:

Definition 4 For a source, its potential relays refer to the nearby idle nodes which can receive the probing packets from both the source and its destination. Without loss of generality, we assume that the potential relays of a source is the idle nodes located in the intersection of the transmission range of the source and the transmission range of its destination. Thus, the number of potential relays for a source follows a Poisson random variable M. We define the set of potential relays of a source as "*PR*".

For a source, the CSI $\gamma_{S,D}$ can be measured by its destination based on the received probing packet [28–30]. In this stage, the potential relays also receive and measure the CSI from the received probing packet sent by the source. The CSI of the link from the source to its ith potential relay is defined as γ_{S,PR_i}. However, it is impossible for the destination to acquire all of γ_{S,PR_i} because the overhead of message passing by a large number of potential relays can be too costly. Thus, the destination have to decide whether to conduct DT only based on the knowledge of $\gamma_{S,D}$. If it decides to conduct DT, the source transmits data to destination directly with full time slot t.

If the destination decides not to conduct DT (i.e., $\gamma_{S,D}$ is too worse), it broadcasts a probing packet to the potential relays. The CSI of the links from the destination to the ith potential relay is defined as $\gamma_{PR_i,D}$. Thus, at this moment, potential relay i has both the CSI of link from the source to potential relay i (i.e., γ_{S,PR_i}) and the CSI of link from potential relay i to the destination (i.e., $\gamma_{PR_i,D}$). By the distributed relay selection algorithm [40–42], the best relay r is selected, and reports $\gamma_{S,r}$, $\gamma_{r,D}$ to the destination. The process would take time $c_{sum} \cdot t$, which is the time cost for a destination spending to select the best relay and get $\gamma_{S,r}$, $\gamma_{r,D}$. The parameter c_{sum} is defined as follows:

$$c_{sum} := \text{ThefractionoftimetofirstlyprobeCSIof} \\ \text{linkstothenearbypotentialrelaysand} \\ \text{thenselectthebestrelay}$$

After the relay selection process, the destination has the CSI of all links of its source-destination pair (i.e., $\gamma_{S,D}$, $\gamma_{S,r}$, $\gamma_{r,D}$), which are used to estimate the achievable data rate of DT and CC, respectively, and then make decision on transmission strategy.

Because of the decision can make transmission strategy choice by $\gamma_{S,D}$ or spend time to collect $\gamma_{S,r}$, $\gamma_{r,D}$ in order to make choice more precisely, the CSI acquisition and the decision of transmission strategy naturally form a two-level decision problem [31], in which the destination is the "decision maker". The two-level decision is described as follows:

(1) First-level decision: The destination decides to

- transmit to destination directly
- select the best relay r and collect the CSI $\gamma_{S,r}$, $\gamma_{r,D}$ in order to make transmission strategy choice more precisely (take time $c_{sum} \cdot t$).

If the destination decides to select the best relay, it broadcasts a probing packet. All of its potential relays receive the packet, and estimate $\gamma_{PR_1,D}, \gamma_{PR_2,D}, ldots, \gamma_{PR_M,D}$, respectively. By the destributed relay selecting algorithm described in [40–42], the potential relay with the highest estimated channel gain is selected and reports its CSI (i.e., $\gamma_{S,r}$, $\gamma_{r,D}$) to the destination.

(2) Second-level decision: The destination decides to

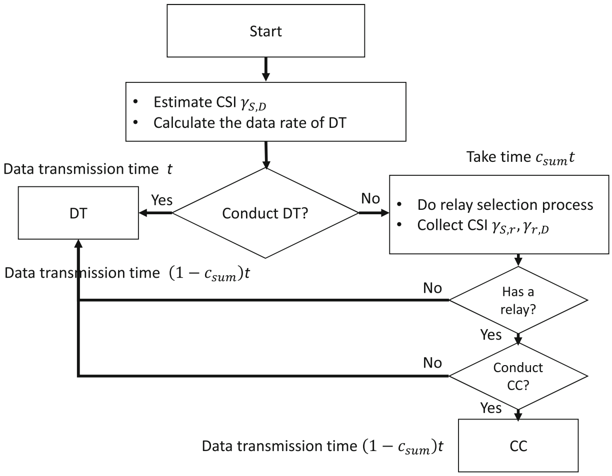
- transmit directly
- conduct cooperative communication (CC)

based on all CSI (i.e., $\gamma_{S,D}$, $\gamma_{S,r}$, $\gamma_{r,D}$) of links of its source-destination pair.

Figure 5 shows that the flow diagram of choosing transmission strategy in this scenario. Since the global information and centralized control is unavailable, the determination of the transmission strategy (DT and CC) of each destination solely depends on the achievable data rate and the time for data transmission. The preference of each transmission strategy (DT or CC) is shown by total data transmitted in a time slot, which is also called "utility" and described in the following subsections.

(*1*) Utility of First-level decision: At the first-level decision, the destination has to make decision on transmission strategy only based on $\gamma_{S,D}$. The utility function $R_{DT,1}$ of doing DT at the first-level decision is the expected data which could be transmitted in a time slot by conducting DT

Fig. 5 The flow diagram of the decision of transmission strategy when the cost of collecting CSI and selecting the best relay can not be ignored



$$R_{DT,1} = t\log(1 + \mathsf{SINR}_{\mathsf{DT}}). \tag{9}$$

And the utility function $R_{CC,1}$ of probing $\gamma_{S,r}$, $\gamma_{r,D}$ and selecting the best relay is the expected data which could be transmitted in a time slot by not conducting DT,

$$\begin{aligned} R_{CC,1} &= (1 - c_{sum})t \\ &\times \mathbb{E}\left[\max_i\{\min\{\log(1 + P_t\gamma_{s,PR_i}), \log(1 + P_t\gamma_{S,D} + P_t\gamma_{PR_i,d})\}\}\right], \end{aligned} \tag{10}$$

where γ_{s,PR_i} and $\gamma_{PR_i,d}$ denotes the channel gain of the link from the source to its ith potential relay and the channel gain of the link from its ith potential relay to its destination, which are exponential random variables since the channel fading is Rayleigh fading.

(*2*) Utility of Second-level decision: At the second-level decision, $\gamma_{S,D}$, $\gamma_{S,r}$ and $\gamma_{r,D}$ are known to the destination, such that the received SINR by conducting DT and CC can be derived easily. The utility function $R_{DT,2}$ of doing DT is

$$R_{DT,2} = (1 - c_{sum})t\log(1 + \mathsf{SINR}_{\mathsf{DT}}), \tag{11}$$

And the utility function $R_{CC,2}$ of conducting CC is

$$R_{CC,2} = (1 - c_{sum})t\log(1 + \mathsf{SINR}_{\mathsf{CC}}), \tag{12}$$

In the following sections, the cooperation beneficial criterion and throughput are discussed based on these utility functions.

4 Throughput Analysis

4.1 The Cost of Acquiring CSI can be Ignored

In this subsection, we explore the benefit of cooperation in ad hoc network by using throughput as our main performance index. The throughput of three different kinds of network scenarios are derived explicitly:

- **Case 1:** The totally non-cooperative scenario.
- **Case 2:** The always-cooperative scenario where each each player blindly executes CC no matter fading gains and other factors.
- **Case 3:** The cooperative scenario, where each node can decide whether to use relay distributively. In Case 3, since each node make the cooperation decision independently and affect the performance of each other through co-channel interference. Game theory provides as an effective analytical tools to predict the outcome of complex interactions among rational entities [47, 48], and is thus employed as the foundation to facilitate our goal. Since a node does not know the preferences about transmission strategies of other pairs, the analysis is facilitated by a Bayesian game. By comparing the results of throughput in three different scenarios, we can identify pros and cons of cooperation in wireless networks.

Case 1 could be seen as a benchmark, Case 2 discusses that is blindly cooperation beneficial to the entire network, and Case 3 discuss that the situation that nodes make decision rationally based on the payoff. These cases are elaborated as follows.

- **Case 1:** We consider an ad hoc network where each player conducts DT without relays. The throughput of this case is considered as the benchmark of throughput.
- **Case 2:** We consider the case that each player blindly executes CC no matter whatever the CSI $\gamma_{S,D}$, $\gamma_{S,r}$, $\gamma_{r,D}$ are.
- **Case 3:** We consider the case that each player decides whether to conduct CC according to available CSI $\gamma_{S,D}$, $\gamma_{S,r}$, $\gamma_{r,D}$ and the payoffs corresponding to strategy "DT" and "CC". We assume that each player is selfish and rational, and makes a decision in order to maximize its own payoff.

In the following theorems, the corresponding performances of these three cases could be evaluated.

Theorem 1 *For Case 1, when every player uses strategy DT, the expected throughput (bits/time slot/Hz/unit area) is*

$$T_{DT}(\lambda, p) = -p\lambda t \int_0^\infty \log(1+x) \mathrm{d}P_{SP}^{DT}(x) \tag{13}$$

Theorem 2 *For Case 2, when every player uses strategy CC, the expected throughput (bits/time slot/Hz/unit area) is shown as*

$$\begin{aligned} T_{CC}(\lambda, p) &= p\lambda t \\ &\times - \int_0^\infty \log(1+x)\Big((1-P_{hr})\mathrm{d}P_{SP}^{DT}(x) + P_{hr}\mathrm{d}P_{SP}^{CC}(x)\Big), \end{aligned} \tag{14}$$

where P_{hr} is the probability that a source has a selected relay after the relay selection process.

For Case 3, an appropriate solution concept is via the Bayesian Nash Equilibrium (BNE), which is a fixed point of the best responses of all players in a non-cooperative game, i.e., no player can improve his/her utility function by a unilateral deviation from the NE. The Bayesian Nash Equilibrium is defined as follows.

Definition 5 $s_i(h_i)$ is a Bayesian Nash Equilibrium if and only if:

$$s_i(\gamma_i) \in \arg\max_{a_j \in s_i} \mathbb{E}\left[\pi_i(a_j, \mathbf{s}_{-\mathbf{i}}(\gamma_{-\mathbf{i}}))|\gamma_{\mathbf{i}}\right] \tag{15}$$

for all γ_i and for all player i, where γ_i is the type vector of player i, and $\mathbf{s}_{-\mathbf{i}}(\gamma_{-\mathbf{i}})$ denotes the collective strategies of all players expect player i.

By (5) and (6), we could derive the expected payoff of DT and CC under the type γ is given. The expected payoff for player i by choosing strategy DT is:

$$\begin{aligned} &\mathbb{E}[R_i(\text{ DT }, \mathbf{s}_{-i}(\gamma_{-\mathbf{i}}))|\gamma_{\mathbf{i}}] \\ &= t\left(-\int_0^\infty \log(1+x)\mathrm{d}P_{SP}^{DT}(x)\right). \end{aligned} \tag{16}$$

For player i choosing strategy CC, if its type belongs to SRRP (see Def. 2), which means that the CSI of link from the source to its selected relay is larger than the sum of the CSI of link from the source to its destination and the CSI of link from its selected relay to destination its, the expected payoff is as

$$\begin{aligned} &\mathbb{E}[R_i(\text{ CC }, \mathbf{s}_{-i}(\gamma_{-\mathbf{i}}))|\gamma_i \in SRRP] \\ &= t\left(-\int_0^\infty \log(1+x)\mathrm{d}P_{SP}^{CC}(x|\gamma_i \in SRRP)\right) \end{aligned} \tag{17}$$

For player i choosing strategy CC, if its type belongs to WRRP, which means that the CSI of link from the source to its selected relay is smaller than the sum of the CSI of link from the source to its destination and the CSI of link from its selected relay to its destination, the expected payoff is as

$$\begin{aligned} &\mathbb{E}[R_i(\text{ CC }, \mathbf{s}_{-i}(\gamma_{-\mathbf{i}}))|\gamma_i \in WRRP] \\ &= t\left(-\int_0^\infty \log(1+x)\mathrm{d}P_{SP}^{CC}(x|\gamma_i \in WRRP)\right) \end{aligned} \tag{18}$$

From (16), (17) and (18), we have found the decision criteria of a player to decide whether to execute CC.

Definition 6 To make the representation of decision criteria and throughput more clearly, we define the achievable data rate by conducting *DT*, conducting *CC* in *SRRP* type, and conducting *CC* in *WRRP* type as follows:

The achievable data rate by conducting *CC* is

$$\mathrm{d}r^{DT} = -\int_0^\infty \log(1+x)\mathrm{d}P_{SP}^{DT}(x),$$

The achievable data rate by conducting CC in SRRP type is

$$\mathrm{d}r_{SRRP}^{CC} = -\int_0^\infty \log(1+x)\mathrm{d}P_{SP}^{CC}(x|h_i \in SRRP)$$

The achievable data rate by conducting *CC* in *WRRP* type is

$$\mathrm{d}r_{WRRP}^{CC} = -\int_0^\infty \log(1+x)\mathrm{d}P_{SP}^{CC}(x|h_i \in WRRP),$$

The following lemma shows the BNE of the game. And then the throughput $T_{EQ}(\lambda, p)$ at equilibrium is derived from this lemma.

Lemma 3 *(Bayesian Nash Equilibrium (BNE)) If player i's type is SRRP, its BNE strategy satisfies*

$$s_i(\gamma_i)^* = \begin{cases} CC & if\ \dfrac{dr^{DT}}{dr^{CC}_{SRRP}} < 1 \\ DT & otherwise. \end{cases} \tag{19}$$

And, if player i's type is WRRP, its BNE strategy satisfies

$$s_i(\gamma_i)^* = \begin{cases} CC & if\ \dfrac{d_{S,r}}{r} < 1\ and\ \dfrac{dr^{DT}}{dr^{CC}_{WRRP}} < 1 \\ DT & otherwise, \end{cases} \tag{20}$$

Proof The proof is presented in Appendix. □

In Lemma 3, dr^{CC}_{WRRP} represents the data rate by conducting CC in type WRRP, dr^{DT} represents the data rate by conducting DT, and dr^{CC}_{SRRP} represents the data rate by conducting CC in type SRRP. Lemma 3 suggests that for player i, if the ratio of the estimated data rate of DT to the estimated data rate of CC is smaller than the fraction of time to transmit data 1, then the source chooses to conduct CC. If not, the source chooses to conduct DT.

Theorem 3 *For Case 3, when every player decides transmission strategy according to its CSI $\gamma_{S,D}$, $\gamma_{S,r}$, $\gamma_{r,D}$ and the payoffs corresponding to conduct strategy "DT" and "CC", the expected throughput at equilibrium (bits/time slot/Hz/unit area) is*

$$T_{EQ}(\lambda, p) = \tag{21}$$

$$\begin{cases} T_{DT}(p,\lambda) & if\ p \le p_{max}\ and \lambda < \lambda_{th}(p) \\ T_{CC}(p,\lambda) & if\ p \le p_{max}\ and \lambda \ge \lambda_{th}(p) \\ P_S T'_{CC}(p,\lambda) + (1-P_S)T'_{DT}(p,\lambda) & if\ p > p_{max}, \end{cases} \tag{22}$$

where p_{max} is the maximal active probability p under which exists a node density threshold $\lambda_{th}(p)$, P_S is the occurring probability of situation SRRP. Under $p \le p_{max}$, if node density $\lambda < \lambda_{th}(p)$, all players would choose strategy DT, if $\lambda \ge \lambda_{th}(p)$, all players would choose strategy CC. $T'_{DT}(p,\lambda)$ and $T'_{CC}(p,\lambda)$ are throughput similar to (13), (14) *but the transmitting node density is replaced to be $(1 + P_{hr}P_S)p\lambda$.*

Proof The proof is presented in Appendix. □

The main theorems in this section supply the explicit formula of throughput in both non-cooperative and cooperative networks. From this theorem, the benefit of throughput by conducting CC in ad hoc networks could be quantified. And then we could know the explicit parameter region of node density and network traffic load where conducting CC is beneficial to the entire network. The derived value of p_{max} is located between 0.2 and 0.3. In Theorems 1, 2, and 3, there are something worth notice:

- If the active probability p is smaller than p_{max}, the throughput achieved by every source maximizing their data rate selfishly $T_{EQ}(p,\lambda)$ is equal to the throughput achieved by every source conducting DT $T_{DT}(p,\lambda)$ when the node density λ is smaller than the

threshold $\lambda_{th}(p)$. When the node density λ is higher than the threshold $\lambda_{th}(p)$, $T_{EQ}(p,\lambda)$ is equal to the throughput achieved by every source conducting CC $T_{CC}(p,\lambda)$, which shows that the T_{EQ} is also the highest throughput under $p < p_{max}$.
- If the active probability p is larger than p_{max}, the throughput achieved by every source maximizing their data rate selfishly $T_{EQ}(p,\lambda)$ is not the highest throughput. In order to achieve the highest throughput, the operation rule of each source should be designed to provide incentive to each source to conducting DT. The reason is that, for a source, conducting CC is more advantageous in outage probability and thus throughput if others conducting DT. The phenomenon is similar to the prisoner's dilemma. Compare with the throughput achieved by selfish behavior $T_{EQ}(p,\lambda)$, the increase of throughput is $T_{DT}(p,\lambda) - T_{EQ}(p,\lambda)$, which is more distinct in larger node density (lower maximum transmission range).

From the above analysis, to control the global throughput by local transmission selection, the algorithm is proposed as follows. To support this algorithm, there are some estimators deployed in the network to estimate current source density [50–53].

Algorithm 1

1: At the beginning of each time slot, each estimator node estimates the node density of current state of network (the time to do estimation assumed to be ignored), and then broadcasts the estimated value of node density to its nearby sources.
2: Each source decides its transmission strategy based on the received node density. **If** the value is below the node density threshold, **then**
3: Each source chooses their strategy which maximizes its transmission data; otherwise, each source chooses to conduct direct transmission.

To control an ad hoc network with heterogeneous nodes, the most important thing is to ensure each node having the aspiration to follow the same protocol. These motivation will be analyzed in our future work.

4.2 The Cost of Acquiring CSI can Not be Ignored

Each node in the network is rational and focuses on maximizing its own transmission data rate. Thus, at the first-level decision, the destination decides to conduct direct transmission if the expected achievable data rate is higher the expected achievable data rate by conducting CC. Otherwise, the destination decides to probe the CSI of links from destination to nearby potential relays $\gamma_{PR_1,D}, \gamma_{PR_2,D}, \ldots, \gamma_{PR_M,D}$ and select the best relay. That is, if

$$\mathbb{E}[R_{CC,1}|\gamma_{S,D}] \geq \mathbb{E}[R_{DT,1}|\gamma_{S,D}], \tag{23}$$

then the destination chooses to do the best relay selection process, where $\gamma_{S,D}$ is the channel of link from the source to its decision and known by the destination in the first-level decision. Since both the best relay r and the CSI $\gamma_{S,r}$, $\gamma_{r,D}$ are unknown to the destination in this decision level, the destination only can estimate the expectation of achievable data rate by conducting CC from the probability distribution of node density and channel fading $\gamma_{PR_i,D}$ $\forall i$. The detail of CSI acquisition of the two-level decision is shown in Fig. 5. From (9) and (10), the decision criteria of the first-level decision could be rewrite as

$$\mathbb{E}\left[\mathbb{E}\left[\max_i\{\log(1+\min\{\gamma_{S,PR_i},\gamma_{S,D}+\gamma_{PR_i,d}\})\}\right]\mid\gamma_{S,D}\right] \geq \frac{\log(1+\gamma_{S,D})}{(1-c_{sum})}, \tag{24}$$

In order to calculate the expectation term of (24), the success transmission probability of choosing to select the best relay r and probing $\gamma_{S,r}$, $\gamma_{r,D}$ in the first-level decision is required. In order to derived the success probability term $P_{SP}(x)$, the probability density function of the expected data rate by selecting the best relay r and probing $\gamma_{S,r}$, $\gamma_{r,D}$ is derived in the following:

Lemma 4 *The probability density function f_{fg} of*

$$\mathbb{E}\left[\max_i\{\min\{\gamma_{s,PR_i},\gamma_{S,D}+\gamma_{PR_i,D}\}\}\right],$$

which is the expected channel gain used to be estimate the achievable data rate by selecting the best relay r and probing $\gamma_{S,r}$, $\gamma_{r,D}$ at the first-level decision, is

$$f_{fg}(x)=f(x)\exp\left(\lambda_r P_S\gamma_{S,D}(F(x)-1)\right), \tag{25}$$

where

$$f(x)=\frac{1}{a\cdot b\cdot c}\left(\exp\left(-\frac{x-P_S\gamma_{S,D}}{a}\right)-\exp\left(-\frac{x-P_S\gamma_{S,D}}{b}\right)\right),$$
$$F(x)\text{is the cumulative distribution function of} f(x),$$

where f is the channel gain of $\min\{\gamma_{s,PR_i},\gamma_{S,D}+\gamma_{PR_i,D}\}$ *for all i since the distribution of node location follows Poisson point process. And f_{fg} is the max-min channel gain of the source-potential relay i-destination paths, for all i.*

By Lemma 4, the probability distribution of the max-min channel gain of the source-the ith potential relay-the destination paths for all i is derived. The success transmission probability term $P_{SP}(x)$ is simply the occurring probability of the achievable data rate of the link in which the max-min SNR is larger than the desired transmission rate threshold R, and derived as follows:

Lemma 5 *The successful transmission probability $P_{SP}(R)$ of selecting the best relay r and probing $\gamma_{S,r}$, $\gamma_{r,D}$ in the first-level decision is*

$$P_{SP}(R)=\int_R^{\infty} f_{fg}(x)\mathrm{d}x, \tag{26}$$

where R is the desired transmission rate threshold, $f_{fg}(x)$ is described in Lemma 4.

The expected achievable data rate can be easily calculated by using the success transmission probability term $P_{SP}(x)$ and the equation of expected transmission data rate $\int_0^{\infty}-\log(1+x)\mathrm{d}P_{SP}(x)$. Since the destination chooses transmission strategy rationally and solely based on achievable transmission rate and the time for data transmission, the decision criteria of the first decision level is derived as follows:

Lemma 6 *The decision criteria of the destination in the first-level decision is*

$$s = \begin{cases} DT & if \, \frac{\int_0^\infty -\log(1+x)\mathrm{d}P_{SP}(x)}{\log(1+\gamma_{S,D})} < \frac{1}{(1-c_{sum})} \\ CC & otherwise, \end{cases}$$

Lemma 6 shows the decision criteria of the first-level decision, which is simply calculated the expected maximum data rate achieved by conducting CC and direct transmission, respectively. Since the destination does not known the information about its selected relay at this decision level, it only could compute the expected maximum data rate based on the probability distribution of node density and $\gamma_{S,D}$.

After the destination broadcasts probing packet, the selected relay r reports the CSI $\gamma_{S,r}$, $\gamma_{r,D}$ to the destination. Thus, at the second-level decision, the destination has all CSI ($\gamma_{S,D}$, $\gamma_{S,r}$, $\gamma_{r,D}$). Since the destination is rationally and only can make transmission strategy choice based on the expected achievable data rate, it conducts direct transmission if the achieved rate by direct transmission is higher than CC. That is, if

$$\mathbb{E}[R_{CC,2}|\gamma_{S,D}, \gamma_{S,r}, \gamma_{r,D}] < \mathbb{E}[R_{DT,2}|\gamma_{S,D}, \gamma_{S,r}, \gamma_{r,D}], \tag{27}$$

the destination decides to do direct transmission. Otherwise, the destination decides to conduct CC. In this decision level, the CSI $\gamma_{S,D}, \gamma_{S,r}, \gamma_{r,D}$ are known to the destination. Thus, the second-level decision criteria is simply described in the following, which is based on (27):

Lemma 7 *The decision criteria of the destination in the second-level decision is*

$$s = \begin{cases} DT & if \, \frac{\min\{\gamma_{S,r}, \gamma_{S,D} + \gamma_{r,D}\}}{\gamma_{S,D}} < 1 \\ CC & otherwise. \end{cases} \tag{28}$$

By the above analysis, in the following theorem we derived the expected throughput (bits/time slot/Hz/unit area) of ad hoc networks in which users can choose transmission strategy based on the achievable data rate and the time cost to measure and collect CSI and select the best relay can not be neglected:

Theorem 4 *The expected throughput T_{TD} (bits/time slot/Hz/unit area) of an ad hoc network with a mixed transmission scheme (DT or CC) under the situation that the time cost to measure and collect CSI and select the best relay can not be ignored is*

$$T_{TD}(p, \lambda) = p\lambda t \left\{ \mu_1 dr^{DT} + \mu_2 \left(P_S dr^{DT}_{SRRP} + (1 - P_S) dr^{DT}_{SRRP} \right) \right\},$$

where

$$\begin{aligned} \mu_1 =& p_{DT,1} + (1 - p_{DT,1}) \\ & \times ((1 - P_{hr})(1 - c_{sum}) + (1 - (1 - P_{hr})(1 - c_{sum}))p_{DT,2}), \\ \mu_2 =& P_S(1 - P_{hr})(1 - c_{sum})(1 - p_{DT,1})(1 - p_{DT,2}) \\ p_{DT,1} =& \mathbb{P}\left(- \int_0^\infty \log(1+x)\mathrm{d}P_{SP}(x) < \frac{\log(1+\gamma_{S,D})}{1 - c_{sum}} \right), \\ p_{DT,2} =& \mathbb{P}\left(\frac{\min\{\gamma_{S,r}, \gamma_{S,D} + \gamma_{r,D}\}}{\gamma_{S,D}} < 1 \right) \\ =& \exp(-\gamma_{S,D}), \end{aligned}$$

where $p_{DT,1}$ is the probability that the destination chooses to conduct direct transmission in the first-level decision, and $p_{DT,2}$ is the probability that the destination chooses to conduct direct transmission in the second-level decision.

From Theorem 4, if all destinations in the network choose direct transmission at the first-level decision ($p_{DT,1} = 1$), that is, no destination conducting CC, then all sources transmit directly to their destination ($p_{DT,2} = 0$). The throughput T_{TD}^{DT} is

$$T_{TD}^{DT}(p,\lambda) = p\lambda t\{dr^{DT}\}, \tag{29}$$

where dr^{DT} is the data rate by conducting direct transmission (See Def. 6). T_{TD}^{DT} is the highest throughput could be achieved under the time cost to get CSI can not be neglected. If all destinations in the network choose CC at the first-level decision ($p_{DT,1} = 0$) and also CC at the second-level decision ($p_{DT,2} = 0$), that is, no destination conducting direct transmission, then the throughput T_{TD}^{CC} is

$$T_{TD}^{CC}(p,\lambda) = p\lambda t\left\{\mu_3 dr^{DT} + \mu_4\left(P_S dr_{SRRP}^{CC} + (1-P_S)dr_{WRRP}^{CC}\right)\right\}, \tag{30}$$

where

$$\mu_3 = (1-P_{hr})(1-c_{sum})$$
$$\mu_4 = P_S(1-P_{hr})(1-c_{sum}),$$

dr^{DT} is the data rate by conducting direct transmission, dr_{SRRP}^{CC} is the data rate by conducting CC in SRRP type, and dr_{WRRP}^{CC} is the data rate by conducting CC in WRRP type (See Def. 6). T_{TD}^{CC} is the lowest throughput could be achieved under situation that the time cost to get CSI can not be neglected. If all destinations choose CC at the first-level decision ($p_{DT,1} = 0$) and all choose direct transmission at the second-level decision ($p_{DT,2} = 1$), that is, both $\gamma_{S,D}$ and $\gamma_{S,r}$ are not good enough, then the throughput $T_{TD}^{DT,P}$ is

$$T_{TD}^{DT,P}(p,\lambda) = p\lambda t\{(1-c_{sum})\cdot dr^{DT}\}, \tag{31}$$

where dr^{DT} is the data rate by conducting direct transmission (See Def. 6). $T_{TD}^{DT,P}$ means the throughput achieved by all destinations decide to conduct direct transmission after spending time to select the best relay and probe $\gamma_{S,r}$, $\gamma_{r,D}$.

The difference between the throughput of all transmission pairs conducting CC and conducting direct transmission is $T_{TD}^{DT} - T_{TD}^{CC}$. We derived the condition of CC beneficial to network on the view of throughput as follows:

$$\begin{cases} DT\text{is more beneficial} & \text{if } \dfrac{P_S dr_{SRRP}^{CC} + (1-P_S)dr_{WRRP}^{CC}}{dr^{DT}} < \dfrac{1-\mu_3}{\mu_4} \\ CC\text{is more beneficial} & \text{otherwise,} \end{cases} \tag{32}$$

where

$$\mu_3 = (1-P_{hr})(1-c_{sum})$$
$$\mu_4 = P_S(1-P_{hr})(1-c_{sum}),$$

dr^{DT} is the data rate by conducting direct transmission, dr_{SRRP}^{CC} is the data rate by conducting CC in SRRP type, and dr_{WRRP}^{CC} is the data rate by conducting CC in WRRP type

(See Def. 6). This condition is derived easily by satisfying $T_{TD}^{DT} - T_{TD}^{CC} < 0$. The throughput improvement can be quantified by this condition.

The main theorem supplies the exact throughput achieved when the time cost to acquire the CSI can not be neglected. From Theorem 4, the cooperation beneficial condition is derived, and the explanation to the cooperation beneficial condition is discussed in the following sections. Theorem 4 shows that the throughput with the cost be neglected is an upper bound of the throughput with the cost can not be neglected, and we discuss some methods to close to the bound of throughput with the cost be neglected in Sect. 5.

5 Result

5.1 The Cost of Acquiring CSI can be Ignored

(1) Simulation step: We consider a realistic wireless ad hoc network, so the parameters of simulation are set to be corresponding the realistic value: The network coverage is set to be 10 km × 10 km, the path-loss exponent α is set to be 4 (urban and suburban networks), and the SINR threshold R is set to be 7.8. The maximum data transmission range is calculated by $d_{max} = \max\left\{d : \mathbb{P}\left(\frac{P_t h d^{-\alpha}}{I+\sigma^2} \le R\right) \le \bar{\epsilon}\right\}$, the transmission power P_t is set to be 20 dBm, and the distance d from source to destination is set to be 0.6 km.
(2) Simulation result: In this subsection, we discuss the cooperation beneficial condition on the view of throughput, and explain the method to achieve highest throughput in ad hoc networks in which nodes choose their transmission strategy independently only based on the achievable data rate. The throughput of the three cases described in Sect. 3.1 are shown in Fig. 6.

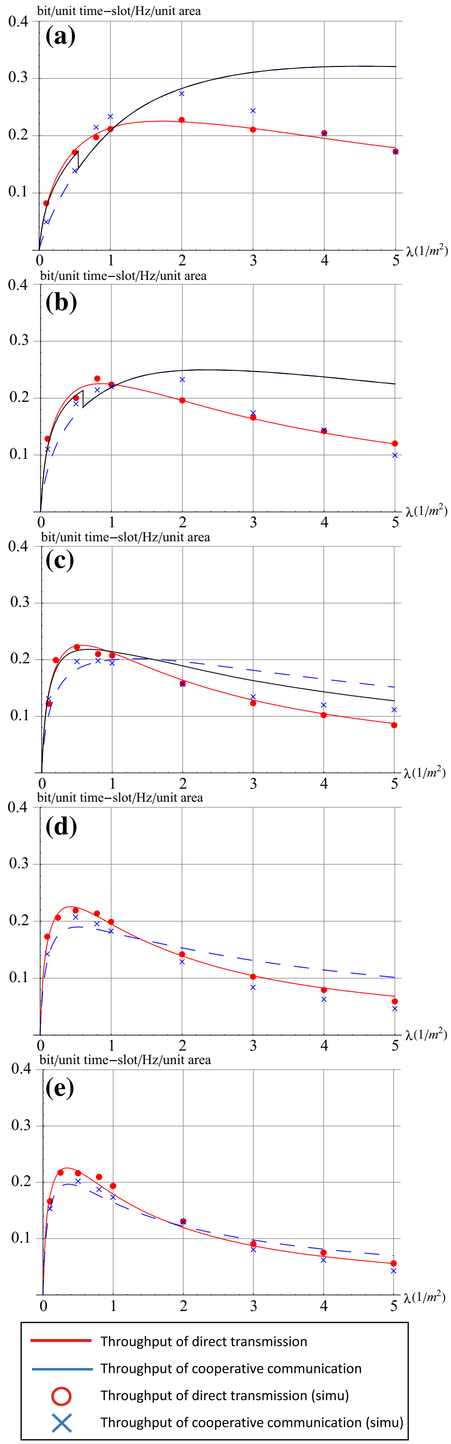
Due to the concern on the accuracy of adopting PPP to model locations of relays, we can observe that the PPP can be extremely accurate when the maximum transmission range d_{max} is smaller than $\sqrt{\frac{\ln \bar{\epsilon}}{-(1+P_{hr})p\lambda\frac{\pi\delta}{\sin \pi\delta}R^{\delta}}}$, which is typical in the practical deployment. Thus, this result suggests the feasibility of adopting the PPP to capture locations of relays. In the following, we use both numerical result and simulation under the maximum transmission range is smaller than $\sqrt{\frac{\ln \bar{\epsilon}}{-(1+P_{hr})p\lambda\frac{\pi\delta}{\sin \pi\delta}R^{\delta}}}$ to make conclusion. Otherwise, we only use simulation result to make conclusion.

From Theorems 1, 2, 3 and Fig. 6, the factors which impact the gain by cooperation in network can be summed up to

(1) traffic load
(2) maximum transmission range

The throughput of Case 1 (never cooperation) and Case 2 (always cooperation) described in Sect. 3.1 show that the throughput by all CC outperforms all direct transmission under lower traffic (lower p) but are almost the same under higher traffic (higher p). The reason is described as follows: When traffic load is higher, the number of packets transmitted simultaneously increases, so the received interference increases too and thus increase outage probability. Conversely, when traffic load is lower, both the received interference and outage probability decrease. For Theorems 1, 2, 3 and Fig. 6, generally speaking, if the maximum transmission range d_{max} satisfies the criterion $\sqrt{\frac{\ln \bar{\epsilon}}{-3(1+P_{hr})p\frac{\pi\delta}{\sin \pi\delta}R^{\delta}}} < d_{max} \cdot \sqrt{\lambda} < \sqrt{\frac{\ln \bar{\epsilon}}{-(1+P_{hr})p\frac{\pi\delta}{\sin \pi\delta}R^{\delta}}}$, the throughput can be improved by conducting CC. Otherwise, the

Fig. 6 The numerical results and simulation results of expected throughput T_{DT} (*red curve*), T_{CC} (*blue curve*) and T_{EQ} (*black curve*) under traffic load **a** $p = 0.1$, **b** $p = 0.2$, **c** $p = 0.3$, **d** $p = 0.4$, **e** $p = 0.5$. (Color figure online)



throughput is decreased. The reason is described as follows: If the length of maximum transmission range is short, CC is not beneficial since the network is disconnected and a source is hard to find a relay with $\gamma_{S,r}$ better than $\gamma_{S,D}$. If the maximum transmission range is long, CC is also not beneficial due to the cooperative gain cancelled by the increased interference. This phenomenon implies that

- CC is only suitable to low data rate wireless ad hoc network, e.g., sensor networks.
- CC relies on carefully designed distributed power control algorithm to maintain the beneficial maximum transmission range in large-scale ad hoc networks.

Figure 6 verifies the analysis in Sect. 4.1. For the graphs of traffic load $p = 0.1$ and $p = 0.2$, if the node density satisfies $\lambda < \lambda_{th}(p)$, the throughput of Nash Equilibrium (NE) is equal to T_D, and if the node density satisfies $\lambda \geq \lambda_{th}(p)$, the throughput of NE is equal to T_{CC}. For the graphs of $p = 0.3$, $p = 0.4$ and $p = 0.5$, the throughput of NE is between T_{DT} and T_{CC}. The highest throughput is equal to T_{DT}. This phenomenon implies that

- under lower traffic load, the highest throughput is achieved easily by each node choosing strategy selfishly based on data rate.
- under higher traffic load, the highest throughput is achieved by carefully design the incentive of each node to choose direct transmission.

5.2 The Cost of Acquiring CSI can Not be Ignored

(1) The Comparison of throughput under Different Traffic Loads: In this subsection, we discuss the situation in which cooperation is beneficial to the network on the view of throughput, and explain the method to achieve highest throughput in ad hoc networks where nodes choose their transmission strategy independently only based on data rate.

From (32), DT is more advantageous than CC on the view of throughput if the CSI of the link from source to destination of each transmission pair is good enough. The reason is shown as follows: If the CSI of the link from source to destination is good enough, then all destination choose to conduct transmission and achieve the highest throughput due to the lower received interference. CC benefits the network only if the two condition is satisfied:

- the time required to probing CSI of links to potential relays and selecting the best relay is lower.
- the node density of network is lower.

The reason is shown as follows: If node density of network is lower, the data rate decrease suffered from received interference becomes smaller, too. If the time cost to probing CSI and select the best relay is lower, each source has more time to transmit data by conducting CC. It means that the data rate by CC is less impacted by the time cost, and CC has more opportunities to outperform direct transmission.

Comparing with Figs. 7, 8 and 9, the throughput difference between all cooperation and all-noncooperation is smaller when the traffic load becomes larger. The reason is described as follows: Since it is hard for a source to have a selected relay under higher traffic load as shown in Fig. 2, most sources only can conduct direct transmission at second-level decision. For the same reason, if network node density increases, the difference of throughput between the network with all cooperation and with all noncooperation decreases, too. Figs. 7, 8 and 9 also shows that, under higher node density, the throughput of lower traffic load is higher than higher traffic load. The reason is that the received interference is lower under lower traffic, so the higher data rate can be achieved.

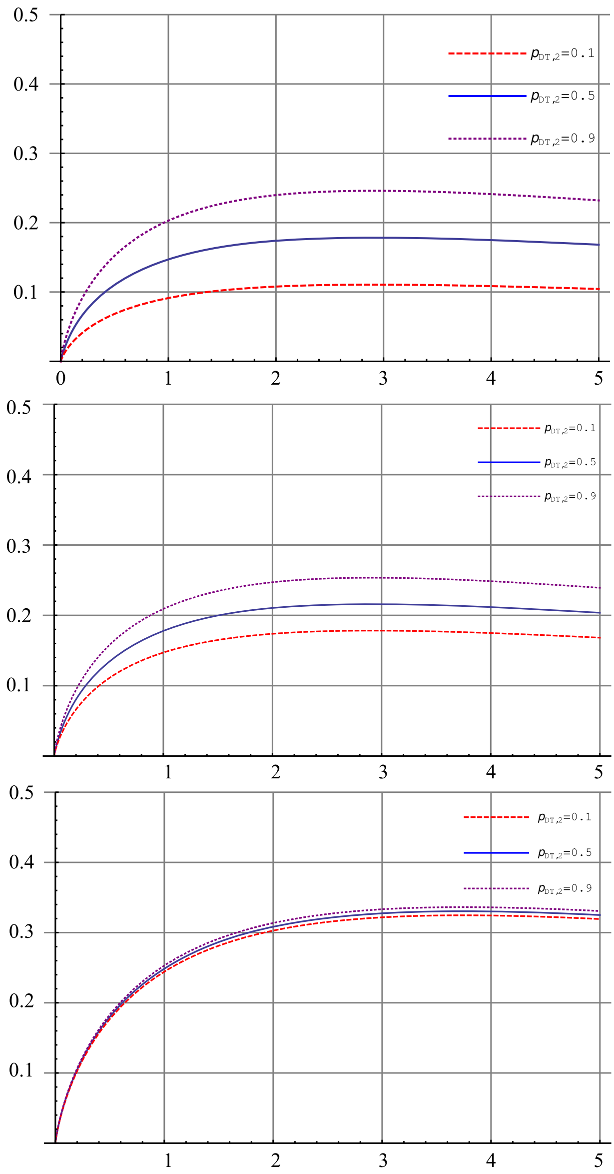


Fig. 7 Throughput versus node density under 0.1 packets transmitted per time slot with the probability of choosing direct transmission at first-level decision ($p_{DT,1}$) is equal to 0.1, 0.5, 0.9 (from *up to down*). The *purple dashed line* represents the throughput under the probability of choosing direct transmission at second-level decision ($p_{DT,2}$) is equal to 0.1, the *blue line* represents the throughput under $p_{DT,2} = 0.5$, and the *red dotted line* represents the throughput under $p_{DT,2} = 0.9$. (Color figure online)

(2) The Comparison of throughput under Different Time Cost: Fig. 10 and (29) show that the comparison of the throughput under different c_{sum}, which is the time cost ratio to probe the CSI of links from the destination to the potential relays and then select the best relay. In order to make CC more beneficial, since the throughput is directly proportional to $1 - c_{sum}$, how to decrease c_{sum} is needed to be considered. The reason is simply due to the

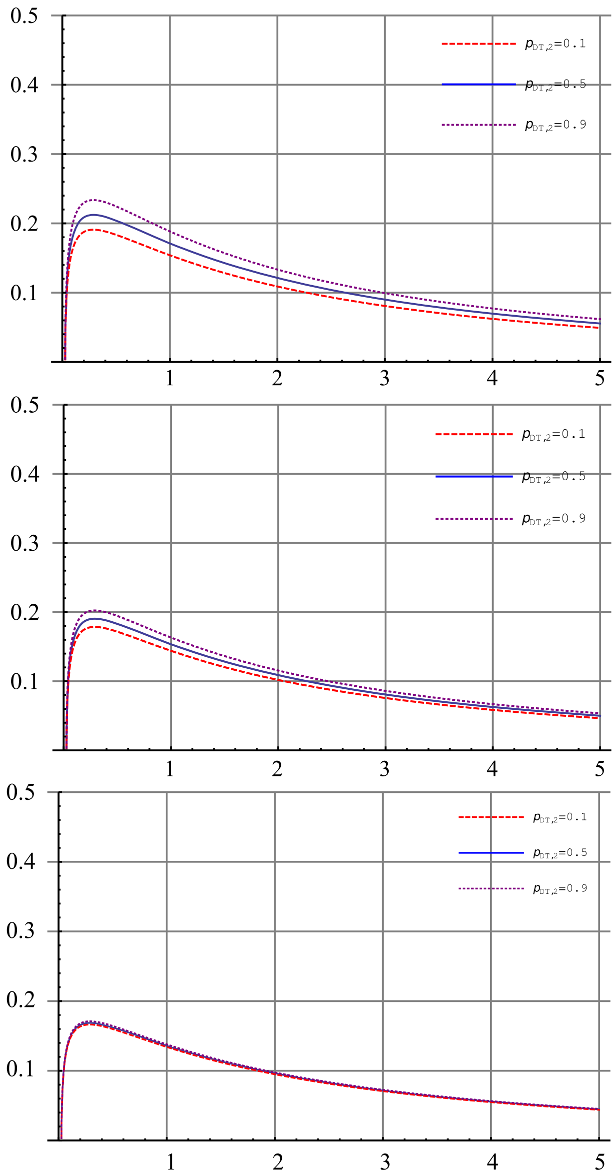
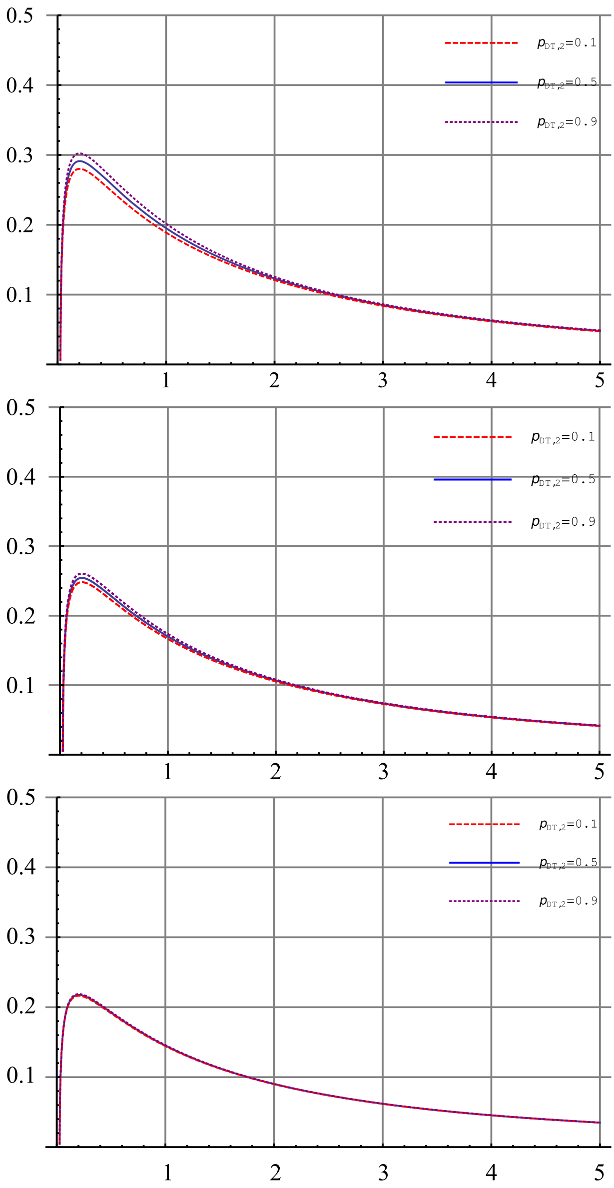


Fig. 8 Throughput versus node density under 0.3 packets transmitted per time slot with the probability of choosing direct transmission at first-level decision ($p_{DT,1}$) is equal to 0.1, 0.5, 0.9 (from *up to down*). The *purple dashed line*represents the throughput under the probability of choosing direct transmission at second-level decision ($p_{DT,2}$) is equal to 0.1, the *blue line* represents the throughput under $p_{DT,2} = 0.5$, and the *red dotted line* represents the throughput under $p_{DT,2} = 0.9$. (Color figure online)

time for data transmission increases when the time cost is reduced. This phenomenon shows that each node should restrict the transmission range such that each destination only probe and select relay from potential relays located in nearby small region. The time to probe the CSI of links to the potential relays and select the best relay can be saved since the time required for relay selection process decreases due to the less number of potential relays of each destination.

Fig. 9 Throughput versus node density under 0.5 packets transmitted per time slot with the probability of choosing direct transmission at first-level decision ($p_{DT,1}$) is equal to 0.1, 0.5, 0.9 (from *up to down*). The *purple dashed line* represents the throughput under the probability of choosing direct transmission at second-level decision ($p_{DT,2}$) is equal to 0.1, the *blue line* represents the throughput under $p_{DT,2} = 0.5$, and the *red dotted line* represents the throughput under $p_{DT,2} = 0.9$. (Color figure online)



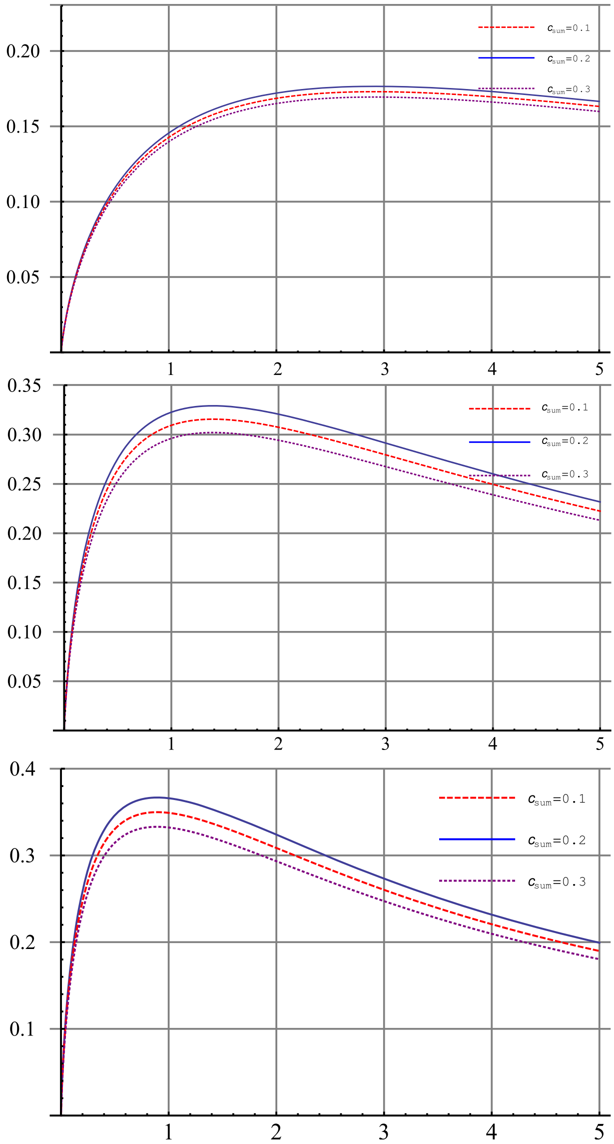


Fig. 10 Throughput versus node density under 0.1, 0.3 and 0.5 packets transmitted per time slot (from *up to down*) with the probability of choosing direct transmission at first-level decision ($p_{DT,1}$) is equal to 0.1. The *purple dashed line* represents the throughput under the cost of cooperation (c_{sum}) is equal to 0.1, the *blue line* represents the throughput under $c_{sum} = 0.2$, and the *red dotted line* represents the throughput under $c_{sum} = 0.3$. (Color figure online)

6 Conclusion

CC can improve performance of a single transmission pair by achieving cooperative diversity. However, the gain by cooperation may be reduced in networks due to the increased interference. In this paper, the fundamental problem for the benefits by conducting cooperation to realistic large-scale wireless ad hoc networks is addressed by a distributed network control paradigm in which competitive situation-aware users choose transmission strategy with regard to their network usage based on the current network conditions and the individual preferences they have. Leveraging the cost of acquiring information about current network conditions and the transmission data rate, we provide the first work on the throughput analysis of realistic wireless ad hoc networks. Furthermore, by analytically quantifying the increase of throughput and deriving the cooperation beneficial region, a novel operation algorithm for each node is proposed to guarantee the highest throughput could be achieve, which provides a way to distributed control the large-scale network performance by local operations.

Appendix

Proof of Lemma 1

The proof is similarly presented in [21, 46]. The term $(1 + P_{hr}\phi)p\lambda$ denotes the transmitting node density of the network.

Proof of Lemma 2

We rewrite

$$\begin{aligned} &P_{SP}^{CC}(R) \\ &=\mathbb{P}\left(\frac{P_t \min\{h_{S,r}d_{S,r}^{-\alpha}, h_{S,D}d^{-\alpha} + h_{r,D}d_{r,D}^{-\alpha}\}}{I_S + I_r + \sigma^2} \geq R\right) \\ &=(1 - P_S)\mathbb{P}\left(\frac{P_t h_{S,r}d_{S,r}^{-\alpha}}{I_S + I_r + \sigma^2} \geq R\right) \\ &\quad + P_S\mathbb{P}\left(\frac{P_t h_{S,D}d^{-\alpha} + P_t h_{r,D}d_{r,D}^{-\alpha}}{I_S + I_r + \sigma^2} \geq R\right) \end{aligned} \tag{33}$$

The rest of proof is similar to [21, 46].

Proof of Theorem 3

From other player's decisions only changed the interference level, that is, ϕ in (16), (17) and (18). No matter what other players' decisions are, (19) and (20) are the dominant strategies for players with $P_t h_{S,r}d_{S,r}^{-\alpha} > P_t h_{S,D}d^{-\alpha} + P_t h_{r,D}d_{r,D}^{-\alpha}$ and $P_t h_{S,r}d_{S,r}^{-\alpha} < P_t h_{S,D}d^{-\alpha} + P_t h_{r,D}d_{r,D}^{-\alpha}$, respectively.

Proof of Theorem 3

According to Lemma 3, when $p \leq p_{max}$, all players would choose strategy DT if $\lambda < \lambda_{th}(p)$, and choose strategy CC if $\lambda \geq \lambda_{th}(p)$. $\lambda_{th}(p)$ depends on p. When $p > p_{max}$, each player whose type satisfies $P_t h_{S,r}d_{S,r}^{-\alpha} > P_t h_{S,D}d^{-\alpha} + P_t h_{r,D}d_{r,D}^{-\alpha}$ would choose strategy CC and each player whose type satisfies $P_t h_{S,r}d_{S,r}^{-\alpha} < P_t h_{S,D}d^{-\alpha} + P_t h_{r,D}d_{r,D}^{-\alpha}$ would choose strategy DT.

References

1. Laneman, J., Tse, D., & Wornell, G. (2004). Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory*, *50*(12), 3062–3080.
2. Sendonaris, A., Erkip, E., & Aazhang, B. (2003). User cooperation diversity. Part i. System description. *IEEE Transactions on Communications*, *51*(11), 1927–1938.

3. Tao, X., Xu, X., & Cui, Q. (2012). An overview of cooperative communications. *IEEE Communications Magazine*, *50*(6), 65–71.
4. Yang, D., Fang, X., & Xue, G. (2012). Game theory in cooperative communications. *IEEE Transactions on Wireless Communications*, *19*(2), 44–49.
5. Kramer, G., Gastpar, M., & Gupta, P. (2005). Cooperative strategies and capacity theorems for relay networks. *IEEE Transactions on Information Theory*, *51*(9), 3037–3063.
6. Kim, Y., & Beaulieu, N. (2014). Relay advantage criterion for multihop decode-and-forward relaying systems. *IEEE Transactions on Wireless Communications*, *13*(4), 1988–1999.
7. Nosratinia, A., Hunter, T., & Hedayat, A. (2004). Cooperative communication in wireless networks. *IEEE Communications Magazine*, *42*(10), 74–80.
8. Mukherjee, A. (2013). Diffusion of cooperative behavior in decentralized cognitive radio networks with selfish spectrum sensors. *IEEE Journal of Selected Topics in Signal Processing*, *7*(2), 175–183.
9. Beres, E., & Adve, R. (2008). Selection cooperation in multi-source cooperative networks. *IEEE Transactions on Wireless Communications*, *7*(1), 118–127.
10. Krikidis, I., Rong, B., & Ephremides, A. (2011). Network-level cooperation for a multiple-access channel via dynamic decode-and-forward. *IEEE Transactions on Information Theory*, *57*(12), 7759–7770.
11. Sirkeci-Mergen, B., & Gastpar, M. (2010). On the broadcast capacity of wireless networks with cooperative relays. *IEEE Transactions on Information Theory*, *56*(8), 3847–3861.
12. Han, J., Baek, J., Jeon, S., & Seo, J. (2014). Cooperative networks with amplify-and-forward multiple-full-duplex relays. *IEEE Transactions on Wireless Communications*, *13*(4), 2137–2149.
13. Zhou, Y., & Zhuang, W. (2013). Beneficial cooperation ratio in multi-hop wireless ad hoc networks. In *Proceedings IEEE INFOCOM*, April 2013, pp. 450–454.
14. Zhu, Y., & Zheng, H. (2008). Understanding the impact of interference on collaborative relays. *IEEE Transactions on Mobile Computing*, *7*(6), 724–736.
15. Goldsmith, A., Effros, M., Koetter, R., Medard, M., Ozdaglar, A., & Zheng, L. (2011). Beyond shannon: The quest for fundamental performance limits of wireless ad hoc networks. *IEEE Communications Magazine*, *49*(5), 195–205.
16. Sheng, Z., Leung, K., & Ding, Z. (2011). Cooperative wireless networks: From radio to network protocol designs. *IEEE Communications Magazine*, *49*(5), 64–69.
17. Weber, S. P., Andrews, J., Yang, X., & de Veciana, G. (2007). Transmission capacity of wireless ad hoc networks with successive interference cancellation. *IEEE Transactions on Information Theory*, *53*(8), 2799–2814.
18. Conti, M., Gregori, E., & Maselli, G. (2004). Cooperation issues in mobile ad hoc networks. In *Proceedings IEEE International Conference on Distributed Computing Systems Workshops*, March 2004, pp. 803–808.
19. Scaglione, A., Goeckel, D., & Laneman, J. (2006). Cooperative communications in mobile ad hoc networks. *IEEE Signal Processing Magazine*, *23*(5), 18–29.
20. Sheng, Z., Ding, Z., & Leung, K. (2009). Interference subtraction with supplementary cooperation in wireless cooperative networks. In *IEEE international conference on communication (ICC)*, June 2009, pp. 1–5.
21. Haenggi, M., Andrews, J., Baccelli, F., Dousse, O., & Franceschetti, M. (2009). Stochastic geometry and random graphs for the analysis and design of wireless networks. *IEEE Journal on Selected Areas in Communications*, *27*(7), 1029–1046.
22. Baccelli, F., & Blaszczyszyn, B. (2009). Stochastic geometry and wireless networks: Volume 1: THEORY, ser. foundations and trends(r) in networking. Now Publishers. [Online]. Available: http://www.google.com.tw/books?id=H3ZkTN2pYS4C
23. Baccelli, F., Blaszczyszyn, B., & Muhlethaler, P. (2006). An aloha protocol for multihop mobile wireless networks. *IEEE Transactions on Information Theory*, *52*(2), 421–436.
24. Baccelli, F., & Zuyev, S. (1997). Stochastic geometry models of mobile communication networks. In J. H. Dshalalow (Ed.), *Frontiers in queueing: Models and applications in science and engineering* (pp. 227–244). Boca Raton: CRC Press.
25. Weber, S. P., Yang, X., Andrews, J., & de Veciana, G. (2005). Transmission capacity of wireless ad hoc networks with outage constraints. *IEEE Transactions on Information Theory*, *51*(12), 4091–4102.
26. Toumpis, S., & Goldsmith, A. (2003). Capacity regions for wireless ad hoc networks. *IEEE Transactions on Wireless Communications*, *2*(4), 736–748.
27. Sheng, Z., Goeckel, D., Leung, K., & Ding, Z. (2009). A stochastic geometry approach to transmission capacity in wireless cooperative networks. In *IEEE 20th international symposium on personal, indoor and mobile radio communications*, September 2009, pp. 622–626.

28. Tang, X., Alouini, M.-S., & Goldsmith, A. (1999). Effect of channel estimation error on m-qam ber performance in rayleigh fading. *IEEE Transactions on Communications*, *47*(12), 1856–1864.
29. Ramanan, S., & Walsh, J. (2010). Distributed estimation of channel gains in wireless sensor networks. *IEEE Transactions on Signal Processing*, *58*(6), 3097–3107.
30. Jones, V., & Raleigh, G. (1998). Channel estimation for wireless ofdm systems. In *The bridge to global integration. IEEE global telecommunications conference and GLOBECOM*, vol. 2. pp. 980–985.
31. Gong, X., Chandrashekhar, T. P. S., Zhang, J., & Poor, H. V. (2012). Opportunistic cooperative networking: To relay or not to relay? *IEEE Journal on Selected Areas in Communications*, *30*(2), 307–314.
32. Ozdaglar, A. (2008) Networks challenge: Where game theory meets network optimization. tutorial. In Kschischang f (ed.), *Proceedings international symposium on information theory (ISIT)*, July 2008.
33. Osborne, M., & Rubinstein, A. (1994). *A course in game theory*. Cambridge: MIT Press.
34. Han, Z. (2012). *Game theory in wireless and communication networks: Theory, models, and applications*. Cambridge: Cambridge University Press.
35. Al Rawi, A. F., Aissa, S., Tsimenidis, C. C., & Sharif, B. S. (2014). Game theoretic framework for future generation networks modelling and optimization. *IEEE Transactions on Wireless Communications*, *13*(3), 1153–1163.
36. Berger, J. (1985). *Statistical decision theory and Bayesian Analysis, ser. Springer series in statistics*. New York: Springer.
37. Feng, H., Wang, H., Dai, L., & Cimini, L. J. Jr. (2014). To cooperate or not to cooperate: An outage analysis of interference-limited wireless networks. *IEEE Transactions on Wireless Communications*, *13*(2), 822–833.
38. Altieri, A., Rey Vega, L., Piantanida, P., & Galarza, C. (2013). Analysis of a cooperative strategy for a large decentralized wireless network. *IEEE/ACM Transactions on Networking*, *PP*(99), 1–1.
39. Haenggi, M. (2005). On distances in uniformly random networks. *IEEE Transactions on Information Theory*, *51*(10), 3584–3586.
40. Bletsas, A., Khisti, A., Reed, D., & Lippman, A. (2006). A simple cooperative diversity method based on network path selection. *IEEE Journal on Selected Areas in Communications*, *24*(3), 659–672.
41. Muller, A., & Speidel, J. (2008). Relay selection in dual-hop transmission systems: Selection strategies and performance results. In *Proceeding IEEE International Conference on Communications (ICC)*, May 2008, pp. 4998–5003.
42. Lee, J., Wang, H., Andrews, J., & Hong, D. (2011). Outage probability of cognitive relay networks with interference constraints. *IEEE Transactions on Wireless Communications*, *10*(2), 390–395.
43. Weber, S., Andrews, J., & Jindal, N. (2010). An overview of the transmission capacity of wireless networks. *IEEE Transactions on Communications*, *58*(12), 3593–3604.
44. Baccelli, F., Blaszczyszyn, B., & Muhlethaler, P. (2006). An aloha protocol for multihop mobile wireless networks. *IEEE Transactions on Information Theory*, *52*(2), 421–436.
45. Hasan, A., & Andrews, J. (2007). The guard zone in wireless ad hoc networks. *IEEE Transactions on Wireless Communications*, *6*(3), 897–906.
46. Haenggi, M., & Ganti, R. K. (2009). *Interference in Large Wireless Networks*. NOW: Foundations and Trends in Networking.
47. MacKenzie, A. B., DaSilva, L. A., & Tranter, W. (2006). *Game theory for wireless engineers*. San Rafael: Morgan and Claypool Publishers.
48. Srivastava, V., Neel, J., MacKenzie, A., Menon, R., DaSilva, L., Hicks, J., et al. (2005). Using game theory to analyze wireless ad hoc networks. *IEEE Communications Surveys Tutorials*, *7*(4), 46–56.
49. Johari, R., & Berry, R. (2009). *Game theory in networks*. Hanover: NoW Publishers.
50. Privault, N., & Torrisi, G. (2011). Density estimation of functionals of spatial point processes with application to wireless networks. *SIAM Journal on Mathematical Analysis*, *43*(3), 1311–1344.
51. Nowak, R. (2003). Distributed em algorithms for density estimation and clustering in sensor networks. *IEEE Transactions on Signal Processing*, *51*(8), 2245–2253.
52. Seetharam, A., Bhattacharyya, A., Naskar, M., & Mukherjee, A. (2008). Estimation of node density for an energy efficient deployment scheme in wireless sensor network. In *Communication systems software and middleware and workshops, 2008. COMSWARE 2008. 3rd International Conference on*, January 2008, pp. 95–98.
53. Safarinejadian, B., & Menhaj, M. B. (2011). Distributed density estimation in sensor networks based on variational approximations. *International Journal of Systems Science*, *42*(9), 1445–1457.

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