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Cooperation in Delay-Tolerant Networks With Wireless Energy Transfer: Performance Analysis and Optimization

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Abstract*—We consider a delay-tolerant network (DTN) whose mobile nodes are assigned to collect packets from data sources and deliver them to a sink (i.e., a gateway). Each mobile node operates by using energy transferred wirelessly from the gateway. For such a network, two main issues are studied. First, when a mobile node is at the data source, this node must decide on whether to accept the packet received from the data source or not. In contrast, whenever a mobile node is at the gateway, it has to decide on whether to transmit the packets collected from the data sources or to request wireless energy transfer. Second, multiple mobile nodes can cooperate and form coalitions to help one another in the delivery of packets from their associated data sources. However, this cooperation may not be always beneficial due to the limited buffer and energy resources. Moreover, some mobile nodes may secretly decide to deviate from a given coalition, thus taking advantage of the other innocent mobile nodes. To address these two issues, this paper introduces a performance analysis and optimization framework, which is based on a joint optimization and game-theoretic framework. The optimization model is used to obtain the packet delivery policy of each individual mobile node. Then, a novel game-theoretic model, namely a *repeated coalition formation game*, is developed to analyze the cooperation strategies of multiple mobile nodes.

***Index Terms*—Cooperative game, delay-tolerant network (DTN), game theory, wireless energy transfer.**

I. Introduction

DELAY-TOLERANT networks (DTNs) have emerged as a promising networking technology for collecting, carrying, and forwarding delay-insensitive data from sources to destinations [1], [2]. The concept of a DTN can be applied to various applications such as sensor networks and networks with big data volume [3], [4]. In the former, mobile nodes can move and visit sensor nodes, collect sensing data, and then move back and offload the data to a data sink. Similarly, in the latter, mobile nodes travel to and download data from big data sources. The mobile nodes subsequently travel to the desired destinations and upload the big data. Clearly, DTNs constitute a viable and promising solution for such applications due to the fact that it may not be technically or economically possible to have direct connections among sensor nodes or data sources to sinks and destinations. For example, a sensor network could be partially disconnected due to its limited transmission range. In addition, it could be too expensive to transmit big data over wireless links.

This paper considers a DTN for the aforementioned scenarios. In this proposed model, we also allow the mobile nodes to be charged wirelessly using wireless energy transfer capability. A few studies present the potential of wireless energy transfer. There are three major approaches for wireless energy charging/transfer, i.e., radio-frequency (RF) energy transfer, resonant inductive coupling, and magnetic resonance coupling. RF energy transfer is based on radiative propagation and can achieve an efficiency value of 0.4% at -40 dBm, above 18.2% at -20 dBm, and over 50% at -5 dBm [5]. Resonant inductive and magnetic resonance coupling are the near-field energy transfer with nonradiative propagation. The resonant inductive coupling can have an efficiency value that ranges from 5.81% to 57.2% when frequency varies from 16.2 to 508 kHz [6]. The magnetic resonance coupling has an efficiency value that ranges from above 90% to above 30% when distance varies from 0.75 to 2.25 m [7].

In DTNs, whenever a mobile node is present at a gateway, it can request wireless energy transfer to replenish its battery. This will obviate the need for physical battery charging or the replacement of the mobile node after the depletion of its energy. However, a number of important challenges must be addressed in such a DTN scenario in which the nodes possess wireless energy transfer capabilities. For instance, each mobile node needs to optimize the schedule of its packet transmission and wireless energy transfer, when it is at the gateway. In addition, due to limited buffer and energy resources, the mobile nodes must selectively collect packets from different sources. In this model, the multiple mobile nodes can potentially help one

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another to deliver the packets from their associated data sources to the gateway. For example, if two mobile nodes cooperate, they can collect each other's data from the data sources and deliver it to the gateway. Here, due to limited resources, the mobile nodes may not always benefit from such a cooperation. Indeed, there is a need to devise a scheme using which the mobile nodes can decide to form stable and beneficial cooperative groups or "coalitions" such that their individual payoffs (i.e., packet delivery rate) are maximized.

The main contribution of this paper is to introduce a comprehensive performance analysis and optimization framework for DTNs having wireless energy transfer capabilities. This framework is composed of the following key components:

- *Optimization model for obtaining an optimal packet delivery policy*: For each individual mobile node, we formulate a constrained Markov decision process (CMDP) to obtain an optimal packet delivery policy. This policy maps the queue and energy states of each mobile node to its action. The action includes accepting or refusing a packet from the data source and transmitting the packet or requesting for wireless energy transfer from the gateway.
- *Game-theoretic model for forming stable cooperative coalitions*: Given the packet delivery policy of each mobile node, we formulate a cooperative game model to analyze and derive the prospective stable coalitions that will form between the different mobile nodes. We introduce the novel concept of a repeated coalition formation game, which takes into account the possible actions (deviations and punishments) that can stabilize the coalitions between the nodes. In this game, each mobile node optimizes not only the instantaneous gain that results from forming or deviating from the coalitions but also the discounted future payoff as well (i.e., long-term payoff).

Although some works in the literature considered similar DTN models (e.g., [8]–[19]), such works do not address the impact of wireless energy transfer on the scheduling policy. Moreover, none of these works studied the use of coalition formation for the DTN, particularly from a repeated game perspective.

The remainder of this paper is organized as follows. Section II presents a review of the related literature. Section III describes the system model. Section IV introduces the proposed queueing model and the CMDP formulation that allows to obtain an optimal packet delivery policy for an individual mobile node. Section V develops the repeated coalition formation game model that enables the mobile nodes to cooperate. Section VI presents the numerical performance evaluation results. Finally, conclusions are drawn in Section VII.

II. Related Work

A. Buffer Management in Delay-Tolerant Networks

DTNs have recently attracted a significant attention in the literature. In essence, a majority of the existing literature has focused on routing in DTNs (e.g., see the extensive surveys in [1] and [2]). Additionally, buffer management [8]–[19] is yet another important problem in DTNs, which is also related to the topic of this paper.

In [8], Li *et al.* considered a delay-tolerant mobile sensor network, in which a mobile node moves, collects, and delivers data to a sink. To support data delivery service in such a network, Li *et al.* in [8] introduced a queue management medium-access-control protocol designed to allow the mobile nodes to discover and receive data from the sources. This protocol can switch the data source and the mobile node to a sleep mode to reduce energy consumption. The work in [9] considered a homing-pigeon-based DTN, in which a mobile node (i.e., a pigeon node) is used to deliver data from a source to a destination on a regular basis. In this paper, a scheduling scheme was developed for buffer management at the pigeon node to minimize packet delay. In particular, a packet that requires a small delay is assigned a higher priority and placed at the head of the buffer. In [10], a message ferry DTN is studied. In this scheme, a ferry node is used to deliver data from a source to a destination. A buffer management scheme based on a max–min fairness model was proposed. The ferry node accepts and places data from different sources in the buffer such that the minimum data rate of any source is maximized.

The message delivery performance of a DTN under different queueing management policies and message forwarding strategies was evaluated in [11]. Using simulation, the work in [11] showed that the performance of a DTN can vary significantly if the queueing management policy and the message forwarding strategy are not jointly optimized. In [12], Li *et al.* studied a scenario in which the bandwidth and buffer space of the nodes in a DTN are limited. To improve the performance with such constraints, Li *et al.* introduced an adaptive optimal buffer management policy. This policy exploits historical encounter statistics and a message dropping strategy to maximize the delivery rate or to minimize the delivery delay. Yin *et al.* [13] considered an analogous problem. By adopting notions from optimal control theory, the optimal policy to accept or drop a packet in a DTN was introduced. The optimization problem formulated in [13] considers delivery ratio, delay, and overhead. Alternatively, Krifa *et al.* [14] proposed a distributed scheduling and drop policy for DTN nodes. Under such a scheduling policy, each node schedules messages to be forwarded to the other nodes within a limited encounter time. The scheduling approach is integrated with the drop policy to selectively accept the messages based on available buffer space.

B. Energy Efficiency

Energy efficiency is another key challenge in DTNs (see, e.g., [20]–[23]). One seminal work in this regard was presented in [20], which analyzed the network capacity region given the energy requirement of the network's nodes. In [21], the duty cycle of mobile nodes in a DTN was optimized in a way to reduce energy consumption. This work allows multiple nodes to cooperatively form clusters so that the nodes can coordinate their active/inactive modes in an effort to save energy. In this case, each active node can receive and forward messages for other nodes in the same cluster. It is shown that the energy consumption of the nodes can be significantly reduced, whereas the message delivery performance is not affected. Ren and Liang [22] studied the data collection problem by a mobile sink in sensor networks with energy harvesting. The optimal trajectory for the mobile sink is defined in a way to maximize the network throughput. While the problem of finding such an optimal trajectory is NP-hard, a heuristic algorithm was proposed, which is then shown to achieve a nearly optimal solution. In [23], an optimal opportunistic message forwarding policy in an energy-limited DTN was considered. This policy is defined as the probability of forwarding a message. Both the static and dynamic policies are derived when the nodes do not have or have the time information of the message (e.g., waiting time), respectively. In [24], a cooperative game model was studied to evaluate the core capacity region of an energy-constrained DTN. When the nodes cooperate to carry and forward each other's messages, the capacity gains can be quantified from the cooperation. However, this work assumes an ideal cooperation and does not consider the formation of coalitions between the nodes for the practical scenario in which not all the nodes can benefit from cooperation due to limited resources. Additionally, to the best of our knowledge, no existing work has considered the optimal data forwarding policy based on the energy state of a mobile node.

A number of existing works have considered wireless energy transfer as a means to support sensor networks. The main idea is to use a mobile charging device to carry energy received from fixed charging stations and to supply this energy to sensor nodes. For example, Li *et al.* [25] introduced a "Qi-Ferry" unit, which is powered by electric energy to carry energy and move around a wireless sensor network. The Qi-Ferry receives energy via wireless energy transfer from an energy station. The Qi-Ferry then visits sensor nodes to wirelessly supply energy, thus extending the sensors' lifetime. An optimization problem was formulated to obtain the charging strategy of the Qi-Ferry unit to maximize the number of sensors that can be charged while meeting the constraint on the energy usage. In [26], Xie *et al.* considered a similar scenario in which a mobile charging unit periodically moves and charges sensor nodes wirelessly. In [26], an optimization problem is introduced to maximize the ratio between the vacant time of the mobile charging unit over the total time. This optimization problem is solved to obtain the optimal traveling path for each mobile charging unit. The wireless power charger placement problem was studied in [27] using an integer linear programming (LP) model. The objective is to maximize the number of sensor nodes receiving wireless energy from the charger.

However, none of these existing works has considered the data delivery or sensor data collection using mobile nodes in a DTN with wireless energy transfer capability as proposed here. Moreover, these works considered an individual mobile charging unit only, thus ignoring the possibility of cooperation between multiple nodes.

III. System Model

A. Delay-Tolerant Network With Wireless Energy Transfer

Consider a single-hop DTN that provides a data delivery service from data sources to a gateway using mobile nodes. This model is similar to the homing-pigeon-based DTN [9] or the message ferry DTN [10]. In particular, each mobile node moves between the data source and gateway. Without loss of generality, each mobile node is associated with a data source. Therefore, we use the same variable to denote a mobile node and a gateway (e.g., mobile node i delivers packets from source i to the gateway). In this network, we consider the possibility of having wireless energy transfer. In this respect, each mobile node i has a data queue (i.e., buffer) of size Q_i packets and an energy storage device (i.e., battery) of size B_i units of energy. Depending on its connectivity, each mobile node can take a different action (see Fig. 1), as follows.

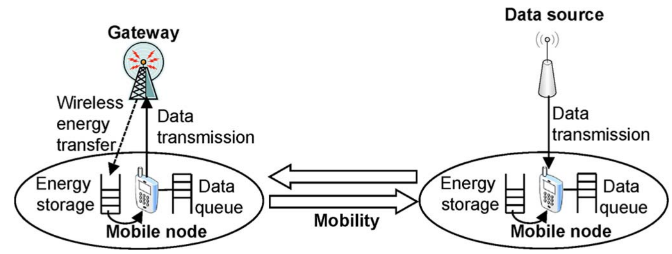

Fig. 1. Gateway, mobile node, and data source.

- When a mobile node is at the gateway, it can request a wireless energy transfer or a data transmission. Here, only one of these two actions can be chosen at a time. This is due to the fact that each mobile node uses the same antenna unit for both data transmission and wireless energy reception. For instance, if the mobile node requests a wireless energy transfer, the gateway will transfer wireless energy, and mobile node i can receive K_i units of energy. Alternatively, the mobile node can decide to transmit the packet in its data queue to the gateway. We use μ_i to denote the successful packet transmission probability. Moreover, the packet transmission by the mobile node consumes J_i units of energy.
- When a mobile node is at the data source, it can make a decision on whether to receive a packet from the data source or not. If not, the mobile node remains idle and consumes no energy (e.g., it switches to a sleep mode). Otherwise, it will consume $\hat{J}_i$ units of energy for packet reception. Note that, in some scenarios, a mobile node can transfer this energy to the data source, which can use this energy for sending data to the mobile node. This is similar to an RFID network, where a reader sends energy to an RFID tag so that the tag can send data back to the reader. The packet generation probability of a data source i is denoted by α_i. The probability of successful packet transmission from the data source to the mobile node is denoted by $\hat{\mu}_i$.

Although a mobile node is assigned to collect packets from a particular data source, it can move around and visit other data sources, which are associated with other mobile nodes. Let $\mathcal{N}$ denote the set of all mobile nodes, where $N = |\mathcal{N}|$ is the total number of all mobile nodes. Fig. 2 shows the considered scenario. In this figure, there are three data sources and three mobile nodes (i.e., $\mathcal{N} = \{1, 2, 3\}$). Each mobile node can visit any data sources. Note that the mobile nodes can also return to any gateway. In this network, the mobile nodes can cooperate

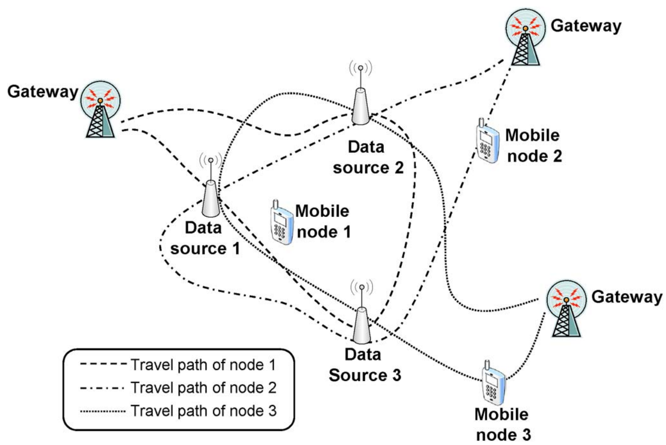

Fig. 2. System model of a DTN with data and energy transfer.

to assist one another in collecting data packets from the data sources associated with other mobile nodes. Such a cooperation may or may not improve the packet delivery rates from the data sources. Therefore, to analyze the packet delivery rates of the mobile nodes with wireless energy transfer, we will propose a performance analysis and optimization framework that considers not only the packet delivery policy of each mobile node but also the cooperation strategies of all the mobile nodes in the network.

The mobility of every mobile node is modeled via a transition probability $m^{(i)}_{l,l'}$, which is the probability that node i moves from location l to l'. Let $\mathcal{L}_G$ be the set of all locations that have a gateway and $\mathcal{L}_S$ be the set of all locations that have a data source. Location $l_i \in \mathcal{L}_S$ has a data source i. We assume that the data sources are not located at the same locations as any of the gateways, i.e., $\mathcal{L}_G \cap \mathcal{L}_S = \emptyset$. In other words, the data sources are not in the coverage of any gateway. The mobility matrix of a given mobile node i is denoted by $\mathbf{M}^{(i)}$, whose elements are $m^{(i)}_{l,l'}$.

B. Performance Analysis and Optimization

For the considered DTN model with wireless energy transfer, we introduce a novel framework to analyze the performance of the data delivery service provided by the mobile nodes from the data sources to the gateways. The framework is composed of 1) an optimization model based on a CMDP that allows to determine an optimal packet delivery policy of each individual mobile node and 2) a game-theoretic model based on a repeated coalition formation game that allows to analyze the cooperation strategy of multiple mobile nodes for data delivery. Here, a *coalition* is defined as a set of mobile nodes (e.g., $\mathcal{S} \subseteq \mathcal{N}$) that cooperate and agree to help collect the packets from the data sources of other nodes in the same coalition and subsequently deliver those packets to a gateway.

The optimization model for a packet delivery policy and game-theoretic model for the cooperation strategy are interrelated. The optimization model utilizes the coalition information from the game-theoretic model to determine the optimal packet delivery policy. The game-theoretic model uses the packet delivery rate as a payoff to determine the best cooperation strategy. Fig. 3 shows the components in the framework and their relations.

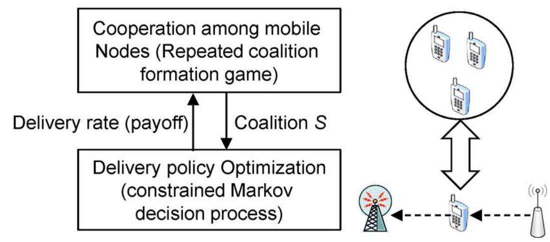

Fig. 3. Performance analysis and optimization framework for the DTN with wireless energy transfer capability.

IV. Wireless Energy Transfer and Data Transmission

Here, we present the CMDP formulation that allows to obtain the optimal packet delivery policy of a particular mobile node i (i.e., the mobile node i tagged in the performance analysis and optimization). This mobile node i can cooperate with other nodes whose coalition is denoted $\mathcal{S}$. The coalition can be a singleton coalition (i.e., $\mathcal{S} = \{i\}$). However, a coalition cannot be empty (i.e., $\mathcal{S} \neq \emptyset$) as each tagged mobile node can at least form a singleton coalition on its own. We first define the state space and action space. Then, we present the optimization formulation. Based on the optimal policy, we derive the important performance measures. Appendix A presents the detailed derivation of the transition probability matrix of the CMDP.

A. State Space and Action Space

We consider a tagged mobile node. For ease of presentation, we omit the subscript $_i$ of the mobile node. The state space of a mobile node is defined as follows:

$$\Theta = \{(\mathcal{L}, \mathcal{B}\mathcal{Q}); \mathcal{L} \in \mathcal{L}, \mathcal{B} \in \{0, 1, \ldots, B\} \quad \mathcal{Q} \in \{0, 1, \ldots, Q\}\} \quad (1)$$

where $\mathcal{L}$, $\mathcal{B}$, and $\mathcal{Q}$ represent, respectively, the location, the energy level (i.e., energy state) of the energy storage, and the number of packets in the data queue of the mobile node. B is the size of the energy storage, Q is the maximum queue size of the node, and $\mathcal{L}$ is the set of all locations. The state is then defined as a composite variable $\theta = (l, b, q) \in \Theta$, where l, b, and q are the location, the energy state, and the number of packets in the data queue, respectively.

The action space of a mobile node can be defined as $\Omega = \{0, 1, 2, 3\}$, where 0, 1, 2, and 3 are defined as follows.

- "0": The mobile node remains idle and does nothing.
- "1": The mobile node requests wireless energy transfer from the gateway. This action can be taken only if the node is located at the gateway.
- "2": The mobile node transmits a packet to the gateway. This action can be taken only if the node is located at the gateway.

- "3": The mobile node receives a packet from the data source. This action can be taken only if the node is located at a particular data source.

B. Optimization Formulation

Given the state and action spaces, we formulate a CMDP optimization model to obtain an optimal packet delivery policy for each mobile node as follows:

$$\max_{\pi} \quad \mathcal{J}_R(\pi) \tag{2}$$

$$\text{s.t.} \quad \mathcal{J}_{L,i'}(\pi) \le L_{i'}, \quad i' \in \mathcal{S} \tag{3}$$

where $\mathcal{J}_R(\pi)$ and $\mathcal{J}_{L,i'}(\pi)$ are, respectively, the steady-state packet delivery rate of the mobile node and the packet blocking probability of source i', which is a member of the same coalition as mobile node i. π is the packet delivery policy of the mobile node, and $L_{i'}$ is the packet blocking probability threshold for source i' that must be guaranteed by mobile node i. In other words, mobile node i aims to maximize the packet delivery rate given that its packet blocking probability at source i' is maintained below the threshold. The steady-state performance metrics can be defined as follows:

$$\mathcal{J}_R = \lim_{t\to\infty} \inf \frac{1}{t} \sum_{t'=1}^{t} \mathbb{E}\left(\mathcal{R}(\theta_{t'}, \omega_{t'})\right) \tag{4}$$

$$\mathcal{J}_{L,i'} = \lim_{t\to\infty} \sup \frac{1}{t} \sum_{t'=1}^{t} \mathbb{E}\left(\mathcal{L}_{i'}(\theta_{t'}, \omega_{t'})\right) \tag{5}$$

where $\theta_{t'} \in \Theta$ and $\omega_{t'} \in \Omega$ are the state and action variables, respectively, for the mobile node at time t'. $R(\cdot)$ and $\mathcal{L}_{i'}(\cdot)$ are functions of the immediate packet delivery rate and the immediate packet blocking probability, respectively.

The immediate packet delivery rate is expressed by

$$\mathcal{R}(\theta, \omega) = \begin{cases} \mu, & (l \in \mathcal{L}_G) \text{ and } (q > 0) \\ & \quad \text{and } (b \ge J) \text{ and } (\omega = 2) \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where $\theta = (l, b, q)$ is a composite state variable. In (6), the immediate packet delivery rate is the successful packet transmission probability in the case where 1) the mobile node is with any gateway (i.e., $l \in \mathcal{L}_G$); or 2) its data queue is not empty (i.e., $q > 0$); 3) the energy level in the energy storage is larger than or equal to the amount required for transmitting a packet (i.e., $b \ge J$); and 4) the mobile node decides to transmit the packet (i.e., $\omega = 2$).

The immediate packet blocking probability is given by

$$\mathcal{L}_{i'}(\theta, \omega) = \begin{cases} 1, & (l = i') \text{ and } \Big((b < \hat{J}) \text{ or } (q = Q) \\ & \quad \text{or } (\omega \ne 3)\Big) \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

A packet is blocked if a mobile node is with the data source i', but 1) this mobile node does not have enough energy in its storage to receive a packet (i.e., $b < \hat{J}$); or 2) its data queue is full (i.e., $q = Q$); or 3) the mobile node decides not to receive the packet (i.e., $\omega \ne 3$).

To solve for an optimal packet delivery policy, we follow the standard method of a randomized policy [28]. The optimal randomized policy is denoted by $\pi^*(\theta, \omega)$ for $\theta \in \Theta$ and $\omega \in \Omega$, which is the probability of taking an action ω when the current state of the node is θ. We first transform the CMDP optimization model into an LP model. Then, we solve for the optimal solution of this LP model, which can be mapped to the optimal randomized policy of the CMDP model. Let $\phi(\theta, \omega)$ be the stationary probability of state θ and action ω. The equivalent LP model can be expressed as follows:

$$\max_{\phi(\theta,\omega)} \quad \sum_{\theta\in\Theta} \sum_{\omega\in\Omega} \phi(\theta, \omega)\mathcal{R}(\theta, \omega) \tag{8}$$

$$\text{s.t.} \quad \sum_{\theta\in\Theta} \sum_{\omega\in\Omega} \phi(\theta, \omega)\mathcal{L}_{i'}(\theta, \omega) \le L_{i'} \quad i' \in \mathcal{S} \tag{9}$$

$$\phi(\theta, \omega = 3) = 0, \quad \text{for } (l \in \mathcal{L}_G) \tag{10}$$

$$\phi(\theta, \omega = 1) = 0, \phi(\theta, \omega = 2) = 0 \quad \text{for } (l \in \mathcal{L} \setminus \mathcal{L}_G) \tag{11}$$

$$\sum_{\omega\in\Omega} \phi(\theta', \omega) = \sum_{\theta\in\Theta} \sum_{\omega\in\Omega} \phi(\theta, \omega) P_{\theta,\theta'}(\omega) \quad \theta' \in \Theta \tag{12}$$

$$\sum_{\theta\in\Theta} \sum_{\omega\in\Omega} \phi(\theta, \omega) = 1, \quad \phi(\theta, \omega) \ge 0 \tag{13}$$

where $P_{\theta,\theta'}(\omega)$ is the element of the transition probability matrix $\mathbf{P}(\omega)$, with $\theta = (s, b, q)$ and $\theta' = (s', b', q')$. Appendix A presents the detailed derivation of matrix $\mathbf{P}(\omega)$. $P_{\theta,\theta'}(\omega)$ is the probability that the action ω is taken and the state changes from θ to θ'.

- The objective in (8) is to maximize the packet delivery rate.
- The constraint in (9) allows to maintain the packet blocking probability below a desired threshold.
- The constraint in (10) indicates that a mobile node cannot receive a packet when it is at a location having a gateway.
- The constraint in (11) indicates that a mobile node cannot request a wireless energy transfer or transmit a packet if it is at a location without a gateway.
- The constraint in (12) satisfies the Chapman–Kolmogorov equation.

A standard LP solver can be applied to obtain the solution $\phi^*(\theta, \omega)$ of the problem in (8)–(13).

The optimal randomized policy of the mobile node can be derived from the optimal solution of the LP model, i.e., $\phi^*(\theta, \omega)$, as follows:

$$\pi^*(\theta, \omega) = \frac{\phi^*(\theta, \omega)}{\sum_{\omega'\in\Omega} \phi^*(\theta, \omega')} \tag{14}$$

for $\theta \in \Theta$ and $\sum_{\omega'\in\Omega} \phi^*(\theta, \omega') > 0$. If $\sum_{\omega'\in\Omega} \phi^*(\theta, \omega') = 0$, then $\pi^*(\theta, 0) = 1$ (i.e., the mobile node will do nothing).

C. Performance Measures

Given that the CMDP is feasible, we can obtain the optimal policy of a given mobile node. The major metric used to characterize the performance of a mobile node is the packet delivery rate (i.e., the number of packets successfully delivered to a gateway per unit time). Here, we assume that whenever the mobile node receives packets from any source, it will deliver these packets to the gateway. In other words, there is no loss during the packet delivery by the mobile node. If a wireless transmission error occurs, the mobile node will retransmit the packets until they are received successfully by the gateway. Therefore, the packet delivery rate of a source i' serviced by a mobile node i is the rate at which mobile node i accepts the packets from source i', i.e.,

$$\tau_{i \triangleleft i'}(\mathcal{S}) = \nu_{i,l_{i'}} \alpha_{i'} \hat{\mu}_{i'} \left(\sum_{b=\hat{J}_i}^{B} \sum_{q=0}^{Q-1} \phi_i^*(\theta, \omega = 3) \right) \quad (15)$$

for $i, i' \in \mathcal{S}$, where $\nu_{i,l_{i'}}$ is the probability that mobile node i will be at the location $l_{i'}$. $\phi_i^*(\theta, \omega)$ is the steady-state probability of taking action ω at state θ with the optimal policy for mobile node i. Let $\vec{\boldsymbol{\nu}}^{(i)}$ denote a vector of $\nu_{i,l_{i'}}$. This vector can be obtained by solving the following equations: $(\vec{\boldsymbol{\nu}}^{(i)})^\top \mathbf{M}^{(i)} = (\vec{\boldsymbol{\nu}}^{(i)})^\top$ and $(\vec{\boldsymbol{\nu}}^{(i)})^\top \vec{\mathbf{1}} = 1$, where $\vec{\mathbf{1}}$ is a vector of ones with an appropriate size. In (15), $\nu_{i,l_{i'}} \alpha_{i'} \hat{\mu}_{i'}$ accounts for the packet arrival rate at mobile node i, while $\sum_{b=\hat{J}_i}^{B} \sum_{q=0}^{Q-1} \phi_i^*(\theta, \omega = 3)$ accounts for the case in which the mobile node has enough energy, the data queue is not full, and the action is to accept the packet from data source i'. Again, a mobile node can cooperate and form a coalition with other nodes to help in and receive help for packet delivery. Therefore, the total packet delivery rate of mobile node i, which is a member of coalition $\mathcal{S}$, is given by

$$\tau_i^{\mathrm{m}} = \sum_{i' \in \mathcal{S}} \tau_{i \triangleleft i'}(\mathcal{S}). \quad (16)$$

Additionally, the total packet delivery rate of a data source i is obtained from

$$\tau_i^{s} = \sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S}). \quad (17)$$

Note that the difference between τ_i^m in (16) and τ_i^s in (17) is that τ_i^m is the total packet delivery rate of mobile node i for all the data sources associated with the mobile nodes that cooperate (i.e., in the same coalition) with i. In contrast, τ_i^s is the total packet delivery rate for a particular source i by all mobile nodes in the same coalition with mobile node i. In other words, τ_i^s is the total gain/benefit reaped by mobile node i when it cooperates and forms a coalition with other nodes (i.e., so that the other nodes deliver packets for source i). This total packet delivery rate will be used as the payoff that captures the benefits from cooperation and coalition formation. The details of the coalition formation process will be discussed in Section V.

The average delivery delay can be analyzed using Little's law. First, the average number of packets in the data queue of the mobile node i is obtained from

$$\overline{q} = \sum_{\omega \in \Omega} \sum_{l \in \mathcal{L}} \sum_{b=0}^{B} \sum_{q=0}^{Q} q \phi_i^*(\theta, \omega). \quad (18)$$

The average delivery delay is obtained from

$$\overline{d} = \frac{\overline{q}}{\tau_i^{\mathrm{m}}}. \quad (19)$$

In this case, the effective packet arrival (if the packet is accepted and queued) is equal to the delivery rate. Therefore, the denominator in (19) is the total packet delivery rate of mobile node i.

The average energy consumption of mobile node i is

$$\overline{e}_i = \sum_{l \in \mathcal{L}} \sum_{b=0}^{B} \sum_{q=0}^{Q} \sum_{\omega=1} \phi_i^*(\theta, \omega). \quad (20)$$

V. Mobile Nodes' Cooperation

Here, we consider the cooperation possibilities between the mobile nodes that seek to cooperatively deliver the packets that they receive from data sources. We introduce a novel repeated coalition formation game concept, which considers the long-term cooperation strategies of the mobile nodes. We first present an example scenario. Then, we introduce the formulation of the repeated coalition formation game. Next, we discuss about the notions of stable coalitions and the stochastic model used to analyze the repeated coalition formation game.

A. Example

As the mobile nodes visit the data sources opportunistically, they can help each other by accepting packets from the data sources associated with other nodes and subsequently forwarding these packets to the gateway. Although this cooperation may improve the packet delivery rate reciprocally, a mobile node has to spend additional resources (i.e., a space in the data queue and energy for packet reception and transmission) to deliver the packets of other data sources. Therefore, if a mobile node does not gain much from cooperation compared with the associated resource consumption, it will decide not to help other nodes and will eventually act alone in delivering packets from its own data source.

Consider the following example. There are two mobile nodes, each of which is associated with its own data source, i.e., 1 and 2. The same parameter setting as given in Section VI-A is used.

- When each mobile node acts alone as a singleton coalition (i.e., $\{1\}$ and $\{2\}$), the packet delivery rate for each data source by each mobile node is $\tau_{1 \triangleleft 1}(\{1\}) = \tau_1^s = \tau_{2 \triangleleft 2}(\{2\}) = \tau_2^s = 2.392 \times 10^{-3}$.
- If these two mobile nodes cooperate and form a single coalition $\mathcal{S} = \{1, 2\}$ to cooperatively deliver packets from their data sources, the total delivery rate for each source will be $\tau_1^s = \tau_2^s = 4.355 \times 10^{-3}$. This is found from $\tau_1^s = \tau_{1 \triangleleft 1}(\{1, 2\}) + \tau_{2 \triangleleft 1}(\{1, 2\})$ (i.e., sum of the delivery rates

of mobile nodes 1 and 2 accepting packets from source 1). Similarly, we have, for source 2, $\tau_2^s = \tau_{1\lhd 2}(\{1,2\}) + \tau_{2\lhd 2}(\{1,2\})$.

Clearly, forming a coalition between mobile nodes 1 and 2 yields higher packet delivery rate for each source. However, if mobile node 1 is selfish and secretly deviates from the coalition (i.e., this mobile node does not deliver the packets received from the data source 2 without informing mobile node 2), the packet delivery rate of data source 1 will become $\tau_1^s = 4.570 \times 10^{-3}$, where $\tau_1^s = \tau_{1\lhd 1}(\{1\}) + \tau_{2\lhd 1}(\{1,2\})$. This delivery rate of source 1 when mobile node 1 deviates from the coalition is larger than the one it achieves if it remains in the coalition. This follows from the fact that mobile node 1 does not need to spend its resource for delivering the packets from data source 2 (i.e., $\tau_{1\lhd 1}(\{1\})$). However, in this scenario, mobile node 2 may still unwittingly help deliver the packets from data source 1 (i.e., $\tau_{2\lhd 1}(\{1,2\})$). In this case, data source 2 is a victim of the deviation by mobile node 1 and its packet delivery rate is just $\tau_2^s = \tau_{2\lhd 2}(\{1,2\}) = 2.177 \times 10^{-3}$. Therefore, there is an incentive for a mobile node to deviate as it can achieve a higher packet delivery rate. Based on this example, the payoff matrix of mobile nodes 1 and 2 can be expressed as in (21), shown at the bottom of the page.

This scenario can be viewed as a static noncooperative game [29]. In particular, the matrix game shown in (21) for mobile nodes 1 and 2 may have a pair of stable strategies (i.e., deviate–deviate). That is, none of the nodes is willing to form a coalition. However, if the mobile nodes consider a long-term payoff (i.e., over multiple time periods), the coalition can be stabilized. In what follows, we will formally formulate a novel repeated coalition formation game to study the long-term cooperation strategies of the mobile nodes to deliver packets from data sources in the considered DTN.

B. *Repeated Coalition Formation*

We develop a repeated coalition formation game based on a classical coalition formation game [29]. In this game, the players are mobile nodes whose set is given by $\mathcal{N}$. The repeated coalition formation game is formulated with nontransferable utility (NTU). Here, the game has NTU since the packet delivery rate cannot be divided arbitrarily. Let $\mathcal{N}$ (i.e., the set of all players) be the *grand coalition* formed by all players. The payoff of player i is defined as the total discounted packet delivery rate from source i over time, i.e.,

$$x_i(\mathcal{S}) = (1-\delta) \sum_{t=0}^{\infty} \delta^t \tau_i^s(\mathcal{S}, t) \qquad (22)$$

for $i \in \mathcal{S}$, where δ $(0 < \delta < 1)$ is the discount factor, and $\tau_i^s(\mathcal{S}, t)$ is the total packet delivery rate from source i at time period t. This rate is obtained from (17). $\tau_i^s(\mathcal{S}, t)$ could be interpreted as the *instantaneous payoff* (i.e., the payoff used in a classical coalition formation game), whereas $x_i(\mathcal{S})$ is the *long-term payoff*.

The players (i.e., mobile nodes) will decide on whether to form coalitions based on their long-term payoffs $x_i(\mathcal{S}), \forall i \in \mathcal{N}$. The players can cooperate and form a coalition if the long-term payoff is higher than the one received when acting alone. However, without any commitment, a selfish player i' can deviate from a given coalition $\mathcal{S}$. This deviating player i' will take advantage of the other innocent players who believe that the deviating player i' is still in the coalition $\mathcal{S}$. These innocent players will deliver the packets from the source of deviating player i' in the following time period. Then, after detecting the deviation in the following period, the innocent players will stop delivering the packets from the source i'.

In a repeated game context, such a deviating player can be punished. That is, the players in the coalition will not allow the deviating player to join the coalition again forever. This is referred to as the *trigger* punishment scheme, which can deter deviations by any player and stabilize the coalition. However, this *trigger* punishment scheme may not be efficient or necessary. In this scheme, if the deviating player is punished, the deviating player and other players in the coalition will not get help in packet delivery forever, which will adversely affect the long-term payoff. Therefore, we consider a *punish-and-forgive* scheme. In this scheme, a player may deviate from the coalition. However, if the other players in the coalition detect the deviation, they will enter the punishment stage. The detection of a deviation can be done by checking whether any of the coalition members is helping to deliver packets in a certain period or not. In the punishment stage, the players will not let the deviating player join the coalition again for $T-1$ time periods, where T is referred to as the punishment duration. If T is large, the punishment is severe, and the player will be less likely to deviate. However, this will be at the cost of lower long-term payoff since there will be a longer period for the punishment stage. Then, after the punishment period is over, the deviating player can be allowed to join the coalition again.

C. *Stable Coalition*

In the following, we consider the stability of a coalition $\mathcal{S}$. A coalition is said to be *stable* if it is internally and externally stable. We define the internal and external stability as follows.

- *Internal stability*: A coalition $\mathcal{S}$ is internally stable if no mobile node can obtain a higher long-term payoff by deviating from coalition $\mathcal{S}$.

(21)

	Cooperate	Deviate
Cooperate	$(4.355 \times 10^{-3}, 4.355 \times 10^{-3})$	$(2.177 \times 10^{-3}, 4.570 \times 10^{-3})$
Deviate	$(4.570 \times 10^{-3}, 2.177 \times 10^{-3})$	$(2.392 \times 10^{-3}, 2.392 \times 10^{-3})$

- *External stability*: A coalition $\mathcal{S}$ is externally stable if it cannot merge with another coalition $\mathcal{S}'$ while yielding higher long-term payoffs for all players in the new coalition $\mathcal{S} \cup \mathcal{S}'$.

For internal stability, we assume that one player can deviate at a time. Therefore, the condition for internal stability is that $x_i(\mathcal{S}) > x_i(\{i\})$ for all $i \in \mathcal{S}$. That is, the long-term payoff $x_i(\mathcal{S})$ of all the players in a coalition $\mathcal{S}$ must be strictly larger than the one achieved if any player deviates and acts alone $x_i(\{i\})$. The long-term payoff of a player i when this player i and other players are members of coalition $\mathcal{S}$ is given by

$$x_i(\mathcal{S}) = (1-\delta) \left\langle \sum_{t=0}^{\infty} \delta^t \left(\sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S}) \right) \right\rangle = \sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S}) \tag{23}$$

where we assume that the packet delivery rate $\tau_{i' \triangleleft i}(\mathcal{S})$ is identical at all time periods. $\sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S})$ is the total packet delivery rate of source i, which is the instantaneous payoff of player i.

If player i deviates from coalition $\mathcal{S}$ at time period T_0, the long-term payoff will be given in (24), shown at the bottom of the page, where we have the following:

- The first and last terms $\sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S})$ represent the total packet delivery rates achieved as if the player i is still in the coalition.
- The second term $\tau_{i \triangleleft i}(\{i\}) + \sum_{i' \in \mathcal{S} \setminus \{i\}} \tau_{i' \triangleleft i}(\mathcal{S})$ is the packet delivery rate of deviating player i who deviates without delivering packets for other innocent players plus the total packet delivery rate from the innocent players in the coalition.
- The third term $\tau_{i \triangleleft i}(\{i\})$ represents the case in which the players other than i punish the deviating player i (i.e., player i has to act alone and cannot join the coalition).

$x_i^D(\mathcal{S})$ could be expressed in a closed form as in (25), shown at the bottom of the next page.

Coalition $\mathcal{S}$ will be internally stable if the long-term payoff achieved by every player when staying in the coalition is larger than the one achieved when deviating, i.e., $x_i(\mathcal{S}) > x_i^D(\mathcal{S})$ for all $i \in \mathcal{S}$. In this case, we can determine the minimum value of the punishment duration T such that the internal stability condition, as given in (26)–(28), shown at the bottom of the next page, is satisfied.

Note that, in Appendix B, we also provide the analysis of the internal stability condition for the *trigger* punishment scheme.

For external stability, the condition requires that all the players must gain higher long-term payoff by merging relative to the case in which they do not merge, i.e., $x_{i'}(\mathcal{S}) > x_{i'}(\mathcal{S} \cup \{i\})$ for all $i' \in \mathcal{S}$ and $x_i(\mathcal{S}) > x_i(\{i\})$.

D. Stochastic Model of Coalition Formation

To analyze the stable coalitions that can potentially form between the DTN's mobile nodes, we can apply a stochastic modeling method based on a discrete-time Markov chain. In particular, for the repeated coalition formation game, the stochastic model will be an extension of the one introduced in [30]. The state space of this Markov chain is defined as $\Psi = \{\psi_1, \ldots, \psi_{D(|\mathcal{N}|)}\}$, where ψ is the partition or coalition structure. The partition is a set of coalitions of all players, i.e., $\bigcup_{\mathcal{S} \in \psi} = \mathcal{N}$. $D(n)$ is the Bell number [31], where n is the number of players in the game. The Bell number is obtained from

$$D(n) = \sum_{n'=0}^{n-1} \binom{n-1}{n'} D(n'), \text{ for } n \geq 1, \text{ and } D(0) = 1. \tag{29}$$

Let $Q_{\psi,\psi'}$ denote the transition probability from partition ψ to partition ψ'. We can derive the transition probability in two cases, i.e., joining and deviating (i.e., splitting).

1) Joining: For a player i that is currently in a singleton coalition (i.e., $\{i\}$), the probability that this player i will join coalition $\mathcal{S}'$ is

$$Q_{\psi,\psi'} = \prod_{i' \in \mathcal{S}' \cup \{i\}} \beta_{i'}(\psi, \psi') \tag{30}$$

for $\mathcal{S}', \{i\} \in \psi$, and $\mathcal{S}' \cup \{i\} \in \psi'$, where $\beta_{i'}(\psi, \psi')$ is the best reply rule. The joining action will be successful if the singleton coalition of player i is not externally stable and the existing

$$\begin{aligned} x_i^D(\mathcal{S}) = (1-\delta) \Bigg\langle & \sum_{t=0}^{T_0-1} \delta^t \left(\sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S}) \right) \\ & + \delta^{T_0} \left(\tau_{i \triangleleft i}(\{i\}) + \sum_{i' \in \mathcal{S} \setminus \{i\}} \tau_{i' \triangleleft i}(\mathcal{S}) \right) \\ & + \sum_{t=T_0+1}^{T_0+T} \delta^t \tau_{i \triangleleft i}(\{i\}) \\ & + \sum_{t=T_0+T+1}^{\infty} \delta^t \left(\sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S}) \right) \Bigg\rangle \end{aligned} \tag{24}$$

players i' in coalition $\mathcal{S}'$ will not receive a lower long-term payoffs if player i joins the coalition, i.e., $x_{i'}(\mathcal{S}' \cup \{i\}) \geq x_{i'}(\mathcal{S}')$. Therefore, the best reply rule is defined as follows:

$$\beta_i(\psi, \psi') = \begin{cases} \frac{\hat{\beta}_i}{|\psi|-1}, & x_i\left(\mathcal{S}' \cup \{i\}\right) > x_i\left(\{i\}\right) \\ \epsilon, & \text{otherwise} \end{cases} \quad (31)$$

$$\beta_{i'}(\psi, \psi') = \begin{cases} \hat{\beta}_{i'}, & x_{i'}\left(\mathcal{S}' \cup \{i\}\right) \geq x_{i'}(\mathcal{S}') \\ \epsilon, & \text{otherwise} \end{cases} \quad (32)$$

for $i' \in \mathcal{S}'$, where $\hat{\beta}_i$ is a constant that represents the probability that player i will perform the joining action, and ϵ is a small probability (e.g., $\epsilon = 10^{-5}$) that the player i will make an irrational action (i.e., not joining the coalition even if it yields higher long-term payoff). The denominator term $|\psi| - 1$ is the number of possible coalitions that the player i can join in partition ψ.

2) Deviating (Split): Assume that player i deviates from coalition with a probability $Q_{\psi,\psi'}$, for $i \in \mathcal{S} \in \psi$ and $\{i\}, \mathcal{S} \setminus \{i\} \in \psi'$. This deviation action will be successful if the coalition is not internally stable or all the players in the coalitions, except player i, can achieve a higher long-term payoff by excluding player i from the coalition. In this case, the transition probability is defined as follows:

$$Q_{\psi,\psi'} = \beta_i(\psi, \psi') \prod_{i' \in \mathcal{S} \setminus \{i\}} \beta_{i'}(\psi, \psi'). \quad (33)$$

In other words, if player i and the rest do not benefit from staying in the same coalition, then either of them will deviate and split from the coalition. The best reply rule here is defined as follows:

$$\beta_i(\psi, \psi') = \begin{cases} \hat{\beta}_i, & x_i^D(\mathcal{S}) > x_i(\mathcal{S}) \\ \epsilon, & \text{otherwise} \end{cases} \quad (34)$$

$$\beta_{i'}(\psi, \psi') = \begin{cases} \hat{\beta}_{i'}, & x_{i'}\left(\mathcal{S} \setminus \{i\}\right) > x_{i'}(\mathcal{S}) \\ \epsilon, & \text{otherwise} \end{cases} \quad (35)$$

for $i, i' \in \mathcal{S} \in \psi$, and $\{i\}, \mathcal{S} \setminus \{i\} \in \psi'$.

Note that, if the partition ψ' is not reachable from partition ψ via a joining or a deviating action, then we have the transition probability $Q_{\psi,\psi'} = 0$.

Let $\vec{\mathbf{q}} = [q_{\psi_1} \ \cdots \ q_{\psi} \ \cdots \ q_{\psi_{D(|\mathcal{N}|)}}]^\top$ denote a vector of stationary probability of the partitions. This vector can be obtained

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$$x_i^D(\mathcal{S}) = (1-\delta)\delta^{T_0} \left(\underbrace{\tau_{i \triangleleft i}\left(\{i\}\right) + \sum_{i' \in \mathcal{S} \setminus \{i\}} \tau_{i' \triangleleft i}(\mathcal{S})}_{\text{Payoff from deviation}} - \underbrace{\tau_{i \triangleleft i}\left(\{i\}\right)}_{\text{Payoff under punishment}} \right) + \left(\underbrace{\left(\sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S}) \right)}_{\text{Payoff from cooperation}} (1 - \delta^{T_0} + \delta^{T_0+T}) + \underbrace{\tau_{i \triangleleft i}\left(\{i\}\right)}_{\text{Payoff under punishment}} (\delta^{T_0} - \delta^{T_0+T}) \right) \quad (25)$$

$$T > \max_i \frac{\log\left(\frac{K_1}{K_2}\right)}{\log \delta} \quad (26)$$

$$K_1 = \underbrace{\left(\sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S}) \right)}_{\text{Payoff from cooperation}} - \underbrace{\tau_{i \triangleleft i}\left(\{i\}\right) + \sum_{i' \in \mathcal{S} \setminus \{i\}} \tau_{i' \triangleleft i}(\mathcal{S})}_{\text{Payoff from deviation}} + \delta \left(\underbrace{\tau_{i \triangleleft i}\left(\{i\}\right) + \sum_{i' \in \mathcal{S} \setminus \{i\}} \tau_{i' \triangleleft i}(\mathcal{S})}_{\text{Payoff from deviation}} - \underbrace{\tau_{i \triangleleft i}\left(\{i\}\right)}_{\text{Payoff under punishment}} \right) \quad (27)$$

$$K_2 = \underbrace{\left(\sum_{i' \in \mathcal{S}} \tau_{i' \triangleleft i}(\mathcal{S}) \right)}_{\text{Payoff from cooperation}} - \underbrace{\tau_{i \triangleleft i}\left(\{i\}\right)}_{\text{Payoff under punishment}} \quad (28)$$

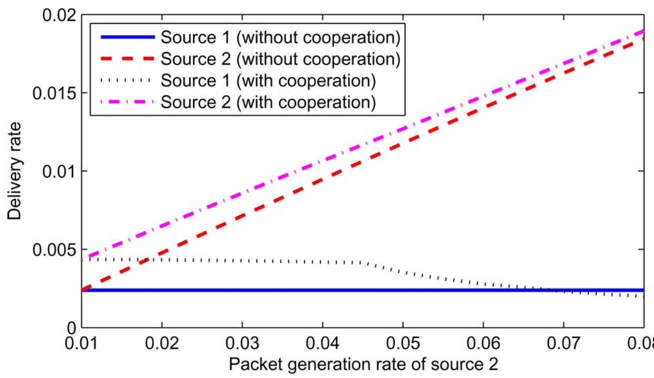

Fig. 4. Packet delivery rates of data sources 1 and 2 under different packet generation rates of data source 2.

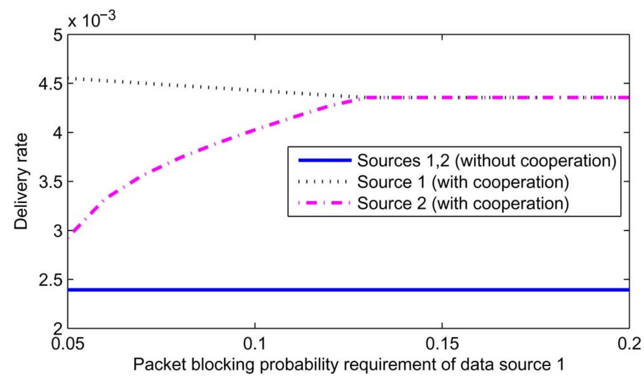

Fig. 5. Delivery rates of data sources 1 and 2 under different delivery ratio requirements of data source 1.

by solving $\vec{\mathbf{q}}^\top \mathbf{Q} = \vec{\mathbf{q}}^\top$ and $\vec{\mathbf{q}}^\top \vec{\mathbf{1}} = 1$, where $\mathbf{Q}$ is the transition probability matrix whose element is $Q_{\psi,\psi'}$.

Let the probability of making an irrational action approach zero (i.e., $\epsilon \to 0$). There could exist an ergodic set $\mathbb{E} \in \Psi$ of states ψ if $\sum_{\psi' \in \Psi \setminus \mathbb{E}} Q_{\psi,\psi'} = 0$ for $\psi \in \mathbb{E}$, and no nonempty proper subset of $\mathbb{E}$ has this property. In this regard, the singleton ergodic set is composed of absorbing states. In other words, once all mobile nodes reach the state (i.e., the partition) in the ergodic set, they will remain in this ergodic set forever. Therefore, the players in the coalitions of the partitions in the ergodic set do not have any incentive to join or deviate from the coalitions. They can be viewed as stable coalitions.

VI. Performance Evaluation

A. Parameter Settings

We consider a DTN similar to the one shown in Fig. 2. There are three data sources and three mobile nodes. Each mobile node is assigned to collect data from its associated data source. A mobile node can collect data from other data sources also if it cooperates with others. Unless otherwise stated, the data source generates a packet with probability 0.01. A mobile node has a data queue of size of five packets and energy storage of size 100 units of energy. Each mobile node visits three data sources and the gateways with identical probabilities. At the gateway, if a mobile node requests a wireless energy transfer, it will receive six units of energy from the gateway. However, if a mobile node transmits a packet, two units of energy will be consumed. At the data source, if a mobile node decides to accept a packet from the data source, one unit of energy will be used. Each mobile node transmits or receives a packet with the successful probability of 0.99.

B. Numerical Results

1) Single Mobile Node Performance: Next, we evaluate the packet delivery rate of two data sources, i.e., 1 and 2, when their mobile nodes cooperate and do not cooperate. Fig. 4 shows the delivery rate when the packet generation probability of data source 2 is varied, whereas that of data source 1 is fixed at 0.01. When mobile nodes 1 and 2 do not cooperate, the delivery rate of data source 1 remains constant and is not affected by the packet generation rate of data source 2. In contrast, the delivery rate of data source 2 increases as its packet generation probability increases. Nevertheless, when mobile nodes 1 and 2 cooperate, we observe that the delivery rates of both data sources are higher than the one achieved without cooperation. However, while the delivery rate of data source 2 increases constantly, the delivery rate of data source 1 will decrease. This is due to the fact that mobile node 1 must use more of its resources (i.e., data queue and energy) to accept, carry, and transmit the packets from data source 2. As a result, mobile node 1 has fewer resources for delivering the packets from its own data source 1. At a certain point (i.e., when the packet generation probability of data source 2 is 0.067), the delivery rate of data source 1 with cooperation with data source 2 becomes lower than the one obtained in the case without cooperation. In this case, node 1 will choose not to cooperate with node 2.

In Fig. 5, we evaluate the impact of the packet blocking probability requirement. This figure shows the delivery rates of data sources 1 and 2, when the packet blocking probability requirement of data source 1 is varied. By contrast, the data source 2 does not have such a requirement. When the packet blocking probability requirement of data source 1 decreases, mobile node 1 must reserve its resources for delivering the packets of data source 1. As a result, mobile node 1 accepts fewer packets from data source 2; hence, the packet delivery rate of data source 2 decreases. Without cooperation, the delivery rates of both data sources are not affected by the packet blocking probability requirement. However, the delivery rates are also always lower than those achieved with cooperation. Note that the packet blocking probability requirement cannot be decreased below 0.05 as it will result in an infeasible solution for the optimization.

2) Cooperation Performance: We consider three types of mobile nodes: one that cooperates, one that deviates from cooperation, and one that is punished. Fig. 6 shows the instantaneous payoff of each mobile node that cooperates and forms a coalition. Note that, in this case, for ease of explanation, we consider identical mobile nodes whose instantaneous payoffs are the same. In this figure, we consider three data sources in the same coalition. Here, we observe that, if one of the mobile nodes deviates from the coalition, this deviating node will achieve a higher instantaneous payoff than by cooperating and staying in

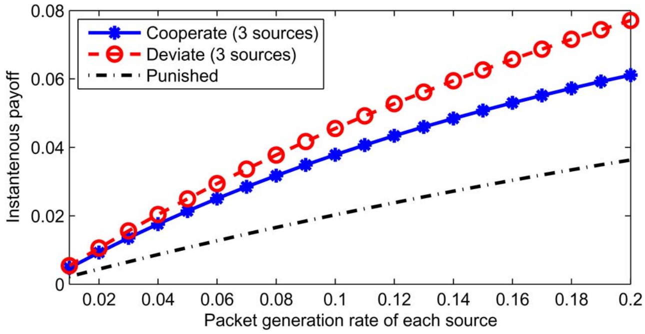

Fig. 6. Instantaneous payoffs of three mobile nodes: one that cooperates, one that deviates from cooperation, and one that is punished.

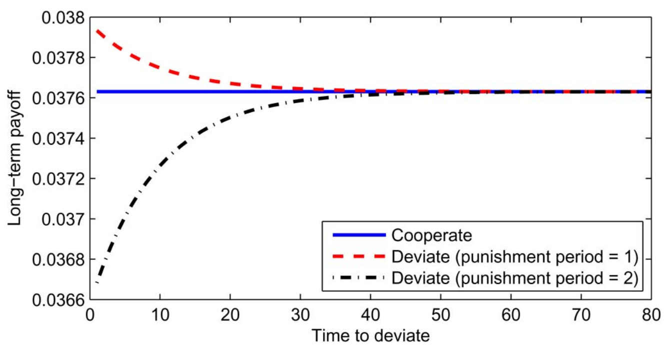

Fig. 7. Long-term payoff of a mobile node under different punishment periods.

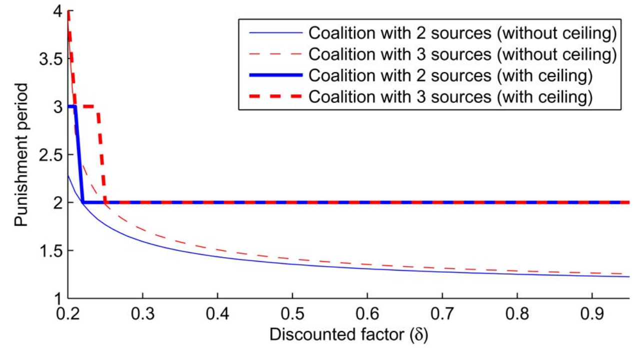

Fig. 8. Minimum punishment period to prevent deviation.

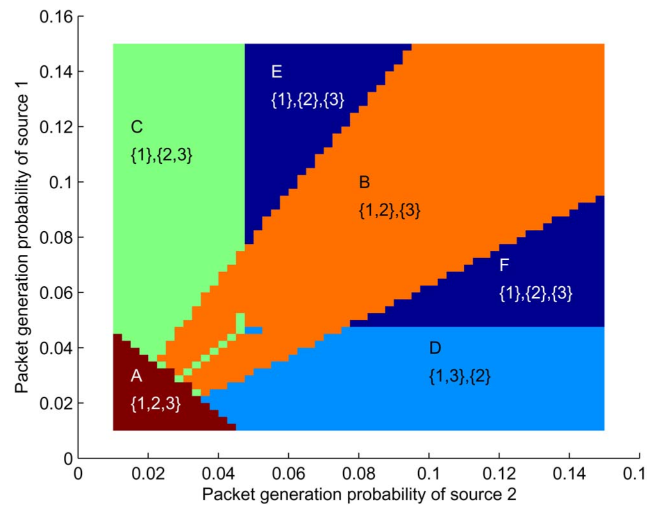

Fig. 9. Stable coalitions under different packet generation probabilities of data sources 1 and 2, whereas that of data source 3 is fixed at 0.01.

the coalition. However, if this deviating node is punished, the instantaneous payoff is the same as the payoff without cooperation, which is lower than the one achieved when the mobile node deviates or stays in the coalition. The differences between these instantaneous payoffs will determine the incentive of any mobile node to deviate and split from the coalition and the punishment period that should be applied to that deviating node so that the coalition can be stabilized.

Fig. 7 shows the long-term payoff of two mobile nodes, when the time to deviate (T_0) is varied. The discount factor is 0.9. We observe that if the punishment period is one, this punishment, applied to the deviating node, is not harsh enough (i.e., the deviating node achieves a higher long-term payoff by deviating rather than by cooperating). As a result, the mobile node will deviate from the coalition. In contrast, if the punishment period is two, the deviating node will experience a long-term payoff lower than in the case of cooperation. Consequently, the mobile node will not deviate. Clearly, the punishment period plays an important role in the coalition formation.

In Fig. 8, we show the minimum punishment period required to prevent the deviation of any mobile node in the network's coalitions. We consider two cases, i.e., two and three players. First, we observe that, as the discount factor increases, the minimum punishment period decreases. This is due to the fact that a mobile node is concerned more about its future payoff. Therefore, a severe punishment for deviation is no longer required to incentivize the mobile nodes to cooperate. Second, in a coalition having more mobile nodes (i.e., three mobile nodes), the minimum punishment period can be larger than that in a coalition having fewer mobile nodes (i.e., two mobile nodes). This stems from the fact that the deviating node can gain more by taking advantage from more innocent nodes in the coalition. Therefore, to prevent any mobile node from deviating, the punishment must be severe enough.

Then, we evaluate the stable coalitions formed by three mobile nodes. We fix the packet generation probability of data source 3 to 0.01, whereas those of data sources 1 and 2 are varied. The discount factor is set to 0.9, and the punishment period is set to 2. Fig. 9 shows the stable coalitions, which can be divided into different regions according to the packet generation probabilities of data sources 1 and 2. The different range of packet generation probabilities yields different stable coalitions whose rationale is derived from Fig. 4. As discussed for Fig. 4, the data source with a large packet generation probability can overwhelm the mobile node of the data source with a small packet generation probability. Therefore, a mobile node serving the data source with a small packet generation probability will not cooperate with the nodes serving the data source with a large packet generation probability. Based on the regions named A, B, C, D, E, and F in Fig. 9, we make the following observations:

- *Region A*: In this region, the packet generation probabilities of all the data sources are relatively small. Therefore, all of them will tend to cooperate as none of them can take advantage of other mobile nodes. Therefore, the stable coalition is the grand coalition $\{1, 2, 3\}$.

- *Region B*: In this region, the packet generation probabilities of data sources 1 and 2 are much larger than that of data source 3. Therefore, data source 3 will not cooperate and form a coalition with data sources 1 and 2. In contrast, data sources 1 and 2 can help each other as their packet generation probabilities are not much different. Therefore, the stable coalitions are {1, 2},{3}.
- *Region C*: In this region, data source 1 generates much more packets than data sources 2 and 3. Therefore, mobile nodes 2 and 3 will form a coalition (i.e., the stable coalitions are {1},{2, 3}).
- *Region D*: Unlike Region C, in Region D, data source 2 generates much more packets than data sources 1 and 3. Therefore, the stable coalitions are {1, 3},{2}.
- *Region E*: In this region, data source 1 generates much more packets than data source 2, and they generate much more packets than data source 3. Therefore, none of them will cooperate, and the stable coalitions are all singleton coalitions, i.e., {1},{2},{3}.
- *Region F*: Similar to Region E, data source 2 generates much more packets than data source 1, and they generate much more packets than data source 3. Therefore, none of them will cooperate, and the stable coalitions are {1},{2},{3}.

From the above performance evaluation, we make the following important observations.

- A mobile node can choose a different action based on its connectivity. If a mobile node is connected to the gateway, this node can either transmit the packet waiting in its data queue or request wireless energy transfer to fill its energy storage. This action depends on the current number of packets in the queue and on the energy level of the energy storage. If a mobile node is connected with a data source, the node will accept the packet from this data source based on the packet blocking probability requirement. For example, a mobile node can accept most of the packets from its own data source while selectively accepting the packets from other data sources.
- The system parameters (e.g., packet generation rate) can affect the packet delivery rate of the mobile nodes. This impact is very important, particularly when the mobile nodes cooperate to deliver packets for each other's data sources. There exists a chance that the mobile nodes will not cooperate if their data sources generate packets with significantly different rates. The resources of a mobile node, in terms of queue space and energy, can be overwhelmed by the data source with high packet generation rate.
- Although mobile nodes can decide to cooperate and form a coalition, some selfish nodes may take advantage of other innocent nodes and quietly deviate from the coalition. Such selfish nodes instantaneously gain the benefit of the other nodes' help without reciprocating this help.
- The innocent nodes can punish a deviating node by not helping it. The punishment period can be adjusted to ensure that none of the nodes has an incentive to deviate.
- The stable coalitions can be determined, depending on the packet generation rate. The proposed analytical and optimization model for the packet delivery service in DTNs and the repeated coalition formation game model can be applied to analyze these stable coalitions.

VII. Conclusion

In this paper, we have considered a DTN whose mobile nodes seek to collect packets from their associated data sources and deliver them to a sink (i.e., a gateway). In such a network, the mobile nodes can harvest wireless energy transferred from the gateway. The mobile nodes can also cooperate to help collect the packets from each other's data sources. We have addressed two major issues in such a network. First, we have formulated an optimization model to derive the optimal policy for each mobile node. This optimal policy determines whether a mobile node will accept a packet from the data source or not and whether it will request wireless energy transfer or, instead, transmit its packet to the gateway. The objective is to maximize the delivery rate of the packets from data sources, given that the packet blocking probability requirement is met. Second, we have introduced a repeated coalition formation game model to capture the cooperation strategies of the mobile nodes. In this game, the mobile nodes decide to help each other based on the long-term payoff rather than the instantaneous payoff. The long-term payoff depends on deviations and punishments. We have provided extensive performance evaluation that clearly showed the benefits of the proposed framework and the properties of the stable coalitions that can potentially form in a DTN.

For future work, we will consider multihop communication between multiple mobile nodes. Moreover, the deviation of multiple nodes from a coalition will be analyzed.

Appendix A
Transition Probability Matrix

We derive the transition probability matrix for the CMDP optimization model. There are three major steps. First, we derive the energy state transition matrix for all four actions. Then, this energy state transition matrix is used to construct the transition matrix with queue state transition. Finally, the transition matrix of the energy and queue states is used to construct the transition matrix with location transition for all actions.

Step 1: Energy State Transition

If a mobile node is at a location having a gateway, and it decides to request wireless energy transfer, the energy level of its energy storage will increase by K units and be bounded by the energy storage capacity B. Let $\mathbf{B}_K$ denote the probability matrix of this case. It can be expressed as follows:

$$\mathbf{B}_K = \begin{bmatrix} 0 & \cdots & 1 & & \\ & & & \ddots & \\ & & & & 1 \\ & & & & \vdots \\ & & & & 1 \end{bmatrix} \begin{matrix} \leftarrow b = 0 \\ \vdots \\ \leftarrow b = B - K \, . \\ \vdots \\ \leftarrow b = B \end{matrix} \qquad (36)$$

In contrast, if a mobile node transmits a packet to the gateway when the energy level is higher than or equal to J, the energy level will decrease by J units. Otherwise, the energy level will remain the same. Let $\mathbf{B}_J$ denote the probability matrix of this case. It can be expressed as follows:

$$\mathbf{B}_J = \left[\begin{array}{cccc} 1 & & & \\ & \ddots & & \\ & & 1 & \\ \hline 1 & & & \\ & \ddots & & \\ & & 1 \cdots & 0 \end{array}\right] \begin{array}{l} \leftarrow b = 0 \\ \vdots \\ \leftarrow b = J-1 \\ \leftarrow b = J \\ \vdots \\ \leftarrow b = B. \end{array} \quad (37)$$

Similarly, if a mobile node receives a packet from a data source when the energy level is higher than or equal to $\hat{J}$, the energy level will decrease by $\hat{J}$ units. Otherwise, the energy level will remain the same. This transition matrix is denoted $\mathbf{B}_{\hat{J}}$, which is similar to $\mathbf{B}_J$, except that the energy level decreases by $\hat{J}$ at row $b = \hat{J}$. Therefore, we omit showing this matrix for brevity. Finally, if the mobile node remains idle, the energy level will remain the same. Therefore, the transition matrix is basically an identity matrix $\mathbf{I}$.

Step 2: Queue State Transition

Then, we combine energy state and queue state transitions. If a mobile node is at a location with a gateway and the node decides to transmit a packet, then the number of packets may decrease, and the energy level decreases by J units. Let $\mathbf{Q}_-$ denote the transition matrix of this case. It can be expressed as follows:

$$\mathbf{Q}_- = \begin{bmatrix} \mathbf{I} & & & \\ \mathbf{T}^s\mathbf{B}_J & \mathbf{T}^u\mathbf{B}_J & & \\ & \ddots & \ddots & \\ & & \mathbf{T}^s\mathbf{B}_J & \mathbf{T}^u\mathbf{B}_J \end{bmatrix} \begin{array}{l} \leftarrow q = 0 \\ \leftarrow q = 1 \\ \vdots \\ \leftarrow q = Q \end{array} \quad (38)$$

where $\mathbf{T}^s$ and $\mathbf{T}^u$ are the probability matrices of successful and unsuccessful packet transmission to the gateway, respectively. The elements of $\mathbf{T}^s$ and $\mathbf{T}^u$ at row b and column b', which correspond to the energy levels, are denoted by $T^s_{b,b'}$ and $T^u_{b,b'}$, and they are obtained from

$$T^s_{b,b'} = \begin{cases} \mu, & J \le b = b' \le B \\ 0, & \text{otherwise} \end{cases} \quad (39)$$

$$T^u_{b,b'} = \begin{cases} 1, & 0 \le b = b' < J \\ 1-\mu, & J \le b = b' \le B \\ 0, & \text{otherwise} \end{cases} \quad (40)$$

for $b = 0, 1, \ldots, B$. In this case, if a mobile node has an energy level less than J, it cannot transmit a packet; hence, the number of packets in the queue remains the same (i.e., the case $0 \le b = b' < J$ of $T^u_{b,b}$). Otherwise, the number of packets will decrease by one with the probability of μ, which is the successful packet transmission probability (i.e., the case $J \le b = b' \le B$ of $T^u_{b,b}$).

If a mobile node is at a location with a data source, and this node decides to accept a packet from the data source, then the number of packets may increase, and the energy level decreases by $\hat{J}$ units. Let $\mathbf{Q}_+$ denote the transition matrix of this case. It can be expressed as follows:

$$\mathbf{Q}_+ = \begin{bmatrix} (1-\alpha)\mathbf{B}_{\hat{J}} & \alpha\mathbf{B}_{\hat{J}} & & \\ & \ddots & \ddots & \\ & & (1-\alpha)\mathbf{B}_{\hat{J}} & \alpha\mathbf{B}_{\hat{J}} \\ & & & \mathbf{I} \end{bmatrix} \begin{array}{l} \leftarrow q = 0 \\ \vdots \\ \leftarrow q = Q-1 \\ \leftarrow q = Q \end{array} \quad (41)$$

where α is the probability of packet arrival at the mobile node from the data source.

If a mobile node requests for wireless energy transfer from the gateway, the number of packets remains the same, and the energy level increases by K units. Let $\mathbf{Q}_o$ denote the transition matrix of this case. It can be expressed as follows:

$$\mathbf{Q}_o = \begin{bmatrix} \mathbf{B}_K & & \\ & \ddots & \\ & & \mathbf{B}_K \end{bmatrix}. \quad (42)$$

If a mobile node decides to do nothing, there is no change for the queue and energy states. Therefore, the transition matrix is basically the identity matrix $\mathbf{I}$ with the size of $(Q+1)(B+1) \times (Q+1)(B+1)$.

Step 3: Location State Transition

Next, we combine the location state with the energy and queue state transitions. The transition probability matrix is denoted as $\mathbf{P}(\omega)$ for action ω. For the action $\omega = 0$ (i.e., the mobile node does nothing), the transition matrix is denoted by $\mathbf{P}(0)$ whose element is $m_{l,l'}\mathbf{I}$, where $\mathbf{I}$ is the identity matrix with the size of $(Q+1)(B+1) \times (Q+1)(B+1)$. This indicates that there is no change to the queue and energy states.

For the action $\omega = 1$ (i.e., the mobile node requests for wireless energy transfer from the gateway), the transition matrix $\mathbf{P}(1)$ has the element of $m_{l,l'}\mathbf{Q}_o$ for $l \in \mathcal{L}_G$ (i.e., the mobile node must be at the location with the gateway so that the energy level can increase by K units). Otherwise, the element of $\mathbf{P}(1)$ is $m_{l,l'}\mathbf{I}$ for $l \notin \mathcal{L}_G$.

For the action $\omega = 2$ (i.e., the mobile node transmits a packet to the gateway), the transition matrix $\mathbf{P}(2)$ has the element of $m_{l,l'}\mathbf{Q}_-$ for $l \in \mathcal{L}_G$ (i.e., the mobile node must be at the location with the gateway so that it can transmit a packet). Otherwise, the element of $\mathbf{P}(2)$ is $m_{l,l'}\mathbf{I}$ for $l \notin \mathcal{L}_G$.

For the action $\omega = 3$ (i.e., the mobile node receives a packet from the data source), the transition matrix $\mathbf{P}(3)$ has the element of $m_{l,l'}\mathbf{Q}_+$ for $l \in \mathcal{L}_S$ (i.e., the mobile node must be at the location with the data source so that it can accept a packet). Otherwise, the element of $\mathbf{P}(3)$ is $m_{l,l'}\mathbf{I}$ for $l \notin \mathcal{L}_S$.

Appendix B
Trigger Punishment Scheme

We can consider the *trigger* punishment scheme for the players who deviate from a coalition. Again, for the internal stability, we assume that one player may deviate at a time. The condition for internal stability of the coalition $\mathcal{S}$ is that $x_i(\mathcal{S}) > x_i(\{i\})$ for all $i \in \mathcal{S}$. The long-term payoff when the

$$x_i^D(\mathcal{S}) = (1-\delta)\left\langle \sum_{t=0}^{T_0-1} \delta^t \left(\sum_{i'\in\mathcal{S}} \tau_{i'\triangleleft i}(\mathcal{S})\right) + \delta^{T_0}\left(\tau_{i\triangleleft i}(\{i\}) + \sum_{i'\in\mathcal{S}\setminus\{i\}} \tau_{i'\triangleleft i}(\mathcal{S})\right) + \sum_{t=T_0+1}^{\infty} \delta^t \tau_{i\triangleleft i}(\{i\}) \right\rangle \tag{43}$$

$$x_i^D(\mathcal{S}) = (1-\delta)\delta^{T_0}\left(\underbrace{\tau_{i\triangleleft i}(\{i\}) + \sum_{i'\in\mathcal{S}\setminus\{i\}} \tau_{i'\triangleleft i}(\mathcal{S})}_{\text{Payoff from deviation}} - \underbrace{\tau_{i\triangleleft i}(\{i\})}_{\text{Payoff under punishment}}\right) + \left(\underbrace{\left(\sum_{i'\in\mathcal{S}} \tau_{i'\triangleleft i}(\mathcal{S})\right)}_{\text{Payoff from cooperation}} (1-\delta^{T_0}) + \underbrace{\tau_{i\triangleleft i}(\{i\})}_{\text{Payoff under punishment}} \delta^{T_0}\right) \tag{44}$$

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player i and other players are in the coalition $\mathcal{S}$ can be obtained from (23). If the player i deviates from the coalition $\mathcal{S}$ at time period T_0, the long-term payoff will be as in (43), which can be expressed in a closed form, as shown at the top of the page.

The coalition $\mathcal{S}$ will be internally stable if the long-term payoff of staying in the coalition is larger than that of deviation, i.e., $x_i(\mathcal{S}) > x_i^D(\mathcal{S})$ for all $i \in \mathcal{S}$. In this case, we can determine the minimum value of the discount factor δ such that the internal stability condition is met. The condition is

$$\delta > \frac{\tau_{i\triangleleft i}(\{i\}) + \sum_{i'\in\mathcal{S}\setminus\{i\}} \tau_{i'\triangleleft i}(\mathcal{S}) - \sum_{i'\in\mathcal{S}} \tau_{i'\triangleleft i}(\mathcal{S})}{\tau_{i\triangleleft i}(\{i\}) + \sum_{i'\in\mathcal{S}\setminus\{i\}} \tau_{i'\triangleleft i}(\mathcal{S}) - \tau_{i\triangleleft i}(\{i\})}. \tag{45}$$

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