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# Stochastic Game Theoretical Model for Packet Forwarding in Relay Networks

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**Abstract** In this article, a new game theoretical method is proposed to model packet forwarding in relay networks. A simple case of relay network that consists of a source, a relay and a destination node communicating on a common channel is considered. A stationary Markovian game model is utilized to optimize the system performance in terms of throughput, delay and power consumption cost. Both cooperative and non-cooperative solutions are provided for this model. Best strategy set taken by players as well as system performance is studied for different system parameters. Also, the proposed method is extended to model a more general case of Ad-hoc networks considering different packet error rates in case of collision occurrence that improves the system performance further.

Simulation results show that performance of the non-cooperative solution, in which players do not require to know each other's selected strategy, asymptotically approaches the cooperative system performance. Hence, the proposed model with non-cooperative solution is an appropriate method to apply in practical Ad-hoc networks.

**Keywords** Relay networks · Game theory · Packet forwarding · Stochastic stationary games · Multiple-access channels

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## 1 Introduction

In Ad-hoc networks, when several transmitters randomly attempt to access a finite number of resources, collision is unavoidable. For instance, simultaneous attempts to access a multiple-access channel produce interference and degrade the system performance in terms of achievable throughput. Optimizing system throughput is still one of the challenging issues in wireless Ad-hoc networks. There are various researches to evaluate system performance due to noise and interference level in wireless systems [1, 2].

Moreover, each node in addition to transmitting its own packets, is supposed to cooperate with other nodes to forward their packets to the destination. This relaying operation, called cooperative diversity, increases system throughput by providing spatial diversity benefits without using an extra antenna array [3]. Although this might result in consuming the limited energy available at each node, but refusing to forward other nodes' packet decreases the network throughput. Study of different relaying methods to achieve high performance in terms of throughput and channel efficiency is an important issue in Ad-hoc networks.

Game theory has been widely used to analyze wireless Ad-hoc networks, due to selfish behavior of the nodes as well as distributed nature of these systems [4–6]. Game theoretical approach is a proper method to model the packet forwarding in Ad-hoc networks. It can be used to analyze the trade off between nodes' interest to avoid forwarding others' packets due to limited power versus providing relay service in order to increase the system throughout [7–9]. Utilizing game theory maximizes the overall system performance considering different desired goals such as maximum throughput and minimum delay requirements as well as low power consumption cost and implementation simplicity.

Repeated game theory is considered to analyze cooperative packet forwarding in [10–13]. In these games, players interact with each other in consecutive stages considering others' actions in previous rounds of the game. Therefore, they can be encouraged to cooperate with each other by using incentive mechanisms such as reputation algorithms. Markov games are also applied to address this issue in Ad-hoc networks. In these games, actions of players are determined based on the current state of the game, instead of considering the complete game history.

In [14], Markov stationary game theory is applied to model the competition between nodes in a basic relay network, where the relay node has one buffer to keep all different types of packets. In addition, the relay node rejects the received packet from source node whenever there is a packet in its transmit buffer. This means that when the source node attempts to send a packet via the relay node to the destination, this packet is rejected by the relay node, if there is a packet in its transmit queue. Therefore, source node's packet will remain at source node queue and the channel remains unused, although there is no collision. This results in lower system throughput performance, which is not desirable in practical applications.

In this paper, we investigate this problem proposing three solutions. In the proposed models, two different buffers are assigned to the relay node to keep its own packets and the received packets from the source node separately, and to apply an appropriate transmission strategy for each buffer. This solution provides the relay node with the option of accepting packets from the source node even if it has a packet in its transmit queue.

Two Markovian stationary game solutions are proposed to model packet forwarding in multiple-access channels, in which simultaneously transmitted packets are dropped. In the first solution, the relay node is assumed to be reliable in the sense that, it transmits the received packets from the source node in the next time slot, even if it has its own packets in the transmit queue. This model, named as *reliable relaying method* is more efficient in terms of channel use, compared to the prior works reported in [14].

In the second solution, another relaying approach is proposed where the relay node can decide to transmit either its own packet or the received packet from source node, when both are in the queue. The advantage of this solution, which is called *flexible relaying method* is that a more flexible strategy is utilized to forward the packets in the relay node.

The third solution covers a more general case of multiple-access channels, where both simultaneously transmitted packets are not discarded. Interference is not avoidable in most of applications, but it does not necessarily cause packet loss. The packet loss depends on several parameters, specially on the level of interference. For instance, in Code Division Multiple Access (CDMA) systems, the receiver captures the desired packet from a number of simultaneously interfering packets using orthogonality of the codes. Even, in a multiple-access slotted ALOHA system, not any collision results in a packet loss [15]. A novel stochastic game theoretical model is proposed to provide a case in which one of the collided packets can be captured based on physical layer parameters.

The first solution is suitable for applications where the main goal is transmitting the source node's packets to the destination. Therefore, the relay node assigns a higher priority to the received packets from source node. While the second solution is applicable in homogeneous systems where both nodes have the same priority to transmit their packets. In this method, the relay node selects a proper strategy to maximize its utility considering the game conditions, which provides a better performance, specially when the relay node has a high packet generation rate.

For the proposed Markovian game theoretical models, state of the game is defined as the number of packets in source and relay nodes' buffers. In all the proposed solutions, it is assumed that this parameter is broadcasted by the nodes on a common channel such that the state of game is known for all players. This assumption makes the proposed solutions applicable to decentralized Ad-hoc networks, becuase there is no need to have a central station to control the network and each node can independently select its best strategy set considering the game conditions.

The rest of this paper is organized as follows. Stochastic game theory is studied in Sect. 2. System model of the proposed relay network is presented in Sect. 3. Reliable relaying method is discussed in Sect. 4. In this section, the corresponding game definitions consisting of available action sets of each node, state transition matrix and utility functions of players are defined. In Sect. 5, a flexible relaying method is developed. The third scenario is specified in Sect. 6. Numerical results for the proposed models are presented in Sect. 7, followed by conclusion in Sect. 8.

## 2 Stochastic Games

In this section, a brief introduction to game theory is presented. A Markovian game theoretical model which is the basis of our proposed analysis model, is studied in more depth.

Game theory is an analytical approach to model the interactions between some rational players that compete to obtain a common interest. It also provides a mathematical method to find the best possible strategy for each player [16,17]. Each game is represented by $(N, \{S_i\}, \{U_i\})$, $i \in N$, where

- $N$ is a set of players.
- $\{S_i\}$ is strategy set of player $i$, and $s_i \in S_i$, a strategy of player $i$.
- $\{U_i\}$ is utility function of player $i$.

Strategy set defines players' behavior facing different situations in the game, including pure and mixed strategies. Pure strategies show the deterministic actions of players in different situations and mixed strategies describe the probability of selecting a pure strategy that provides a chance of choosing one of the available actions, in random. Strategy profile of the game is denoted as $S$, with $S = S_1 \times S_2 \times \ldots \times S_N$, where $S_i$ is the strategy set of player $i$.

Solution of the game achieves the Nash equilibrium strategy set of all players when each rational player selects its best possible response to other players' strategies, provided that neither player can increase its utility by unilaterally changing its strategy. A strategy profile, $S^*$ achieves Nash equilibrium iff,

$$\forall i \in N,\ \forall s_i \in S_i,\ U_i(s_i^*,\ s_{-i}^*) \geq U_i(s_i,\ s_{-i}^*) \tag{1}$$

where, $s_{-i}$, denotes the strategy profile of all players except player $i$.

In one-stage game, each selfish player decides to maximize its own utility. In this case, it is not possible to enforce players to cooperate with each other. In repeated games, game is played several times and in each round, the actions and outcomes of previous rounds are observable. Considering the current reputation of players, they can be encouraged to cooperate with each other. In Markov games, instead of considering the complete history of the game, agents' actions are based on the current state of the game. A Markov game can be modeled with a $n \times n$ state transition matrix, denoted by $T$, where $n$ represents the number of states. Each element of this matrix, $p_{ij}$ shows the probability of moving from state $i$ in time $n$ to state $j$ in time $n+1$, where $p_{ij} \geq 0, \forall i, j$, and $\sum_{j=1}^{n} p_{ij} = 1, \forall i$.

Class of stochastic games first introduced in [18]. In these games, complete history of the game in each round is summarized in a state, that follows a Markov process. Hence, the current state and the action profile of players determine the next state [19,20].

A discrete time stochastic game with $N$ player is shown by $(Q,\ \{A_i\}_{i=1}^{N}, \{U_i\}_{i=1}^{N}, t)$, where

- $Q$, is the Borel state space.
- $A_i$, is the action set of player $i$, and $A = A_1 \times \ldots \times A_N$, denotes the action profile of all players.
- $U_i :\ Q \times A \to \mathbb{R}$, where $\mathbb{R}$ is Real set. $U_i$ determines the immediate utility function of player $i$, which depends on the current state and the action profile of the game.
- $t :\ Q \times A \to [0, 1]$, is the transition probability function.

In these games, the action set of players in time slot $n$ is denoted by $A^n$, where $A^n \in A$. Action set $A^n$ is a function of the current state of the game $q^n$, ($q^n \in Q$). Next state is specified by the current state, $q^n$ and the selected action sets by player in current time slot, $A^n$. Transition function $T(q^{n+1}|q^n, A^n)$, determines the transition probability from state $q^n$ to state $q^{n+1}$. In this time slot, the immediate utility of player $i$ is a function of the game action profile and the current state of the game, therefore $U_i^n = f(A^n,\ q^n)$.

History of the game in the $n^{th}$ time slot is defined as a sequence of the current state of the game, all the previous states, and action profiles of the game that are observable by all players and is denoted as,

$$h^n = (\ q^0,\ A^0,\ q^1,\ A^1,\ q^2,\ A^2, \ldots,\ q^{n-1},\ A^{n-1},\ q^n) \tag{2}$$

where it is assumed that the game is started at state $q^0$ in time $n = 0$. Strategy profile of the game in the $n^{th}$ time slot, is denoted as,

$$S = (S_1,\ S_2, \ldots, S_N) \tag{3}$$

As mentioned before, in mixed strategy games, strategy profile describes the probability of choosing action profile $A = (A_1,\ A_2,\ \ldots,\ A_N)$ by the players.

If $P_{q^0}^S$ determines the probability distributions of game over the action profile and states of the whole game history, for any strategy profile $S$ and any initial state $q^0$, the expected time averaged payoff of player $i$ is defined as follows [20],

$$U_i(S, q^0) = \lim_{T\to\infty} \frac{1}{T} E_{q^0}^S [\sum_{n=1}^{T} U_i^n(A^n, q^n)] \tag{4}$$

where $E_{q^0}^S[\,]$ is the expectation operation over the probability distribution $P_{q^0}^S$.

A strategy is called stationary if the strategy profile of the game in the $n^{th}$ time slot shown by $(S^n)$ only depends on the current state of the game, rather than on the complete game history. The stationary strategy profile of all players is denoted by $\delta = (\delta_1,\ \delta_2, \dots,\ \delta_N)$. Notation $\Pi(\delta)$ represents the stationary probability distribution over states, such that $\Pi(\delta) = \Pi(\delta) \times T(\delta)$, where $T(\delta)$ is the state transition matrix and $\times$ denotes matrix multiplication. For example $\Pi_k(\delta)$ determines the stationary probability of the $k^{th}$ state.

In the stationary case, instead of time averaged expectation, the expectation over state distribution is applicable, hence the stationary utility function of player $i$ is driven as follows,

$$U_i(\delta) = \sum_{q_k \in Q} \Pi_k(\delta) E[U_i(q_k, \delta)] \tag{5}$$

where $E[U_i(q_k, \delta)]$ is the expected utility of player $i$ in the $k^{th}$ state over the stationary strategy $\delta$.

In Markov stationary games, a stationary strategy profile, $\delta^*$ is Nash equilibrium for any initial state, $q^0$ iff,

$$\forall i \in N,\ U_i(q^0, \delta_i^*,\ \delta_{-i}^*) \geq U_i(q^0, \delta_i,\ \delta_{-i}^*) \tag{6}$$

It is proved in [16] that a stochastic game with finite number of states and actions has a Nash equilibrium. In this paper, a two-player Markov game with finite number of states and finite number of possible actions for each player is defined to model the packet forwarding in a basic relay network. Both cases of non-cooperative and cooperative games are considered in this study. In non-cooperative games, each player $i$ selfishly maximizes its own stationary utility function, $U_i(\delta)$ to reach the best response Nash equilibrium strategies, based on (5),(6). While in cooperative games, players collaborate with each other to jointly maximize the total utility of the game.

## 3 System Model

In this paper, a basic relay network which consists of a source node, a relay node and a destination node is considered, as depicted in Fig. 1. The source node can either send its packet directly to the destination or to the relay node to be forwarded to the destination. The relay node can either accept the received packet or reject it. It also may transmit its own packet or forward the previously received packet to the common destination. The study of algorithms to find the best relay node from available intermediate nodes is out of the scope of this article and it is assumed that the best relay node is already selected considering energy efficiency, path length and link quality.

In the proposed model, it is assumed that source and relay nodes share the same channel to transmit their packets to the destination and simultaneous transmission results in collision. Source and relay nodes attempt to transmit their packets randomly based on slotted ALOHA protocol. Moreover, it is assumed that both source and relay nodes broadcast the number of packets in their buffers at the end of each time slot. Also the broadcast information includes the delivery status of the packets as well as the channel quality. This assumption enables transmitters to adjust their transmit power to ensure successful packet delivery to the destination when no collision occurred. Therefore, packets leave the transmit buffer after successful transmission with appropriate power level. In the case of packet transmission failure in any time slot, packets remain in the buffer until they are transmitted in the next time slots by an Automatic Repeat-reQuest (ARQ) retransmission protocol.

The system is modeled as a two-player game, including source and relay nodes, denoted by $S$ and $R$, respectively. The source node has a single transmit buffer to keep the generated packets prior to sending and the relay node has two transmit buffers, all of which lengths are equal to one. The first buffer of relay node is called *internal buffer* and contains the generated packets at the relay node. The second one is called *forward buffer*, which contains the received packets from the source node in the previous time slots. Packets are generated at source and relay nodes independently by rates $g_s$ and $g_r$, respectively provided that their buffers are empty at the end of the previous time slot. The system is modeled as a Markovian stationary process, in which occupancy status of buffers is defined as the state of the Morkovian game. The buffer occupancy has two possible states that is either empty or full. Therefore, the

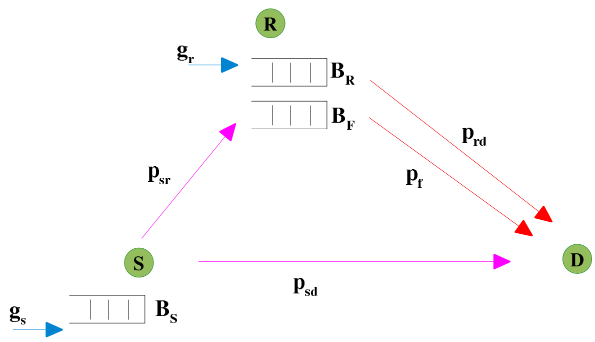


**Fig. 1** System model for the proposed relay network, where $S$, $R$ and $D$ represent source, relay and destination nodes, respectively.

total number of states is $2^3 = 8$. State of the game is defined as $\{B_S,\ B_R,\ B_F\}$, where the elements represent number of packets in the source buffer, the relay node internal buffer and the relay node forward buffer, respectively.

The proposed game is modeled as a complete information game, where each player knows the current state and available action sets as well as the outcomes of actions for all the players. Therefore, each of the two players are aware of all the possible actions of the other player and the corresponding utility of each action. Moreover, considering the information provided by the broadcast channel, both players can observe the current state of the game in each time slot that is defined by the number of packets in the buffers. However, they are not aware of the selected action by the other node. For instance, they do not know whether their opponent attempts to send its packet or not, therefore in each time slot, they select their actions based on the game status, including current state, packet transmit energy, packet arrival rate, as well as cooperation reward regardless of the action actually taken by the other node.

In the rest of this paper, three different relaying methods are proposed. In the first two methods, a scenario is considered where simultaneous packet transmission ends up with packet failure, but in the third method, a more general case where one of the simultaneously transmitted packets can be captured at the destination is considered taking into account the channel conditions and the signal power.

## 4 Reliable Relaying Method

The first approach in this article is to utilize the proposed system model in a reliable relay network, in which it is assumed that the relay node can behave selfishly, but it is neither a malicious player nor an unreliable player. This means that the relay node might reject the packet sent by the source node, but it never drops the accepted packet from the source. Moreover, the reliable relaying approach is considered such that the relay node certainly transmits the accepted packet in the next time slot even if there is a generated packet in its internal buffer.

### 4.1 Strategy set of players for reliable relaying method

In this section, possible action sets of players are described. When the transmit buffer of source is occupied, the source node takes one of the three possible actions, including (i) sending the packet directly to the destination, (ii) relaying it to the relay node and (iii) waiting. These possible actions of source node are denoted by vector $(S_{sd}, S_{sr}, W_s)$. Similarly, the action set of relay node is shown by vector $(S_{rd}, S_f, W_r, A_f, R_f)$, where the parameters are (i) sending its own packet to the destination, (ii) forwarding the source packet, (iii) waiting, (iv) accepting a packet from the source node and (v) rejecting it, respectively.

The mixed stationary strategies of players is defined as the probability distribution of the available actions. Strategy space of source node is denoted by $(p_{sd},\ p_{sr},\ p_{sw})$, where

- $p_{sd}$, is the probability of sending a packet from the source node to the destination node.
- $p_{sr}$, is the probability of sending a packet from the source node to the relay node.
- $p_{sw}$, is the probability of waiting at source node.

Source node selects one of the three available actions, therefore summation of these probabilities is one and two of them completely define strategy set of the source node. Strategy set of the relay node is denoted by vector $(p_{rd},\ p_f,\ p_{rw},\ p_{ac},\ p_r)$, which consists of probabilities of different actions taken by the relay node including,

- $p_{rd}$, probability of sending a packet from the relay node to the destination.
- $p_f$, probability of forwarding the received packet to the destination.
- $p_{rw}$, probability of waiting at the relay node.
- $p_{ac}$, probability of accepting the received packet from the source node.
- $p_r$, probability of rejecting the received packet from the source node.

Since a reliable relaying is desired, relay node certainly transmits the packet in its forward queue, which means $p_f = 1$ for states $\{(0,0,1),\ (0,1,1),\ (1,0,1)$ and $(1,1,1)\}$, and $p_f = 0$ for other states. As a result, probability of forwarding a packet by the relay node is completely determined by the state of the game. When there is a packet in the forward buffer, the relay node does not accept a packet from the source node. When the forward buffer is empty, the relay node can either transmit its own packet if there is any or wait. Similar to the above justification for the source node, the equations $p_{rd} +\ p_f +\ p_{rw} = 1$, and $p_{ac} +\ p_r = 1$ can be written for the relay node as well. $p_f$ is already specified by the state of the game, therefore, $(p_{rd},\ p_{ac})$ can be selected to present the strategy set of relay node. Consequently, mixed stationary strategy profile of the game is determined by $\delta = (p_{sd},\ p_{sr},\ p_{rd},\ p_{ac})$.

It is noticed that in complete information games, players are aware of the current state of the game and the possible action sets of their opponents in different

**Table 1** Strategy set of players for reliable relaying method

| Current State of the Game $(B_S, B_R, B_F)$ | Strategy Set of Players $(p_{sd}, p_{sr}, p_{rd}, p_{ac})$ |
|---|---|
| $S_1 = (0, 0, 0)$ | $(0, 0, 0, p_{ac})$ |
| $S_2 = (0, 0, 1)$ | $(0, 0, 0, 0)$ |
| $S_3 = (0, 1, 0)$ | $(0, 0, p_{rd}, p_{ac})$ |
| $S_4 = (0, 1, 1)$ | $(0, 0, 0, 0)$ |
| $S_5 = (1, 0, 0)$ | $(p_{sd}, p_{sr}, 0, p_{ac})$ |
| $S_6 = (1, 0, 1)$ | $(0, 0, 0, 0)$ |
| $S_7 = (1, 1, 0)$ | $(p_{sd}, p_{sr}, p_{rd}, p_{ac})$ |
| $S_8 = (1, 1, 1)$ | $(0, 0, 0, 0)$ |

states. When there is a packet in the relay node's forward buffer, the source node realizes that it would be sent by relay node, so if the source node attempts to transmit its own packet, both packets will be blocked on the channel due to collision. In this case, to avoid collision and reduce energy consumption by both nodes, a cooperative response is assigned to the source node, such that it waits, no matter there is a packet in its own queue or not.

According to the above terminology and assumptions, the mixed strategy sets of nodes regarding the current state of the game is summarized in table 1.

### 4.2 State transition probability matrix for reliable relaying method

Transition matrix specifies the transition probability between states. Transition probability from state $i$ to $j$ in consecutive time slots is denoted as $T_{ij}(\delta), i, j \in \{1, ..., 8\}$.

According to the defined states and the strategy sets of players, the state transition matrix, $T(\delta)$ is provided in Appendix A. For example, the seventh row of the state transition probability matrix for the proposed game is presented in Fig. 2.

### 4.3 Expected payoff function of players

Payoff function of players are defined as the difference between the obtained rewards and paid costs for a specific strategy set. As mentioned in Sect. 2, in stationary Markovian games, the expected value of utility over the state distribution is defined as the utility function of each player.

The assigned costs and rewards to different possible actions are based on the following rules.

Each node receives the delivery reward, denoted by $R^d$, for successful delivery of a packet to the destination node. Basically, a selfish relay node intends to transmit its own packet and avoids cooperation by rejecting the

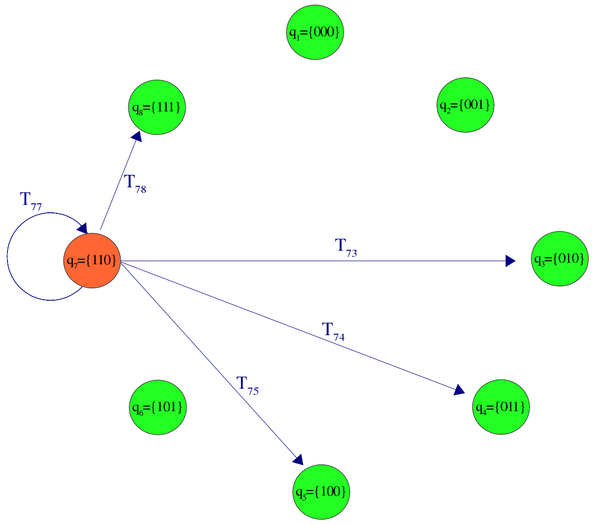


**Fig. 2** State diagram representing the $7^{th}$ row of the state transition matrix

source node's packets. Hence it should be encouraged by a method to forward the source node's packets to the destination in order to increase the system throughput. To do so, a reward based mechanism is utilized, in such a way that whenever the relay node accepts a packet from the source node, it receives a reward called forwarding reward, $R^f$ from the source node. This reward is considered to provide incentive to the relay node for accepting source node's packet and forwarding it to the destination node in the next time slots. The source node receives the delivery reward, $R^d$ when the relay node successfully transmits the forwarded packet to the destination.

Transmission cost is defined as the cost of the required energy for transmission of a single packet with acceptable reliability over the channel and is denoted by $C^t_{ij}$, where $i$ and $j$ represent the origin and target nodes, respectively. This cost depends on several parameters such as length and quality of the path. For example, $C^t_{sr}$ is the transmission cost of sending a packet from the source node to the relay node.

Keep cost, $C^k$ is defined to encourage nodes to attempt sending their packets and prevent waiting as much as possible. Waiting is not desirable since it will contribute to the latency in the network and will reduce the systems throughput. This delay cost, is also applied to the retransmission of the corrupted packets, due to collision, as well as the rejected packets by relay node that should be retransmitted to the destination in the next time slot. Relaying delay cost, $C^r$ is defined as a cost that the source node pays if it decides to send its packet via the relay node to the destination, due to causing undesired delay in the system.

According to aforementioned definitions, utility functions of both source and relay nodes are presented in (7) and (8) based on definition of stationary utility function in equation (5).

$$
\begin{aligned}
U_1(\delta) &= \Pi_2(\delta) \times \{\ (R^d)\} + \Pi_4(\delta) \times \{\ (R^d)\} \\
&+ \Pi_5(\delta) \times \{p_{sd}(R^d - C^t_{sd}) + p_{sr} . p_{ac}(-R^f - C^t_{sr} - C^r) \\
&+ p_{sr}(1 - p_{ac})(-C^k - C^t_{sr}) +\ (1 - p_{sr} - p_{sd})(-C^k)\} \\
&+ \Pi_6(\delta) \times \{(R^d - C^k)\} \\
&+ \Pi_7(\delta) \times \{\ p_{sd}(1 - p_{rd})(R^f - C^t_{sd}) \\
&+ p_{sd} . p_{rd}(-C^k - C^t_{sd}) \\
&+ p_{sr}(1 - p_{rd}).\ p_{ac}(-R^d - C^t_{sr} - C^r) \\
&+ p_{sr}(1 - p_{ac} + p_{rd}.\ p_{ac})(-C^k - C^t_{sr}) \\
&+ p_{sr}.\ p_{rd}(-C^k - C^t_{sr}) +\ (1 - p_{sr} - p_{sd})(-C^k)\} \\
&+ \Pi_8(\delta) \times \{R^d - C^k\} \qquad (7)
\end{aligned}
$$

$$
\begin{aligned}
U_2(\delta) &= \Pi_2(\delta) \times \{(-C^t_{rd})\} \\
&+ \Pi_3(\delta) \times \{p_{rd}(R^d - C^t_{rd}) + (1 - p_{rd})(-C^k)\} \\
&+ \Pi_4(\delta) \times \{(-C^t_{rd} - C^k)\} \\
&+ \Pi_5(\delta) \times \{\ p_{sr}.\ p_{ac}(R^f)\} \\
&+ \Pi_6(\delta) \times \{(-C^t_{rd})\} \\
&+ \Pi_7(\delta) \times \{\ p_{rd}(1 - p_{sr} - p_{sd})(R^d - C^t_{rd}) \\
&+ p_{rd}(p_{sr} +\ p_{sd})(-C^k - C^t_{rd}) \\
&+ (1 - p_{rd}).\ p_{sr}.\ p_{ac}(R^f - C^k) \\
&+ (1 - p_{rd})(1 - p_{sr}.\ p_{ac})(-C^k)\} \\
&+ \Pi_8(\delta) \times \{(-C^t_{rd} - C^k)\} \qquad (8)
\end{aligned}
$$

## 5 Flexible Relaying Method

In this section, the second proposed method is described. In the first proposed method, the relay node prefers to forward the received packets from the source node rather than transmitting its own packets. However, in some wireless Ad-hoc networks, there is no priority between packets generated at the source node and the relay node. A new method called as *flexible relaying method* is defined to optimize the overall throughput of these systems. In this method, when the relay node has both its own packet and received packet from the source node, it can select to transmit either of them. Consequently, one more degree of freedom is added to the strategy set of relay node that enables it to make a better decision to increase its utility.

Strategy set of the relay node in this method is presented by $(p_{rd},\ p_f,\ p_{rw},\ p_{ac},\ p_r)$, which are probability of (i) sending a packet to the destination, (ii) forwarding the received packet, (iii) waiting, (iv) accepting the source node packet, and (v) rejecting it, respectively. Since, $p_{rd} +\ p_f +\ p_{rw} = 1$, and $p_{ac} +\ p_r = 1$, therefore, $(p_{rd},\ p_f,\ p_{ac})$ are selected to present the strategy set of relay node. The following probability vector models the strategy profile of the game $(p_{sd},\ p_{sr},\ p_{rd},\ p_f,\ p_{ac})$.

According to the above terminology and assumptions, the action sets of nodes for all possible states are provided in table 2.

### 5.1 State transition probability matrix for flexible relaying method

The corresponding state transition matrix of this scenario is developed and presented in Appendix B. Similar to reliable relaying method, each element of state transition matrix, $T_{ij}(\delta)$ represents the transition probability of stationary strategy profile $(\delta)$ from state $i$ to $j$ in two consecutive time slots.

### 5.2 Expected payoff function of player

Payoff functions of flexible relaying model are defined in this section. All rewards and costs are defined similar to reliable relaying game model.

Keeping forward cost denoted by $C^{kf}$ is paid by relay node when it avoids transmitting the packet in the forward buffer. This cost is selected greater than keep cost, $C^k$ in order to encourage the relay node to transmit these packets with higher priority than its own packets. Otherwise, the relay node performs selfishly and prefers to transmit its own packets.

The expected utility functions of both source and relay nodes in the stationary strategy profile of $(\delta)$ for this method are defined in (9) and (10).

**Table 2** Strategy set of players for flexible relaying method

| Current State of the Game $(B_S, B_R, B_F)$ | Strategy Set of Players $(p_{sd},\ p_{sr},\ p_{rd},\ p_f,\ p_{ac})$ |
|---|---|
| $s_1 = (0, 0, 0)$ | $(0,\ 0,\ 0,\ 0,\ p_{ac})$ |
| $s_2 = (0, 0, 1)$ | $(0,\ 0,\ 0,\ p_f,\ 0)$ |
| $s_3 = (0, 1, 0)$ | $(0,\ 0,\ p_{rd},\ 0,\ p_{ac})$ |
| $s_4 = (0, 1, 1)$ | $(0,\ 0,\ p_{rd},\ p_f,\ 0)$ |
| $s_5 = (1, 0, 0)$ | $(p_{sd},\ p_{sr},\ 0,\ 0,\ p_{ac})$ |
| $s_6 = (1, 0, 1)$ | $(p_{sd},\ p_{sr},\ 0,\ p_f,\ 0)$ |
| $s_7 = (1, 1, 0)$ | $(p_{sd},\ p_{sr},\ p_{rd},\ 0,\ p_{ac})$ |
| $s_8 = (1, 1, 1)$ | $(p_{sd},\ p_{sr},\ p_{rd},\ p_f,\ 0)$ |

$$
\begin{aligned}
U_1(\delta) = &\,\Pi_2(\delta) \times \{\ p_f.\ R^d\ \} + \Pi_4(\delta) \times \{\ p_f.\ R^d\ \} \\
&+ \Pi_5(\delta) \times \{p_{sd}(R^d - C^t_{sd}) \\
&+ p_{sr}.\ p_{ac}(-R^f - C^t_{sr} - C^r) \\
&+ p_{sr}(1 - p_{ac})(-C^k - C^t_{sr}) + (1 - p_{sr} - p_{sd})(-C^k)\} \\
&+ \Pi_6(\delta) \times \{\ p_{sd}(1 - p_f)(R^d - C^t_{sd}) \\
&+ p_{sd}.\ p_f)(-C^k - C^t_{sd}) + p_{sr}(-C^k - C^t_{sr}) \\
&+ (1 - p_{sr} - p_{sd}) \times [p_f(R^d - C^k) + (1 - p_f)(-C^k)]\ \} \\
&+ \Pi_7(\delta) \times \{\ p_{sd}(1 - p_{rd})(R^d - C^t_{sd}) \\
&+ p_{sd}.\ p_{rd}(-C^k - C^t_{sd}) \\
&+ p_{sr}(1 - p_{rd}).\ p_{ac}(-R^f - C^t_{sr} - C^r) \\
&+ p_{sr}(1 - p_{ac} + p_{rd}.\ p_{ac})(-C^k - C^t_{sr}) \\
&+ (1 - p_{sr} - p_{sd})(-C^k)\} \\
&+ \Pi_8(\delta) \times \{\ p_{sd}(1 - p_{rd} - p_f)(R^d - C^t_{sd}) \\
&+ p_{sd}(p_{rd} + p_f)(-C^k - C^t_{sd}) + p_{sr}(-C^t_{sr} - C^k) \\
&+ (1 - p_{sr} - p_{sd})(-C^k) + (1 - p_{sr} - p_{sd}).\ p_f(R^d)\}.
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
U_2(\delta) = &\,\Pi_2(\delta) \times \{p_f(-C^t_{rd}) + (1 - p_f)(-C^{kf})\} \\
&+ \Pi_3(\delta) \times \{p_{rd}(R^d - C^t_{rd}) + (1 - p_{rd})(-C^k)\} \\
&+ \Pi_4(\delta) \times \{p_{rd}(R^d - C^t_{rd} - C^{kf}) \\
&+ p_f(-C^t_{rd} - C^k) + (1 - p_{rd} - p_f)(-C^k - C^{kf})\} \\
&+ \Pi_5(\delta) \times \{\ p_{sr}.p_{ac}(R^f)\} \\
&+ \Pi_6(\delta) \times \{p_f(1 - p_{sr} - p_{sd})(-C^t_{rd}) \\
&+ p_f(p_{sd} + p_{sr})(-C^{kf} - C^t_{rd}) + (1 - p_f)(-C^{kf})\} \\
&+ \Pi_7(\delta) \times \{\ p_{rd}(1 - p_{sr} - p_{sd})(R^d - C^t_{rd}) \\
&+ p_{rd}(p_{sr} + p_{sd})(-C^k - C^t_{rd}) \\
&+ (1 - p_{rd}).\ p_{sr}.\ p_{ac}(R^f) + (1 - p_{rd})(-C^k)\} \\
&+ \Pi_8(\delta) \times \{p_{rd}(1 - p_{sr} - p_{sd})(R^d - C^t_{rd}) \\
&+ p_{rd}(p_{sr} + p_{sd})(-C^k - C^t_{rd}) \\
&+ p_f(1 - p_{sr} - p_{sd})(-C^t_{rd}) \\
&+ p_f(p_{sr} + p_{sd})(-C^{kf} - C^t_{rd}) \\
&+ (1 - p_{rd} - p_f)(-C^{kf} - C^k)\ \}
\end{aligned} \tag{10}
$$

## 6 Collision adaptive method

In previously discussed methods, both source and relay nodes' packets are dropped in the case of simultaneous transmission due to collision. In this section, a different scenario is defined where one of the simultaneously transmitted packets can be captured based on the physical layer parameters. To consider collision in this system model, first the collision effect on bit error rate (BER) and packet error rate (PER) in multiple-access channels is investigated, then packet error rate is considered as a function of system transmission specifications.

In interference channels, signal to interference and noise ratio ($SINR$) is defined as,

$$
SINR = \frac{h_i.P_i}{N_0 + \frac{1}{L}\sum\limits_{j=1,j\neq i}^{N} h_j.P_j} \tag{11}
$$

where $P_i$ is the transmission power of node $i$, $h_i$ is the channel gain between transmitter $i$ and the receiver, $N_0$ is the noise power at the receiver and $L$, is the processing gain, where $L = 1$ for narrowband systems and $L \gg 1$ for wide band systems. In the sequel, $i = 1$ is assigned to the source node, and $i = 2$ is considered for the relay node, unless explicitly specified otherwise.

Probability of error is a function of $SINR$. This means $p_b = f(SINR)$, where $f$ is a system's function depending on transmission parameters, such as transmitter structure, receiver sensitivity level, modulation, channel coding, data transmission rate and several additional factors. Packet error rate, is a function of probability of bit error and packet length. In most practical applications, a $n$-bit message is discarded even if one bit is corrupted [21]. Therefore, packet error rate is related to probability of bit error as follows,

$$
PER = 1 - (1 - p_b)^n \tag{12}
$$

A system dependent threshold level, $\Gamma$, is defined such that when $SINR$ is greater than it, the probability of bit error is negligible; therefore, almost all packets are received at the destination successfully. In other words, $SINR > \Gamma$, guarantees error-free communication between source and destination node [15].

Both source and relay nodes adjust their powers such that the $SINR$ level at destination be higher than $\Gamma$, provided that there is no interfering node. Hence, minimum transmission power, $P^t_i(min)$ of the $i^{th}$ node is calculated as follows,

$$
SINR_i = \frac{P^r_i}{N_0} = \frac{P^t_i.h_i}{N_0} \geq \Gamma \tag{13}
$$

$$
P^t_i(min) = \Gamma.N_0/h_i \tag{14}
$$

If both nodes attempt to transmit simultaneously with the minimum power, the $SINR$ value of node $i$ is converted to

$$SINR_i = \frac{P_i^r}{N_0 + P_{\bar{i}}^r} = \frac{P_i^t.h_i}{N_0 + P_{\bar{i}}^t.h_{\bar{i}}}$$
$$= \frac{\Gamma}{\Gamma + 1}, \quad \bar{i}, i = 1, 2, \; \bar{i} \neq i. \quad (15)$$

This degradation at $SINR$ level affects signal reception severely depending on transmission technology. This effect in some cases such as uncoded BPSK is more visible and almost all the packets are lost, while in the other category of systems such as DS-CDMA, the system performance does not change considerably [22].

For instance, if a protocol with 64-bit length packets is utilized using the uncoded Binary Phase Shift Keying (BPSK) transmission system and coherent detection, probability of error for this system is calculated as follows,

$$P_b = Q(\sqrt{2SNR}) \quad (16)$$

Therefore for an acceptable $BER$ of $10^{-6}$, the required $SINR$ threshold to achieve this BER is $\Gamma = 11.2975$ ($\approx 10.53dB$). In this system, if simultaneous packet transmission occurs, the $SINR$ level reduces to $\frac{\Gamma}{\Gamma+1} = 0.9187$. Consequently, the error probability increases to 0.0876, that results in packet error rate equal to $1 - (1 - 0.0919)^{64} = 0.9979$. This means that almost all the packets are lost. Based on this justification, packet error probability of 1 is used to model the most vulnerable systems to collision.

The other extreme case is CDMA systems, which are very robust to interference. In CDMA systems, since transmitters use orthogonal codes, the interfering signals do not affect successful detection of the desired signal. In this technique, $\Gamma$ is a very small value and it does not considerably change when divided by $\Gamma + 1$. Hence, $BER$ and $PER$ of CDMA systems are not changed considerably if new transmitters are added to the system while they use orthogonal codes. This can be considered as a system that is more robust to interference. In the proposed scenario, receiver expects signals from both source and relay nodes and since the received power of both nodes are almost equal, one of the transmitted signals is randomly detected. In this extreme case, packet error rate for both source and relay nodes is assumed to be one half [23,24].

The following joint probabilities are defined in table 3 to model packet error rate in case of collision for arbitrary transmission techniques that makes the game model applicable for different transmission technologies.

Since, just one packet can be detected by destination node at each time slot, we have

**Table 3** Probability of packet reception at destination node when collision occurs

| Parameter | Definition |
|---|---|
| $p(s, \bar{r}\|d)$ | Probability of successful reception of source node packet only, when collision occurs at destination |
| $p(\bar{s}, r\|d)$ | Probability of successful reception of relay node packet only, when collision occurs at destination. |
| $p(s, r\|d)$ | Probability of successful reception of both packets. |
| $p(\bar{s}, \bar{r}\|d)$ | Probability of failure of both packets. |

$$p(s, r|d) = 0 \quad (17)$$
$$p(s, \bar{r}|d) + p(\bar{s}, r|d) + p(\bar{s}, \bar{r}|d) = 1 \quad (18)$$

Therefore, the probability of failure of source and relay nodes' packets are calculated as,

$$p_e(s|d) = p(\bar{s}, r|d) + p(\bar{s}, \bar{r}|d) \quad (19)$$
$$p_e(r|d) = p(s, \bar{r}|d) + p(\bar{s}, \bar{r}|d) \quad (20)$$

### 6.1 Averaged system throughput

In Ad-hoc wireless systems with ALOHA access protocol that all nodes make independent channel requests, Multi-Packet Reception (MPR) matrix, denoted by $R$ is defined to model the channel efficient throughput [24, 25].

$$R = \begin{pmatrix} \rho_{10} & \rho_{11} & 0 & 0 & \dots & 0 & \dots \\ \rho_{20} & \rho_{21} & \rho_{22} & 0 & \dots & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \rho_{n0} & \rho_{n1} & \rho_{n2} & \dots & \dots & \rho_{n0} & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \end{pmatrix} \quad (21)$$

where $\rho_{ij}$ is the probability of successful reception of $j$ packets from $i$ transmitted packets. The average throughput of the system, with $n$ transmitter nodes is defined as the expected number of successfully transmitted packets when all the nodes transmit simultaneously,

$$\mu = \sum_{k=0}^{n} k\rho_{nk} \quad (22)$$

The MPR matrix for the proposed two player case is simplified to

$$R = \begin{pmatrix} \rho_{10} & \rho_{11} & 0 \\ \rho_{20} & \rho_{21} & \rho_{22} \end{pmatrix} \quad (23)$$

This model is applied to calculate the efficient throughput of the proposed system model.

$\mu_i(q)$ is defined as the probability of successful packet transmission by node $i$ at state $q$, which is calculated as follows

$$\mu_i(q) = p_i^{send}(q).[(1 - p_{\bar{i}}^{send}(q)) + p_{\bar{i}}^{send}(q).\ p(i, \bar{i}|d)] \tag{24}$$

where $p_i^{send}(q)$ is the probability of sending a packet by node $i$ at state $q$. The average throughput of each node $i$, denoted by $\bar{\mu}_i$ is calculated as follows

$$\bar{\mu}_i = E(\sum_{q=1}^{8} \Pi_q \times \mu_i(q)) \tag{25}$$

where $\Pi_q$ is the probability of state $q$ of the game. The average throughput of the system, $\bar{\mu}$ is the summation of source and relay nodes throughputs, $(\bar{\mu} = \sum_{i=1}^{2} \bar{\mu}_i)$.

### 6.2 Averaged transmission delay

One other important specification of the system is the average delay of packet transmission. In applications, with strict latency requirement, the maximum transmission delay of the system should be less than an acceptable value. Averaged packet transmission delay is defined similar to average throughput of the system. If a packet remains at each of transmit buffers, a delay counter is set for the corresponding node. If the source node's packet is transmitted to relay, a delay is counted for source node and while the packet remains at forward buffer of the relay node, more delay counters are accumulated until it is forwarded to the destination. The average delay of both source and delay nodes presented by $\bar{d}_i$ as well as the average delay of system denoted by $\bar{d}$ are defined as,

$$\bar{d}_i = E(\sum_{q=1}^{8} \Pi_q \times d_i(q)) \tag{26}$$

$$\bar{d} = \frac{\sum_{i=1}^{2} g_i.\bar{d}_i}{\sum_{i=1}^{2} g_i} \tag{27}$$

where $g_i$ is the packet generation rate at node $i$ and $d_i(q)$ is the probability of keeping a packet at transmit buffer of node $i$ at state $q$.

### 6.3 Strategy set and state transition matrix for the collision adaptive method

Considering these facts, a new stochastic game theoretical model is defined. Players' strategy profile of this scenario is similar to Sect. 5, which was described in table 2. The proper transition probability matrix is defined for this new system model as well as the corresponding utility of players.

For instance, the transition from state 110 to 010 is calculated as follows. This transition occurs when the source buffer becomes empty due to successful transmission of a packet from the source node to the destination, while there is no new generated packet at the source node. There are two possibilities for this transition,

- Source node attempts to transmit a packet to the destination, while the relay node waits. This probability is calculated as, $(1 - g_s)p_{sd} \times (1 - p_{rd})$.
- Source node attempts to transmit a packet to the destination, while relay node also attempts to transmit a packet from its internal buffer to the destination that causes collision. Hence an extra term is considered to represent the probability of successful delivery of source node packet. This probability can be calculated as, $(1 - g_s)p_{sd} \times [p_{rd}.p(s, \bar{r}|d)]$.

The complete transition matrix for this scenario is presented in Appendix C.

### 6.4 Expected payoffs of players

In this section, utility functions of players are defined. Similar to 5.2, rewards and costs for different actions are considered. The expected utility functions of source and relay nodes in a stationary strategy profile ($p_{sd}, p_{sr}, p_{rd}$, $p_f, p_{ac}$) are defined as follows.

$$\begin{aligned}
U_1(\delta) &= \Pi_2(\delta) \times \{\ p_f.\ R^d\ \} + \Pi_4(\delta) \times \{\ p_f.\ R^d\ \} \\
&+ \Pi_5(\delta) \times \{p_{sd}(R^d - C_{sd}^t) + p_{sr}.\ p_{ac}(-R^f - C_{sr}^t - C^r) \\
&+ p_{sr}(1 - p_{ac})(-C^k - C_{sr}^t) + \ (1 - p_{sr} - p_{sd})(-C^k)\} \\
&+ \Pi_6(\delta) \times \{\ p_{sd}(1 - p_f + p_f.\ p(s, \bar{r}|d)(R^d - C_{sd}^t) \\
&+ p_{sd}.\ p_f.\ p(\bar{s}, \bar{r}|d)(-C^k - C_{sd}^t) \\
&+ p_{sd}.\ p_f.\ p(\bar{s}, r|d)(R^d - C_{sd}^t - C^k) \\
&+ p_{sr}(-C^k - C_{sr}^t) + p_{sr}.\ p_f(1 - p_e(r|r))(R^d) \\
&+ (1 - p_{sr} - p_{sd}) \times [p_f(R^d - C^k) + (1 - p_f)(-C^k)]\ \}
\end{aligned}$$

$$+ \Pi_7(\delta) \times \{ p_{sd}(1 - p_{rd} + p_{rd}.\ p(s, \bar{r}|d))(R^d - C^t_{sd})$$
$$+ p_{sd}.\ p_{rd}.\ p(\bar{s}, r|d)(-C^k - C^t_{sd})$$
$$+ p_{sr}(1 - p_{rd}).\ p_{ac}(-R^f - C^t_{sr} - C^r)$$
$$+ p_{sr}(1 - p_{ac} + p_{rd}.\ p_{ac})(-C^k - C^t_{sr})$$
$$+ (1 - p_{sr} - p_{sd})(-C^k)\}$$
$$+ \Pi_8(\delta) \times \{ p_{sd}(1 - p_{rd} - p_f + (p_{rd} + p_f).\ p(s, \bar{r}|d)$$
$$\times (R^d - C^t_{sd})$$
$$+ p_{sd}(p_{rd} + p_f)(1 - p(s, \bar{r}|d))(-C^k - C^t_{sd})$$
$$+ p_{sd}.\ p_f.\ p(\bar{s}, r|d)(R^d) + p_{sr}(-C^t_{sr} - C^k)$$
$$+ p_{sr}.\ p_f(1 - p_e(r|r))(R^d) + (1 - p_{sr} - p_{sd})(-C^k)$$
$$+ (1 - p_{sr} - p_{sd}).\ p_f(R^d)\}. \quad (28)$$

$$U_2(\delta) = \Pi_2(\delta) \times \{p_f(-C^t_{rd}) + (1 - p_f)(-C^{kf})\}$$
$$+ \Pi_3(\delta) \times \{p_{rd}(R^d - C^t_{rd}) + (1 - p_{rd})(-C^k)\}$$
$$+ \Pi_4(\delta) \times \{p_{rd}(R^d - C^t_{rd} - C^{kf})$$
$$+ p_f(-C^t_{rd} - C^k) + (1 - p_{rd} - p_f)(-C^k - C^{kf})\}$$
$$+ \Pi_5(\delta) \times \{ p_{sr}.p_{ac}(R^f)\}$$
$$+ \Pi_6(\delta) \times \{p_f \times [1 - p_{sr} - p_{sd} + p_{sr}(1 - p_e(r|r))$$
$$+ p_{sd}.\ p(\bar{s}, r|d)](-C^t_{rd})$$
$$+ p_f \times [p_{sd}(1 - p(s, \bar{r}|d)) + p_{sr}.\ p_e(r|r)]$$
$$\times (-C^{kf} - C^t_{rd}) + (1 - p_f)(-C^{kf})\}$$
$$+ \Pi_7(\delta) \times \{ p_{rd} \times [1 - p_{sr} - p_{sd} + p_{sr}(1 - p_e(r|r))$$
$$+ p_{sd}.\ p(\bar{s}, r|d)] \times (R^d - C^t_{rd})$$
$$+ p_{rd} \times [p_{sr}.\ p_e(r|r) + p_{sd}(1 - p(s, \bar{r}|d))](-C^k - C^t_{rd})$$
$$+ (1 - p_{rd}).\ p_{sr}.\ p_{ac}(R^f) + (1 - p_{rd})(-C^k)\}$$
$$+ \Pi_8(\delta) \times \{p_{rd}(1 - p_{sr} - p_{sd} + p_{sr}(1 - p_e(r|r))$$
$$+ p_{sd}.\ p(\bar{s}, r|d))(R^d - C^t_{rd})$$
$$+ p_{rd}(p_{sr}.\ p_e(r|r) + p_{sd}(1 - p(s, \bar{r}|d)))(-C^k - C^t_{rd})$$
$$+ p_f(1 - p_{sr} - p_{sd} + p_{sr}(1 - p_e(r|r))$$
$$+ p_{sd}.\ p(\bar{s}, r|d))(-C^t_{rd})$$
$$+ p_f(p_{sr}.\ p_e(r|r) + p_{sd}(1 - p(s, \bar{r}|d)))(-C^{kf} - C^t_{rd})$$
$$+ (1 - p_{rd} - p_f)(-C^{kf} - C^k)\ \} \quad (29)$$

## 7 Numerical Results

In this section, numerical results are provided to investigate system performance in terms of achieved utility, average throughput and average transmission delay for three proposed methods versus different system parameters.

System performance is analyzed for both cooperative and non-cooperative solutions of the game scenarios. In a cooperative solution, both nodes try to maximize the summation of both utilities jointly, so the utility is the maximum achievable utility for the game model in a given condition. While in non-cooperative solution, each node selfishly tries to find the best possible strategy set to maximize its own payoff function based on (5). Best response Nash equilibrium strategy profile is evaluated as system behavior in non-cooperative scenario that does not necessarily result in a maximum total utility and it is more likely to yield a local maximum for the utility. Performance of a non-cooperative solution may be compared with a cooperative solution to verify how far it is from the maximum achievable utility. Utilities of players may be considered as a criteria to evaluate the system performance. Besides that, the proposed systems performance is examined in terms of throughput and latency to demonstrate optimality of the taken strategies in different conditions.

In this section, first, the simulation results for reliable relaying method are provided as different strategy profiles of the non-cooperative game versus different energy transmission cost. Also, utility, throughput and delay of the system are presented for both cooperative and non-cooperative solutions of the second proposed model named as flexible relaying method. In continue the transmission delay of these two systems are compared. Finally, performance of third proposed method, collision adaptive method is considered and compared to the second system to investigate the effect of different packet error rates on the system performance.

Low packet transmission latency is one of the most important parameters in system performance analysis. However, there is a trade off between nodes' tendency to transmit their packets in order to get lower keep cost and waiting to avoid collision. Keep cost, $C^k$ models the system delay tolerance in the suggested game theoretical models. In table 4, best response Nash strategy sets of players in the non-cooperative game for reliable relaying method is presented for different keep cost values. Based on this table result, it is concluded that tendency

**Table 4** Strategy Profile of the game analysis for different keep costs, when $C^t_{sd} = 0.5, C^t_{sr} = 0.1, g_r = g_s = 0.3, C^t_{rd} = 0.2, R^f = 0.4, C^r = 0.05$.

| Keep cost $C^k = 0.3$ | Keep cost $C^k = 0.5$ |
|---|---|
| $p_{sd} =$ 0.65 | $p_{sd} =$ 0.75 |
| $p_{sr} =$ 0.35 | $p_{sr} =$ 0.15 |
| $p_{rd} =$ 0.55 | $p_{rd} =$ 0.65 |
| $p_{ac} =$ 0.75 | $p_{ac} =$ 0.85 |

of nodes to transmit their packets to the destination increases for higher cost values, such that both source and relay nodes prefer to transmit their packets rather than keeping them.

In Fig. 3, the effect of path loss between source and destination nodes on the system behavior is considered. $C^t_{sd}$ determines cost of reliable communication between source and destination nodes, which in turn depends on path length, quality of path and channel interference level. To study source node behavior as a function of the channel condition, other parameters are fixed at $C^t_{sr} = C^t_{rd} = 0.1, g_s = g_r = 0.3, C^k = 0.1, R^f = 0.4, C^r = 0.05$ that are also used in all other simulations, unless explicitly specified otherwise. It is shown that if the required cost of transmitting a packet to the destination increases, probability of directly transmitting packets from the source node to the destination node, $p_{sd}$ is decreased and probability of transmitting packets via the relay node, $p_{sr}$ is increased. In other words, the source node's incentive to directly transmitting its packets to the destination is reduced and it prefers to transmit its packets via the relay node.

The summation of nodes' utilities is depicted in Fig. 4 versus packet generation rate of source node for different keep cost values in both cooperative and non-cooperative solutions. The utility of system increase as the packet generation rate of source node increases due to more packet delivery reward. Also, as expected, the sum utility of cooperative game is greater than non-cooperative game due to joint optimization scheme in cooperative games. However, the performance of system for non-cooperative solution is slightly lower than cooperative one and it asymptotically approaches the cooperative system performance. This result confirms the appropriate strategy set of non-cooperative game model that is more applicable in practical systems, where nodes are not aware of each other's selected strategy set. Moreover, the effect of different delay cost values $C^k = 0.1,\ 0.2$ on the utility of players is analyzed in Fig. 4. Summation of players's utilities decreases as the delay cost of system is increased. Players adaptively take an appropriate strategy set to maximize their utility noting the cost of transmission delay. A higher value is set for keep cost in systems, where low latency is desirable. Hence, the maximum achievable utility in these systems is less than systems without strict delay requirements.

In Fig. 5, throughput of both source and relay nodes are shown versus the packet generation rate of relay node, $g_r$. In this case, the rest of system parameters are set at $C^t_{sd} = 0.4, C^t_{sr} = C^t_{rd} = 0.1, g_s = 0.3, R^f = 0.4, C^r = 0.05$. The throughput of relay node increases for higher values of packet generation rate due to more successful packet transmission. On the other hand, since relay node attempts to occupy the channel more often, source node intends to keep its packets as much as possible to avoid collision that results in lower throughput per time slot. Also, the probability of collision and consequently failure to source node packet transmission increases that causes more reduction in source node throughput. Besides that, the relay node's incentive to cooperate with the source node is reduced because of trade-off between sending its own packets and received packets from the source node. All that results in lower

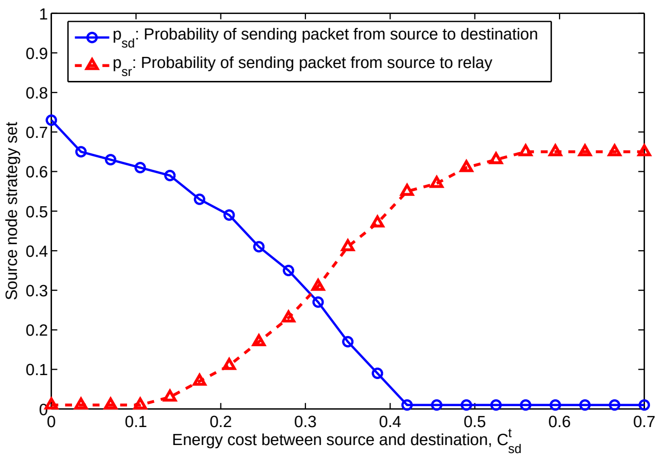


**Fig. 3** Best response Nash equilibrium strategy set of source node versus transmission cost between source and destination nodes in reliable relying method, $C^t_{sd}$. Game parameters are $C^t_{sr} = C^t_{rd} = 0.1$, $g_r = g_s = 0.3$ , $C^k = 0.1$, $R^f = 0.4$, $C^a = 0.1$.

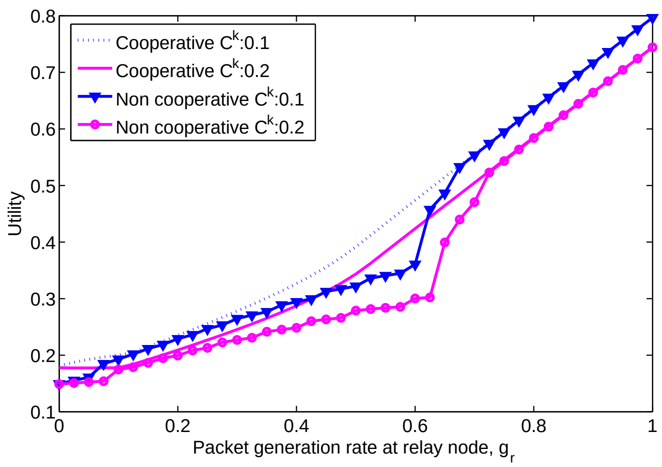


**Fig. 4** Summation of utilities of source and relay nodes versus the relay node packet generation rate for cooperative and non-cooperative game models and different keep cost values in reliable relying method, The game parameters are $C^t_{sr} = 0.4, C^t_{sr} = C^t_{rd} = 0.1$, $g_s = 0.3$ , $R^f = 0.4.$, $C^a = 0.1$.

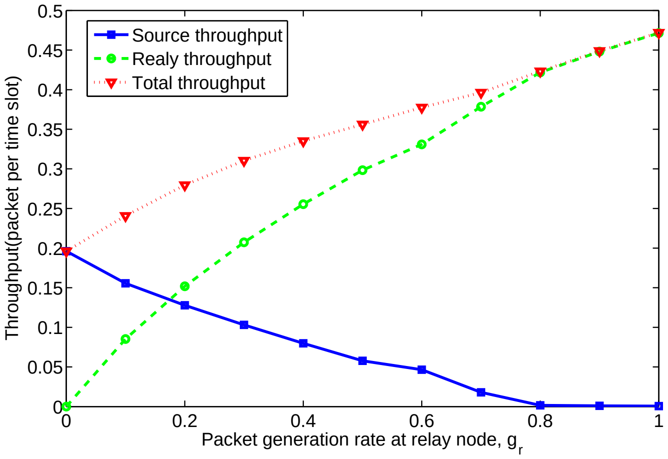


**Fig. 5** Throughput of nodes versus packet generation rate at relay node in flexible relying method.

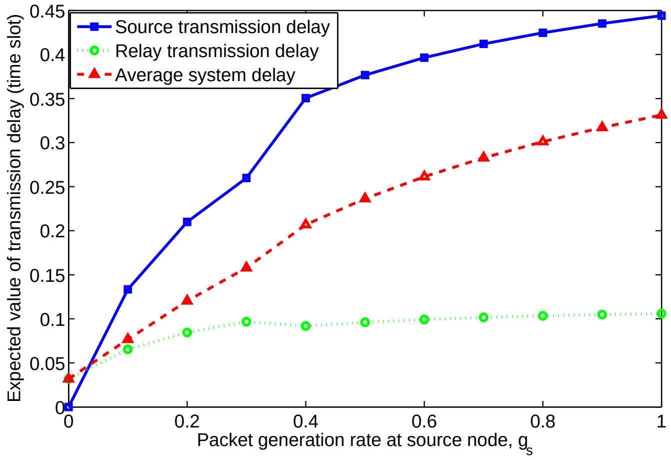


**Fig. 6** Average packet transmission delay of system versus packet generation rate at source node in flexible relaying method.

rates of source node packet transmission as a side effect of higher packet generation rate of relay node. However, the total throughput of system increases for higher packet generation rates in relay node since the increase in relay node throughput is dominant.

Figure 6 demonstrates the effect of packet generation rate of source node on the average transmission delay of system. It is obvious that higher packet generation rates increase the probability of simultaneous packet transmission on the common channel that consequently increases transmission delay because of retransmission of collied packets. Also, both source and relay nodes select their strategy to avoid immediate transmission of their packets in order to prevent collision. Consequently, average transmission delay of the system, as well as delay of both nodes will be increased.

Transmission delay of the first and second proposed models are compared in Fig. 7. As mentioned in Sect. 4, in reliable relaying method a higher priority is assigned to source nodes' packets such that relay node transmits the received packets from the source when both its internal and forward buffers are occupied. Consequently, in this method source node has a lower transmission delay comparing to the flexible relaying method in which relay node can decide between transmitting its own packets or received packets from the source node. The same comparaison result is also valid for the average transmission delay of the system.

Figure 8 compares the average throughput of the third proposed system (collision adaptive method) for different packet error rates in case of collision occurrence. The result demonstrates that the maximum achievable throughput is higher for the systems that are more robust to channel interference and their packet error rates are lower in case of collision. The proposed model is an adaptive model in which players can take more appropriate strategies considering packet loss rate. One extreme case is packet error rate equal to one that is equivalent to second proposed model (flexible relying method), where we assumed that all packets are lost if collision occurs. Packet error rate equal to zero is another extreme case that models interference robust systems such as CDMA. In these systems, the packet is captured in an almost error-free manner, if simultaneous packet transmission occurs. Since the destination node can capture only one packet in each time slot, in case of collision, one of two simultaneously transmitted packets by source and relay nodes is randomly captured

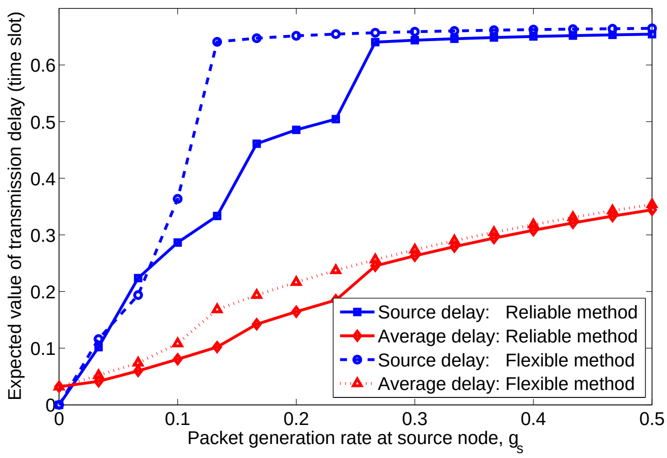


**Fig. 7** Comparison of average packet transmission delay between reliable and flexible relying methods versus packet generation rate at source node.

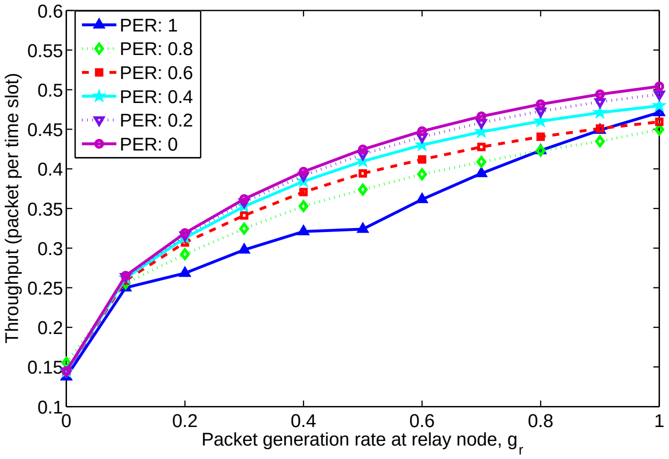


**Fig. 8** Throughput of collision adaptive method versus packet generation rate at relay node for different packet error rates in case of collision.

by the destination. The results confirm that the system with lower probability of packet loss achieves higher data throughput under the same conditions.

Average delay of the third proposed system is also depicted in 9. The average delay of packet transmission decreases as the packet error rate of system decreases. For systems that are vulnerable to collision, the average delay is about 0.25 time slot per packet, while this value is less than 0.05 time slot for systems with $PER < 0.5$. Because in intereference robust systems, the collision rarely results in less packet loss and retransmission. Moreover, since in the third proposed model, $PER$ is utilized by nodes to select an appropriate strategy, they intend to transmit their packets sooner to maximize their payoffs and achieve delivery reward while avoiding the keep cost. Therefore, the average transmission delay of system will be very low.

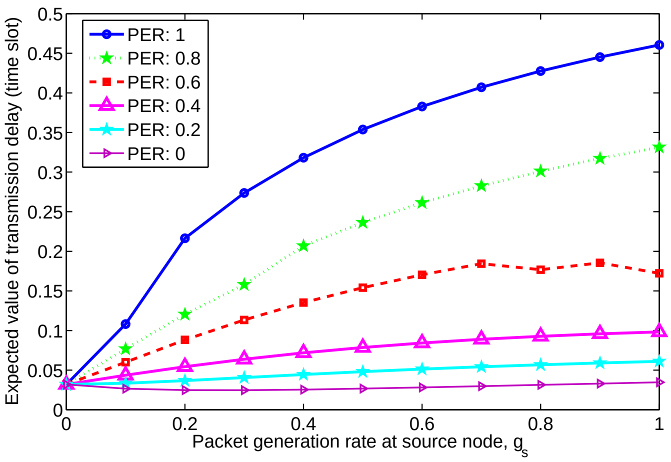


**Fig. 9** Average delay of packet transmission of collision adaptive method versus packet generation rate at source node for different packet error rates in case of collision.

## 8 Conclusion

In this article, the problem of optimizing a basic relay network performance is investigated using Markov stationary game theoretical model. In this approach, successful packet delivery appears as a reward for relay and source nodes as players of the game, while system requirements and limitations such as power consumption and transmission delay appear as the paid cost by players to define the game. Hence, players intelligently take the best possible strategies to obtain maximum reward and keep the paid cost as less as possible. The nodes behavior is analyzed as the strategy profile of the game versus different energy costs and keep costs.

In the proposed model, two separate buffers are deployed at the relay node to apply different strategies for the generated packets at the relay node and the received packets from the source node. The relay node can apply different strategies to these packets based on the system specifications and performance criteria. Cooperative and non-cooperative solutions for this model are provided. Simulation results demonstrate that the system performance for non-cooperative solution being very close to the cooperative system. Despite the cooperative solution, in the proposed non-cooperative solution, the players do not require to know each others strategy sets. Hence, the proposed method can be utilized in most practical applications of Ad-hoc wireless networks.

In the first model called reliable relaying method, the relay node immediately forwards the received packet from source node, even if it has its own packet to transmit. This method is developed to model the systems in which the first priority is to transmit source node packets. A different model, named flexible relaying method is developed to address the systems with the same priorities for source and relay node packets such as homogeneous Ad-hoc networks. In this model, the relay node is not enforced to transmit received packets from the source immediately. In this case, the total utility of system may be increased due to usage of a more flexible strategy set in the relay node.

Finally, the proposed model is extended to cover a more general relay system, in which the collision occurrence does not necessarily yield packet loss. The probability of packet loss in the case of collision is considered as an input parameter of the game such that players consider this probability in selecting their strategy sets.

This method results in higher system performance. The throughput of system increases and the transmission delay decreases for lower packet error rates in the system.

**Appendix A**

In this appendix, the state transition probability matrix of proposed Markovian game for reliable relaying method is presented. To simplify the notation $(T_{ij})$ is used instead of $T_{ij}(\delta)$ to show the transition probability of stationary strategy profile $(\delta)$.

$$T_{11} = (1-g_s)(1-g_r),\ T_{12} = 0,\ T_{13} = g_r(1-g_s),$$
$$T_{14} = 0,\ T_{15} = g_s(1-g_r),\ T_{16} = 0,$$
$$T_{17} = g_s.\ g_r,\ T_{18} = 0$$

$$T_2 = T_1$$

$$T_{31} = (1-g_s)(1-g_r).\ p_{rd},\ T_{32} = 0,$$
$$T_{33} = (1-g_s)(1-p_{rd}+g_r.p_{rd}),$$
$$T_{34} = 0,\ T_{35} = g_s(1-g_r).\ p_{rd},\ T_{36} = 0,$$
$$T_{37} = g_s(1-p_{rd}+g_r.p_{rd}),\ T_{38} = 0$$

$$T_{41} = T_{42} = 0,\ T_{43} = (1-g_s),$$
$$T_{44} = T_{45} = T_{46} = 0,\ T_{47} = g_s,\ T_{48} = 0$$

$$T_{51} = (1-g_s)(1-g_r).\ p_{sd},$$
$$T_{52} = (1-g_s)(1-g_r).\ p_{sr}.\ p_{ac},$$
$$T_{53} = g_r(1-g_s).\ p_{sd},\ T_{54} = g_r(1-g_s).\ p_{sr}.\ p_{ac},$$
$$T_{55} = (1-g_r)\times[1-p_{sr}-p_{sd}+p_{sd}.\ g_s+p_{sr}(1-p_{ac})],$$
$$T_{56} = g_s(1-g_r).\ p_{sr}.\ p_{ac},$$
$$T_{57} = g_r\times[1-p_{sr}-p_{sd}+\ p_{sd}.\ g_s+p_{sr}(1-p_{ac})]$$
$$T_{58} = g_s.\ g_r.\ p_{sr}.\ p_{ac}$$

$$T_{61} = T_{62} = T_{63} = T_{64} = 0,\ T_{65} = (1-g_r),$$
$$T_{66} = 0,\ T_{67} = g_r,\ T_{68} = 0\ \} \tag{30}$$

$$T_{71} = T_{72} = 0,\ T_{73} = (1-g_s).\ p_{sd}(1-p_{rd}),$$
$$T_{74} = (1-g_s).\ p_{sr}.\ p_{ac}(1-p_{rd})$$
$$T_{75} = (1-g_r)(1-p_{sr}-p_{sd}).\ p_{rd},\ T_{76} = 0,$$
$$T_{77} = (1-p_{sr}-p_{sd})(1-p_{rd})+\ p_{sd}.\ p_{rd}+p_{sr}.\ p_{rd}$$
$$+\ p_{sr}(1-p_{rd})(1-p_{ac})+\ g_s.\ p_{sd}(1-p_{rd})$$
$$+\ g_r(1-p_{sr}-p_{sd}).\ p_{rd}$$
$$T_{78} = g_s.\ p_{sr}.\ p_{ac}(1-p_{rd})$$

$$T_{81} = T_{82} = T_{83} = T_{84} = T_{85} = 0,$$
$$T_{86} = 0,\ T_{87} = 1,\ T_{88} = 0 \tag{31}$$

**Appendix B**

In this appendix, the transition probability matrix of proposed Markovian game for flexible relaying method is presented. To simplify the notation $(T_{ij})$ is used instead of $T_{ij}(\delta)$ to show the transition probability of stationary strategy profile $(\delta)$.

$$T_{11} = (1-g_s)(1-g_r),\ T_{12} = 0,\ T_{13} = g_r(1-g_s),$$
$$T_{14} = 0,\ T_{15} = g_s(1-g_r),$$
$$T_{16} = 0,\ T_{17} = g_s.\ g_r,\ T_{18} = 0$$

$$T_{21} = (1-g_s)(1-g_r).\ p_f,$$
$$T_{22} = (1-g_s)(1-g_r)(1-p_f),$$
$$T_{23} = g_r(1-g_s).\ p_f,\ T_{24} = g_r(1-g_s)(1-p_f),$$
$$T_{25} = g_s(1-g_r).\ p_f,\ T_{26} = g_s(1-gr)(1-p_f),$$
$$T_{27} = g_s.\ g_r.\ p_f,\ T_{28} = g_s.\ g_r(1-p_f)$$

$$T_{31} = (1-g_s)(1-g_r).\ p_{rd},$$
$$T_{32} = 0,\ T_{33} = (1-g_s)(1-p_{rd}+g_r.p_{rd}),$$
$$T_{34} = 0,\ T_{35} = g_s(1-g_r).\ p_{rd},\ T_{36} = 0,$$
$$T_{37} = g_s(1-p_{rd}+g_r.p_{rd}),\ T_{38} = 0$$

$$T_{41} = 0,\ T_{42} = (1-g_s)(1-g_r).\ p_{rd},$$
$$T_{43} = (1-g_s).\ p_f,$$
$$T_{44} = (1-g_s)(1-p_{rd}-p_f+g_r.\ p_{rd}),$$
$$T_{45} = 0,\ T_{46} = g_s(1-g_r).\ p_{rd},\ T_{47} = g_s.\ p_f,$$
$$T_{48} = g_s(1-p_{rd}-p_f+g_r.\ p_{rd})$$

$$T_{51} = (1-g_s)(1-g_r).\ p_{sd},$$
$$T_{52} = (1-g_s)(1-g_r).\ p_{sr}.\ p_{ac},$$
$$T_{53} = g_r(1-g_s).\ p_{sd},\ T_{54} = g_r(1-g_s).\ p_{sr}.\ p_{ac},$$
$$T_{55} = (1-g_r)\times[1-p_{sr}-p_{sd}+g_s.\ p_{sd}+p_{sr}(1-p_{ac})],$$
$$T_{56} = g_s(1-g_r).\ p_{sr}.\ p_{ac},$$
$$T_{57} = g_r\times[1-p_{sr}-p_{sd}+g_s.\ p_{sd}+p_{sr}(1-p_{ac})]$$
$$T_{58} = g_s.\ g_r.\ p_{sr}.\ p_{ac}$$

$$T_{61} = 0,\ T_{62} = (1-g_s)(1-g_r).\ p_{sd}(1-p_f),$$
$$T_{63} = 0,\ T_{64} = g_r(1-g_s).\ p_{sd}(1-p_f),$$
$$T_{65} = (1-g_r).\ p_f\times[1-p_{sr}-p_{sd}$$
$$T_{66} = (1-g_r)[(1-p_{sr}-p_{sd})(1-p_f)$$
$$+(p_{sr}+p_{sd}).\ p_f+p_{sr}(1-p_f)$$
$$+g_s.\ p_{sd}(1-p_f)],$$
$$T_{67} = g_r.\ p_f(1-p_{sr}-p_{sd}),$$
$$T_{68} = g_r\times[(1-psd-p_{sr})(1-p_f)+(p_{sr}+p_{sr})p_f$$
$$+p_{sr}(1-p_f)+g_s.\ p_{sd}(1-p_f)]$$

$$T_{71} = T_{72} = 0,$$
$$T_{73} = (1-g_s).\ p_{sd}(1-p_{rd}),$$
$$T_{74} = (1-g_s)p_{sr}.\ p_{ac}(1-p_{rd})$$
$$T_{75} = (1-g_r)p_{rd}\times[1-p_{sr}-p_{sd}],\ T_{76} = 0,$$
$$T_{77} = (1-p_{sr}-p_{sd})(1-p_{rd})$$
$$+p_{sr}(1-p_{rd})(1-p_{ac})+g_s.\ p_{sd}(1-p_{rd})$$
$$+\ g_r.\ p_{rd}(1-p_{sr}-p_{sd})$$
$$T_{78} = g_s.\ p_{sr}.\ p_{ac}(1-p_{rd})$$

$$T_{81} = T_{82} = T_{83} = 0,$$
$$T_{84} = (1-g_s).\ p_{sd}(1-p_{rd}-p_f),\ T_{85} = 0,$$
$$T_{86} = (1-g_r).\ p_{rd}(1-p_{sr}-p_{sd}),$$
$$T_{87} = p_f\times[1-p_{sr}-p_{sd}],$$

$$T_{88} = (1-p_{sr}-p_{sd})(1-p_{rd}-p_f) + (p_{sd}+p_{sr})(p_{rd}+p_f) + p_{sr}(1-p_{rd}-p_f) + g_s.\ p_{sd}(1-p_{rd}-p_f) + g_r.\ p_{rd}(1-p_{sd}-p_{sr})\ \} \quad (32)$$

**Appendix C**

The state transition matrix of the third proposed model, collision adaptive method is presented. Again, to simplify the notation $(T_{ij})$ is used instead of $T_{ij}(\delta)$ to show the transition probability of stationary strategy profile $(\delta)$.

$$T_{11} = (1-g_s)(1-g_r),\ T_{12}=0,\ T_{13} = g_r(1-g_s),$$
$$T_{14} = 0,\ T_{15} = g_s(1-g_r),$$
$$T_{16} = 0,\ T_{17} = g_s.\ g_r,\ T_{18} = 0$$

$$T_{21} = (1-g_s)(1-g_r).\ p_f,$$
$$T_{22} = (1-g_s)(1-g_r)(1-p_f),$$
$$T_{23} = g_r(1-g_s).\ p_f,\ T_{24} = g_r(1-g_s)(1-p_f),$$
$$T_{25} = g_s(1-g_r).\ p_f,\ T_{26} = g_s(1-gr)(1-p_f),$$
$$T_{27} = g_s.\ g_r.\ p_f,\ T_{28} = g_s.\ g_r(1-p_f)$$

$$T_{31} = (1-g_s)(1-g_r).\ p_{rd},$$
$$T_{32} = 0,\ T_{33} = (1-g_s)(1-p_{rd}+g_r.p_{rd}),$$
$$T_{34} = 0,\ T_{35} = g_s(1-g_r).\ p_{rd},\ T_{36} = 0,$$
$$T_{37} = g_s(1-p_{rd}+g_r.p_{rd}),\ T_{38} = 0$$

$$T_{41} = 0,\ T_{42} = (1-g_s)(1-g_r).\ p_{rd},$$
$$T_{43} = (1-g_s).\ p_f,$$
$$T_{44} = (1-g_s)(1-p_{rd}-p_f+g_r.\ p_{rd}),$$
$$T_{45} = 0,\ T_{46} = g_s(1-g_r).\ p_{rd},\ T_{47} = g_s.\ p_f,$$
$$T_{48} = g_s(1-p_{rd}-p_f+g_r.\ p_{rd})$$

$$T_{51} = (1-g_s)(1-g_r).\ p_{sd},$$
$$T_{52} = (1-g_s)(1-g_r).\ p_{sr}.\ p_{ac},$$
$$T_{53} = g_r(1-g_s).\ p_{sd},\ T_{54} = g_r(1-g_s).\ p_{sr}.\ p_{ac},$$
$$T_{55} = (1-g_r)\times[1-p_{sr}-p_{sd}+g_s.\ p_{sd}+p_{sr}(1-p_{ac})],$$
$$T_{56} = g_s(1-g_r).\ p_{sr}.\ p_{ac},$$
$$T_{57} = g_r\times[1-p_{sr}-p_{sd}+g_s.\ p_{sd}+p_{sr}(1-p_{ac})]$$
$$T_{58} = g_s.\ g_r.\ p_{sr}.\ p_{ac}$$

$$T_{61} = 0,\ T_{62} = (1-g_s)(1-g_r).\ p_{sd}(1-p_f+p_f.\ ssd),$$
$$T_{63} = 0,\ T_{64} = g_r(1-g_s).\ p_{sd}(1-p_f+p_f.\ ssd),$$
$$T_{65} = (1-g_r).\ p_f\times[1-p_{sr}-p_{sd} + p_{sr}(1-p_e(r|d)) + p_{sd}.\ p(\bar{s},r|d),$$
$$T_{66} = (1-g_r)[(1-p_{sr}-p_{sd})(1-p_f) + p_{sr}.\ p_f.\ p_e(r|r) + p_{sd}.\ p_f.\ p(\bar{s},\bar{r}|d) + p_{sr}(1-p_f) + g_s.\ p_{sd}(1-p_f+p_f.\ sdd)],$$
$$T_{67} = g_r.\ p_f(1-p_{sr}-p_{sd}+p_{sr}(1-p_e(r|r)) + p_{sd}.\ p(\bar{s},r|d)),$$
$$T_{68} = g_r\times[(1-psd-p_{sr})(1-p_f) + p_{sr}.\ p_f.\ p_e(r|r) + p_{sd}.\ p_f.\ p(\bar{s},\bar{r}|d) + p_{sr}(1-p_f) + g_s.\ p_{sd}(1-p_f+p_f.\ ssd)]$$

$$T_{71} = T_{72} = 0,$$
$$T_{73} = (1-g_s).\ p_{sd}(1-p_{rd}+p_{rd}.\ p(s,\bar{r}|d),$$
$$T_{74} = (1-g_s)p_{sr}.\ p_{ac}(1-p_{rd})$$

$$T_{75} = (1-g_r)p_{rd}\times[1-p_{sr}-p_{sd}+p_{sd}.\ p(\bar{s},r|d) + p_{sr}(1-p_e(r|r))],\ T_{76} = 0,$$
$$T_{77} = (1-p_{sr}-p_{sd})(1-p_{rd}) + p_{sd}.\ p_{rd}.\ p(\bar{s},\bar{r}|d) + p_{sr}.\ p_{rd}.\ p_e(r|r) + p_{sr}(1-p_{rd})(1-p_{ac}) + g_s.\ p_{sd}(1-p_{rd}+p_{rd}.\ p(s,\bar{r}|d) + g_r.\ p_{rd}(1-p_{sr}-p_{sd}+p_{sd}.p(\bar{s},r|d)+p_{sr}(1-p_e(r|r)))$$
$$T_{78} = g_s.\ p_{sr}.\ p_{ac}(1-p_{rd})$$

$$T_{81} = T_{82} = T_{83} = 0,$$
$$T_{84} = (1-g_s).\ p_{sd}(1-p_{rd}-p_f+(p_{rd}+p_f)p(s,\bar{r}|d),\ T_{85} = 0,$$
$$T_{86} = (1-g_r).\ p_{rd}(1-p_{sr}-p_{sd}+p_{sd}.\ p(\bar{s},r|d) + p_{sr}(1-p_e(r|r))),$$
$$T_{87} = p_f\times[1-p_{sr}-p_{sd}+p_{sd}.\ p(\bar{s},r|d)+p_{sr}(1-p_e(r|r))],$$
$$T_{88} = (1-p_{sr}-p_{sd})(1-p_{rd}-p_f) + p_{sd}(p_{rd}+p_f).\ p(\bar{s},\bar{r}|d) + p_{sr}(1-p_{rd}-p_f) + p_{sr}(p_{rd}+p_f)p_e(r|r) + g_s.\ p_{sd}\times[1-p_{rd}-p_f+(p_{rd}+p_f).\ p(s,\bar{r}|d] + g_r.\ p_{rd}\times[1-p_{sd}-p_{sr}+p_{sd}.\ p(\bar{s},r|d)+p_{sr}(1-p_e(r|r))]\} \quad (33)$$

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