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Game theoretic approach in routing protocol for wireless ad hoc networks

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ABSTRACT

This paper introduces a game theoretic method, called forwarding dilemma game (FDG), which controls routing overhead in dense multi-hop wireless ad hoc networks. The players of the game are the wireless nodes with set of strategies {*Forward*, *Not forward*}. The game is played whenever an arbitrary node in the network receives a flooding packet. In FDG, every player needs to know the number of players of the game. That is why a neighbor discovery protocol (NDP) is introduced. In order for NDP to function, a field is attached to the flooding packets (routing overhead packets). The mixed strategy Nash equilibrium is used as a solution for the FDG. This provides the probability that the flooding packet would be forwarded by the receiver node. FDG with NDP is implemented in AODV protocol in Network Simulator NS-2 to verify its performance with simulations. FDG with NDP improves performance of the AODV compared to the same network with only AODV protocol in moderate and high node densities. FDG can be applied to any routing protocol that uses flooding in the route discovery phase.

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1. Introduction

Mobile ad hoc networks (MANETs) have received significant attention in recent years. Applications of this type of network range from military and disaster response applications to connecting a group of computers in a classroom. Numerous routing protocols have been introduced for ad hoc networks. Broadly, these protocols can be classified as 1. proactive routing protocols and 2. on-demand (reactive) routing protocols. In proactive routing, routing information is periodically exchanged between network nodes, while in reactive protocols, the routing information is obtained only when it is needed. Flooding is used as the basic mechanism to propagate control packets in reactive routing protocols such as AODV [1] and DSR [2] or for data forwarding in MANETs. Unfortunately, it has been shown that flooding is a problem even in networks with moderate node densities [3]. Flooding generates a large number of

redundant packets that consume network resources like bandwidth and power, and causes contention, packet collision, packet loss, and delays. Since flooding is a fundamental method in almost every routing protocol for wireless ad hoc networks, a more efficient flooding algorithm could significantly improve the performance of the routing. However, reducing the number of redundant flooding messages may cause disconnectivity in the network. Therefore, a delicate balance must be maintained between routing overhead related to flooding and connectivity. To reduce the number of redundant messages, two mechanisms have been proposed in the literature: (1) clustering and (2) selective dropping of flooding. Clustering or cluster-based routing [4,5] can be described as grouping nodes into clusters. A representative of each group is called the cluster head and other nodes are called cluster members. In order to form and maintain clusters, network nodes need to cooperate and exchange information with each other which may increase the control overhead packets. Passive clustering [5] has been proposed to exploit ongoing data traffic to propagate cluster related information. Although passive clustering eliminates cluster related overhead packets during the formation and maintenance of clusters,

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it still requires some partial information about the neighbors and ongoing data traffic. Another mechanism to reduce flooding is to selectively decrease the number of messages. These mechanisms could be loosely classified as probabilistic schemes [3,6–9] or location-based schemes [10,11]. The simplest probabilistic approach is pure probabilistic flooding [3] in which nodes that receive a broadcast packet retransmit the packet with some probability p or discard (drop) the packet with probability $(1 - p)$. There is a critical value for p that depends on the number of neighbors of a node [7]. As the number of neighbors of each node increases, the critical value of p would decrease. The major problem of probabilistic schemes is that the probability at which a node would rebroadcast is not universal, but specific to each network topology and there is no analytical formula to obtain the probability p . Local topology information is used to avoid unnecessary rebroadcasts in location-based schemes. In [11,12], self-pruning and neighbor-coverage schemes are proposed where a node does not rebroadcast if the packet is delivered to all neighbors of this node by a prior broadcast.

Our approach in this paper falls into selectively reducing the number of flooding messages by applying Game Theory. Game Theory is not new to the area of telecommunications and wireless networks. It has been used to model the interaction between users, to eliminate the selfish nodes and to coordinate nodes in ad hoc networks. The topology control problems in ad hoc networks were studied and modeled as non-cooperative games in [13]. In that model, network nodes can choose their power level to ensure desired connectivity. The model was divided into connectivity and reachability games. In the connectivity game, a node chooses a power level that sustains connection to other nodes while minimizing its cost. In the reachability game, each node tries to reach as many other nodes as possible while minimizing its transmission range. A cooperation enforcement mechanism based on game theory has been proposed in [14,15] that provides the study and analysis of strategies for cooperation and packet forwarding enforcement among nodes. Basically, a node analyzes the past behavior of its neighbors as well as the availability of its resources prior to choosing its next action. Additionally, the cooperation game was described and investigated in [14] as a repeated game for ad hoc networks with a tit-for-tat (TFT) strategy, applying cooperation enforcement. It was shown that by implementing such a strategy in the ad hoc network, a node will not forward more packets than it sends on average. In [15], nodes of the network were classified based on their energy level. Normalized acceptance rate (NAR), the ratio of the number of forwarded packets by the node to the number of forward requests, was considered as an evaluation metric for every node. Generous tit-for-tat (GTFT) strategy was investigated in cooperating repeated game in [15] as well. It was proved that GTFT is a Nash equilibrium and converges to the rational and Pareto optimal NARs. In [16], a game theoretic framework based on the Nash bargaining game was introduced that solved the selfishness problem while reserving bandwidth in the forwarding node's neighborhood. The authors showed that Nash equilibrium could be considered as a pricing scheme that provides optimality in bandwidth res-

ervation and that applying the game theoretic model efficiently eliminated selfish nodes. A game theoretic approach for the analysis of slotted Aloha with selfish users was proposed in [17]. It was shown that the performance of the selfish slotted Aloha system is near optimum, and the system performance is close to the best non-game theoretic systems. In [18], slotted Aloha with multi-packet reception was studied and it was proved that the stability of a slotted Aloha system with multi-packet reception with selfish users is dependent on the transmission cost of a packet. It was also shown that the throughput of a MAC protocol with selfish users could be lower than that of other slotted Aloha implementations. One-shot random access game introduced in [19] analyzed the behavior of the nodes using the tools of game theory. It was shown that the mixed strategy Nash equilibrium provided the focal equilibrium among $2^n - 1$ equilibrium points of the game, and that it had fairness property as well.

In this paper, a game theoretic framework called forwarding dilemma game (FDG) will be introduced where wireless nodes of the network are the players of the game. The game is played when a node receives a flooding packet from other nodes in the network. The player has two strategies to play: 1. forward the packet or 2. drop (not forward) the packet. The FDG has three components: 1. number of players, N , the number of nodes that are receiving the flooding packet, 2. forwarding cost, and 3. network gain factor, G . Mixed strategy Nash equilibrium will be employed to provide the probability of forwarding the flooding messages. In order to enable nodes to discover the number of the players of the FDG, a neighbor discovery protocol (NDP) will also be introduced. In NDP, wireless nodes use either medium access messages or HELLO messages that are inherent in some of the routing protocols such as AODV and WRP [20]. In this paper, the FDG is implemented in AODV with existing HELLO messages where these messages are used for NDP with slight modification. The FDG limits the number of nodes that participate in the route discovery of the protocol without disturbing the connectivity. By conducting connectivity tests, we verified that FDG not only improved connectivity in dense networks, but also improved the network performance. This architectural change that reduces the routing overhead significantly helps nodes to find routes faster and reduces contention in the MAC layer. All of these would reduce the average end-to-end delay.

The rest of the paper is organized into five sections. Section 2 discusses the proposed forwarding dilemma game. Section 3 presents the implementation of the FDG in AODV protocol. Section 4 investigates an optimum value for the network gain factor, G , through analysis and simulations. Section 5 presents NS-2 simulation results for the proposed protocol and compares the results with those of AODV. Section 6 provides the conclusions of this study.

2. Forwarding dilemma game

In MANETs, the connection between the nodes is established by the flooding of data packets or control packets (route discovery part of the reactive routing protocol). In

either case, flooding or rebroadcasting is the most reliable technique to transfer data packets to a destination node or to find a route between source and destination. Fig. 1 depicts a portion of a wireless ad hoc network where a source node, S , has a data packet to be sent to a destination node that is located outside of its wireless transmission range. Nodes that are located in the wireless transmission range of source node S are neighbors of S . If the routing protocol is simply flooding, S will broadcast the data packets and then these data packets are rebroadcasted by every neighbor of S , and every other node that receives them from the neighbors of S , until they reach the destination. When reactive routing protocols such as DSR or AODV are utilized, instead of broadcasting data packets, S initiates a route discovery protocol that involves broadcasting smaller route request (RREQ) packets. The RREQ packets are rebroadcasted (i.e. flooded) by neighbors of S and any other node that receives the RREQ from neighbors of S . When the RREQ arrives at the destination node, the path is discovered from the route that the RREQ traveled through to get to the destination. Then the destination node sends the discovered route to the source node using the route reply packet (RREP). When the source node receives the RREP, it starts sending data packets through the route that was returned by RREQ. If the network is dense, there will be a lot of redundant broadcasts of RREQ and RREP packets. That redundancy not only makes the route selection complicated, but also degrades the overall performance of the network because of the shared wireless channel. In a shared medium, overhead packets increase delay per packet and the number of collisions, which in turn degrades the packet delivery ratio and throughput. Here, we investigate if a game theoretic packet forwarding model in a multi-hop network can be used to minimize the degrading effect of flooding in dense MANETs. Game theory is a part of applied mathematics that describes and studies interactive and multi-player decision-making problems. Decision makers (i.e. players) follow certain objectives while considering knowledge or expectations of other decision makers. Game theory has been widely applied in economics, social science, and biology [21–23].

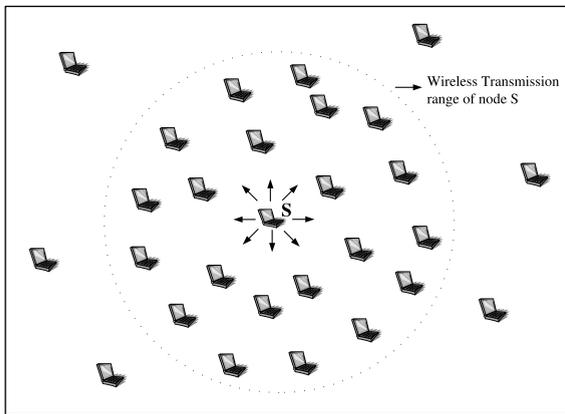


Fig. 1. Forwarding game played among neighboring nodes of the source node S .

Here, a forwarding game is defined as

$$G = \{N, (S_i)_{i \in N}, (U_i)_{i \in N}\}, \tag{1}$$

where N is the number of participating wireless nodes (players of the game), S_i is the strategy set, and U_i is the utility function for the node (player) i . Strategy S_i is the action set of the node i and $S_i = \{0, 1\}$, where $S_i = 1$ denotes that node i is forwarding while $S_i = 0$ denotes that node i is not forwarding the flooding message. If the node chooses to forward, it is called a Forwarding Node (FN) or a Mobile Node (MN). Node i will receive utility U_i upon choosing a strategy. The game defined in Eq. (1) is played whenever arbitrary node i receives a packet p_{jk} that is destined for node k from node j . Here node i needs to make a decision whether to forward p_{jk} or not. The number of players of the game is the number of nodes that receive p_{jk} in the same time slot as node i .

It is desirable that only a limited number of neighbors of the source node participate in forwarding. This strategy will improve resource utilization by reducing the number of overhead packets, which in turn improves the performance of the network. The problem is the selection of the necessary number of neighbors. This problem is similar to a situation in public economics where players would like to save their resources. Only some contributors are needed to bear the cost while the benefit is enjoyed by all players. In a voluntary contribution game, each person in a group must decide whether to make a costly contribution or to rely on others' contributions. Diekman [24,25] introduced a game in which a collective good can be provided by a volunteer from a group of players. Here, Diekman's game is adopted to the game of forwarding or not forwarding a flooding packet and is called the forwarding dilemma game (FDG). In this game, every node in the network has a cost for rebroadcasting packets for other nodes. Because of the forwarding cost in the model, neighbors will not forward the flooding packet right away, but expects other neighboring nodes to forward. Let $N > 1$ be the number of players. Arbitrary player i chooses between forwarding ($S_i = 1$) and not forwarding ($S_i = 0$). A node that forwards bears a cost of $f(c)$, where c is the forwarding cost and $f(\cdot)$ is a decreasing function. Utility G_i denotes the gain or benefit that node i receives if at least one of the players of the game spends the forwarding cost and forwards the packet. Utility of node i in FDG is defined as

$$U_i(S) = \begin{cases} G_i - f(c_i) & \text{if } S_i = 1 \\ G_i & \text{if } S_i = 0, \text{ and } \exists S_j = 1 \text{ for some } j \neq i, \\ 0 & \text{if } S_j = 0 \text{ for all } j \end{cases} \tag{2}$$

where N players are neighbors of the originator of the flooding packet and are receiving the flooding packet in the same time slot. G_i and $f(c_i)$ are the utility and cost function for arbitrary node i , related to the flooding packet under process. The game has N equilibria with exactly one forwarding node and $N - 1$ mobile nodes. There exists also a mixed strategy equilibrium. If arbitrary node i forwards the flooding packet with probability p_i , the expected utility of node i can be written as

$$E[U_i] = p_i(G_i - f(c_i)) + G_i \left((1 - p_i) \left(1 - \prod_{j \neq i} (1 - p_j) \right) \right). \quad (3)$$

The best response function for the players can be written as

$$\frac{\partial E[U_i]}{\partial p_i} = -f(c_i) + G_i \prod_{j \neq i} (1 - p_j). \quad (4)$$

Setting the derivative equal to zero, we get the following system of equations

$$f(c_i) = G_i \prod_{j \neq i} (1 - p_j). \quad (5)$$

If we denote $\lambda_i = \frac{f(c_i)}{G_i}$ and $q_i = (1 - p_i)$, the system of Eq. (5) can be written as

$$\begin{cases} q_2 q_3 \dots q_{N-1} q_N = \lambda_1 \\ q_1 q_3 \dots q_{N-1} q_N = \lambda_2 \\ \vdots \\ q_1 q_2 \dots q_{N-2} q_N = \lambda_{N-1} \\ q_1 q_2 \dots q_{N-2} q_{N-1} = \lambda_N \end{cases} \quad (6)$$

If we multiply the above N equations, we can write:

$$(q_1 q_2 q_3 \dots q_{N-1} q_N)^{N-1} = \lambda_1 \lambda_2 \dots \lambda_{N-1} \lambda_N. \quad (7)$$

The forwarding probability of arbitrary node i , p_i , can be written by substituting Eq. (6) into Eq. (7):

$$p_i = 1 - \frac{\sqrt[N-1]{\prod_{j=1}^N \lambda_j}}{\lambda_i}. \quad (8)$$

The cost function $f(c)$ is considered a decreasing function to encourage nodes with lower cost to increase their forwarding probability.

In the case where the gain and forwarding cost of the nodes are equal ($\lambda_1 = \lambda_2 = \dots = \lambda_N$), the forwarding dilemma game (FDG) will be symmetric and can be depicted in the matrix form shown in Fig. 2. Please note that the source node S is not necessarily the originator of the packet and it could be any intermediate node that is forwarding a flooding packet, such as RREQ packets. Player one (row player) in the FDG of Fig. 2 is any node that has received a flooding packet and needs to make a decision to forward or not forward that packet based on the forwarding game. The column player of the forwarding game of Fig. 2 are other $(N - 1)$ neighbors of S . If player 1 forwards, its utility will be $G - C$ regardless of the action of other neighbors. If none of the neighbors forward, then all of them lose and receive a payoff of 0. It is assumed that $C < G$, so each node would

		"N-1" Other Players	
		"All" Not Forward	At least "one" Forwards
Player 1	Not Forward	0	G
	Forward	G - C	G - C

Fig. 2. Symetric forwarding dilemma game (FDG) matrix.

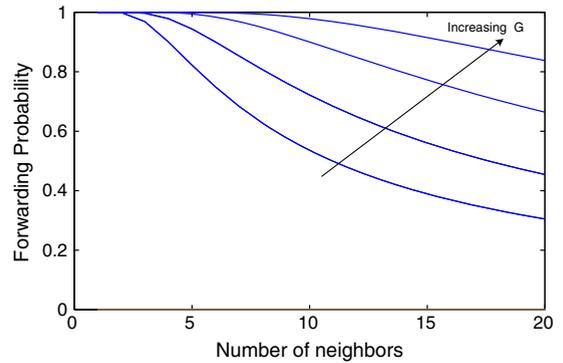


Fig. 3. Forwarding probability changes with node density of the network and the defined gain G for the nodes, $C = 1$.

prefer to forward if no other node does. But if one node is expected to forward, then each of the others would prefer to “free ride” and would not spend their energy and occupy unnecessary bandwidth.

The forwarding game depicted in Fig. 2 has N equilibria, where only one node forwards and the other nodes do not forward. Since the players (nodes) make independent decisions, the strategy chosen by the players is unknown by others. On the other hand, since $G - C > 0$, there exists no dominant strategy.¹ In a symmetric mixed strategy² Nash equilibrium for the forwarding game of Fig. 2, let us denote the forwarding probability (probability that a player chooses the “Forward” strategy) as p , consequently probability that a player plays the “Not Forward” strategy is $(1 - p)$. All $(N - 1)$ other players will not forward with a probability of $(1 - p)^{N-1}$. Therefore, we can write the probability of having at least one forwarding node out of the $(N - 1)$ neighbors as $1 - (1 - p)^{N-1}$. With that, the mixed strategy Nash equilibrium can be constructed as follows:

$$G - C = G(1 - (1 - p)^{N-1}). \quad (9)$$

From the above equation, the probability of forwarding can be calculated as

$$p = 1 - \left(\frac{C}{G} \right)^{\frac{1}{N-1}}. \quad (10)$$

In Eq. (10), if $C < G$, then $\frac{C}{G} < 1$. Therefore, the probability of forwarding for an arbitrary node decreases when the number of neighbors, N , increases. For example, in the limiting cases, while N is changing from 1 to infinity, the probability of forwarding will be changing from 1 to 0. Fig. 3 depicts the forwarding probability that is given in Eq. (10) with increasing number of neighbors of the source, from 1 to 20, for different values of network gain, G . When the number of neighbors of the source is lower, the forwarding probability is higher. For example, for $N = 1$, regardless of the value of G and forwarding cost C , the forwarding probability will be 1. In a denser network, the number of neighbors of the source will be higher than 1, and every node

¹ Dominant strategy for a player is the one that yields the best utility regardless of the strategies that other players choose.

² Mixed strategy for a player is a probability distribution over the set of pure strategies of that player.

will reduce its forwarding probability. For example, for $N = 20$, the forwarding probability can be between 0.3 and 0.8, as shown Fig. 3, based on the parameter G that was defined for the network. This defines G as an important parameter that controls the decision process in the node, consequently routing overhead in the network. The selection of the value for G and its effect on network performance will be investigated in the following sections.

3. Implementation of forwarding dilemmas game in AODV

In this section, the implementation of the forwarding dilemma game (FDG) into AODV routing protocol is explained. In the AODV protocol, HELLO messages are periodically broadcasted by nodes and are used for link monitoring. When node A receives a HELLO message from node B , it discovers that node B is in its wireless transmission range and therefore its neighbor. On the other hand, not receiving a HELLO message from a node is interpreted as a broken link. In order to utilize AODV HELLO messages to obtain neighbor information for FDG, a neighbor discovery protocol (NDP) is introduced in Fig. 4. In NDP, it is assumed that the links are symmetric. The source ID of the sender is deciphered from the header of the HELLO messages. Every node generates a time-stamped list of its neighbors (i.e. the source ID of the HELLO message that it has received). The neighbor list is updated periodically and outdated entries are removed. The number of neighbors of a node is the number of entries in the updated neighbor list.

In order to implement the FDG protocol, the route discovery process and the structure of RREQ packets in AODV protocol is modified. An extra field is added to the RREQ to carry the number of neighbors of the source node. Fig. 5 shows the modification in the route discovery process of AODV. When a source node generates a RREQ packet, in addition to its ID, it also inserts the number of its neighbors N , into the RREQ packet. This is also done at the intermediate nodes. When the RREQ packet is forwarded by an intermediate node, the number of neighbors of the intermediate node as well as its ID is inserted into the related fields of the RREQ packet. When the RREQ is received by other nodes, the number of neighbors, N , of the originator (forwarder) of the RREQ can be discovered. Using N in Eq. (10), the receiver of the RREQ can calculate the probability of forwarding for that RREQ. Then, the forwarding probability is compared to a generated uniform random number to make the forwarding decision. In the FDG protocol, if the source node does not receive a RREP from the destination for any reason (e.g. link quality), it initiates another RREQ. Nodes that did not forward the RREQ in the previous round increase their forwarding probability by 20% each time. This is similar to the ring search technique in AODV and guarantees arrival of the RREQ at the destination.

4. Disconnectivity vs. greedy flooding: optimum value for G

In the previous section, the forwarding dilemma game (FDG) and a mixed strategy Nash equilibrium as the solu-

tion of this game were explained. The probability of forwarding for every node, derived in Eq. (10), depends strictly on the network gain parameter G . Without the loss of generality in this investigation, a forwarding cost of $C = 1$ is assumed. The investigation shifts to determining the range of values for parameter G , such that network connectivity is established with minimum routing overhead. When G is low, the forwarding probability is low, which might cause isolated nodes and disconnectivity in the network. In this case, the cost-gain ratio $\frac{C}{G}$ is not large enough to encourage selfish nodes to forward a packet for others. On the other hand, for high values of G , nodes increase their forwarding probability to obtain high utility value. When $G \rightarrow \infty$, the performance of the protocol would not improve by FDG. This case is called greedy flooding. There has been extensive research conducted on the connectivity conditions of ad hoc networks. The critical power and the number of neighbors needed to obtain overall network connectivity by using stochastic modeling is analyzed in [26]. Authors showed that the critical neighbor number (CNN) for connectivity is $k \log N$, with $0.074 < k < 5.1774$. Determining the minimum number of nodes that is required for full connectivity in a stationary network with uniform node spatial distribution is formulated in [27]. That formulation showed that in an ideal case, without inter-node interference, the minimum number of neighbors required for full connectivity is π . Under the guidance of the results presented in [26,27], it is considered that, on average, 4 neighbors for each node would suffice to establish connectivity among the nodes with high probability. If a node is processing a packet whose source has fewer than 4 neighbors, it should have a probability of forwarding, p , in the range of $0.9 \leq p \leq 0.99$. In other words, if q is the probability of not forwarding, then q is required to be in the range $0.01 \leq q \leq 0.1$. Hence, Eq. (10) can be rewritten for q as

$$q = \left[\frac{C}{G} \right]^{\frac{1}{N-1}}. \quad (11)$$

By taking the logarithm of both sides of Eq. (11), the following can be obtained

$$(1 - N) \log q = \log(G). \quad (12)$$

Since it is required to have $0.01 \leq q \leq 0.1$ for $N \leq 4$, the network gain G should be in the range of $3 \leq \log(G) \leq 6$ to provide optimum operation. This range provides equitable trade offs between connectivity and network performance.

In order to verify the feasible values of G and to test the effect of G on network performance, we performed a series of experiments utilizing network simulator (NS-2) [28]. In the simulations, nodes were uniformly distributed in an area of 1000 by 1000 m. The network gain factor G was varied in the simulations, and forwarding cost C was set to 1 for all nodes. There were 60 sources with CBR (constant bit rate), where each were sending one 512 byte packet per second. The source nodes and their start time were randomly chosen. Simulations ran for 200 s with modified AODV routing protocol with the FDG. In order to explore the effect of different node densities on the

```

1 ReceiveHelloMessage(*Packet Hello){
2 ·   // Extracting the source of the packet
3 ·   SourceID=Hello → src;
4 ·   Call CreateNeighborList(SourceId);
5 }
6 CreateNeighborList(ThisNeighborId) {
7 ·   //search the list and add it if it is not in the list.
8 ·   if (SearchNeighborList(ThisNeighborId)=0) {
9 ·   ·   for i = 1 to ListSize
10 ·   ·   {
11 ·   ·   ·   //Find the end of the list and add it there
12 ·   ·   ·   if (NeighborList[i] → NeighborId = emty)
13 ·   ·   ·   {
14 ·   ·   ·   ·   MyNeighborList[i] → NeighborId=SourceId
15 ·   ·   ·   ·   MyNeighborList[i] → Time=CurrentTime
16 ·   ·   ·   ·   break;
17 ·   ·   ·   }
18 ·   ·   }
19 ·   }
20 }
21
22 Bool SearchNeighborList(ThisNeighborId) {
23 ·   for i = 1 to ListSize
24 ·   {
25 ·   ·   if (NeighborList[i] → NeighborId≠ ThisNeighborId)
26 ·   ·   {
27 ·   ·   ·   //This was already in the list
28 ·   ·   ·   MyNeighborList[i] → Time=CurrentTime
29 ·   ·   ·   return 1;
30 ·   ·   ·   break;
31 ·   ·   }
32 ·   ·   else {
33 ·   ·   ·   return 0;
34 ·   ·   }
35 ·   }
36 }
37 UpdateNeighborList(NodeId) {
38 ·   //Entries older than ExpPeriod seconds are expired
39 ·   Expired=CurrentTime -ExpPeriod
40 ·   for i = 1 to ListSize
41 ·   {
42 ·   ·   if (NodeId → MyNeighborList[i] → Time < ExpiredTime)
43 ·   ·   {
44 ·   ·   ·   //remove this neighbor from the list
45 ·   ·   }
46 ·   }
47 }
48 //This function is called when a node needs neighbors count
49 CountMyNeighbors(MyNodeId){
50 ·   Call UpdateNeighborList(MyNodeId)
51 ·   for i = 1 to ListSize {
52 ·   ·   if (MyNodeId → MyNeighborList[i] → NeighborId ≠ Empty)
53 ·   ·   ·   NeighborCount ++;
54 ·   }
55 ·   return NeighborCount;
56 }
57
58

```

Fig. 4. Integrating NDP with AODV.

results, experiments with 100 and 160 nodes were performed as well. Figs. 6 and 7 depict average end-to-end delay and packet delivery ratio of the network, respectively, for different values of network gain factor, G . For smaller values of G , the incentive to forward packets is minimal

compared to the cost (e.g. $\log(G) < 3$). Since the forwarding probability calculated by the nodes is small, the chance that RREQ packets do not reach the destination in the first round is high. In that case, the RREQ packet is re-sent by the source, and the receiving nodes increase their forward-

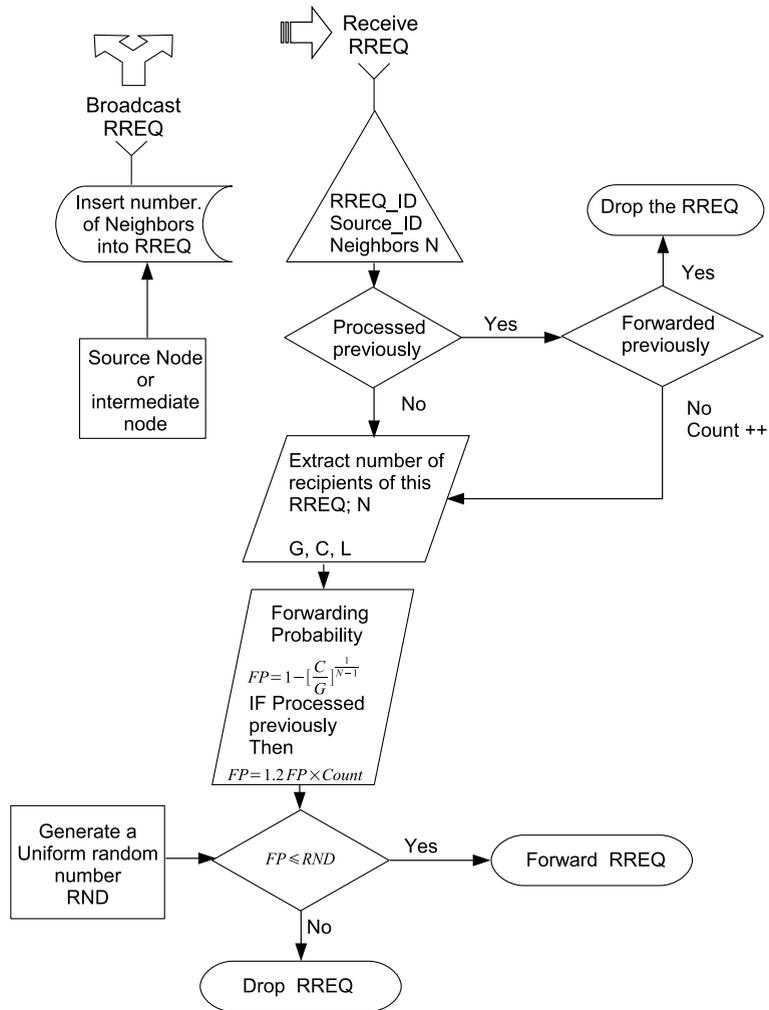


Fig. 5. Flowchart: implementing the forwarding game protocol.

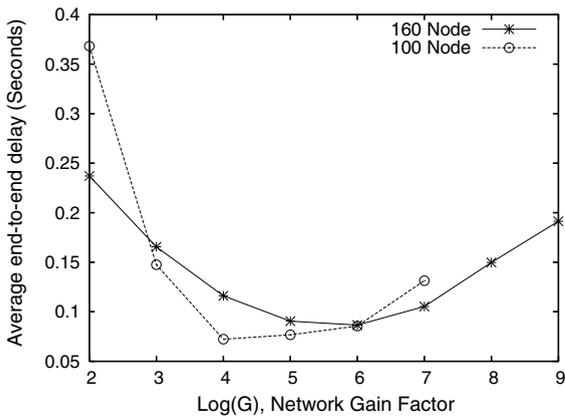


Fig. 6. Average end-to-end delay vs. network gain factor G.

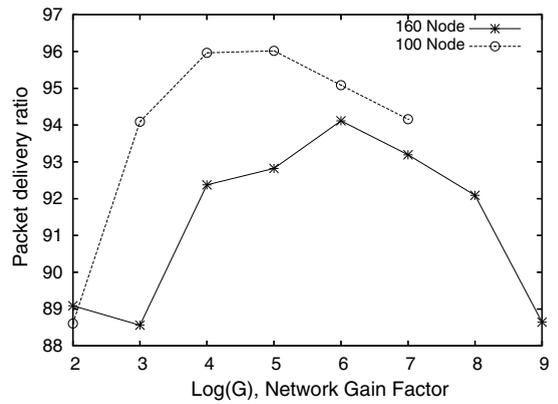


Fig. 7. Packet delivery ratio vs. network gain factor G.

ing probability by 10%. This explains higher than average end-to-end delay for smaller values of G (Fig. 6). For $\log(G) \geq 6$, the average end-to-end delay starts to in-

crease. This shows that due to high utility, nodes increase their forwarding probability up to a point where every node decides to forward RREQs. The simulation results

confirm that the near optimum value for $\log(G)$ is between 4 and 6.

5. Simulation model and results

In order to evaluate performance and verify connectivity of the FDG with AODV protocol, NS-2 simulations were performed. In the simulations, the effective transmission range of the wireless radio was 250 m and the medium access control (MAC) protocol was IEEE 802.11 with 2 megabits per second channel capacity. IEEE 802.11 MAC was in distributed coordination function mode and used request-to-send (RTS) and clear-to-send (CTS) control packets [29] for unicast data transmission to a neighboring node. The RTS/CTS exchanges precede the data packet transmission and implement a form of virtual carrier sensing and channel reservation to reduce the impact of the hidden terminal problem. Data packet transmission is followed by an ACK. To compare the performance of the proposed protocol, the FDG with AODV, and only AODV, the following metrics were considered:

- Average end-to-end delay per packet is the end-to-end delay (in seconds) for successfully received packets.
- Packet delivery ratio is the ratio between the number of successfully received packets and the number of generated packets by the CBR sources.
- Normalized routing overhead is the number of routing packets per one data packet that is successfully received at the destination.

5.1. Connectivity

Connectivity is a major concern in any routing protocol for ad hoc networks. Because the FDG functionality is based on probability, one concern is that flooding messages may not be forwarded by some of the nodes. In FDG, if the source node does not receive a reply from the destination, the flooding packet will be rebroadcasted by the source. Neighbors that have not forwarded the flooding packet in the previous rounds, increase their forwarding probability by 20% in each round. A test was conducted to verify connectivity in FDG and compare it with AODV results. In this test, source and destination nodes are positioned at two diagonal corners in a 1000 by 1000 m field, while other nodes are uniformly distributed in the area and do not generate data packets. All of the nodes are static and there is no mobility. At the beginning of the simulation the source node generates only one data packet for the destination node. To discover the route, a RREQ packet is broadcasted by the source. If source does not receive a RREP from the destination within a certain time (30 ms in this setup), it broadcasts another RREQ up to a predefined number of times (4 times in our setup) [1]. If the data packet is not received by the destination within 4 s, this event is declared as disconnectivity, otherwise it is counted as connectivity. The number of nodes in the network were varied from 40 to 180 nodes, and simulations were repeated 1000 times for every scenario with different ran-

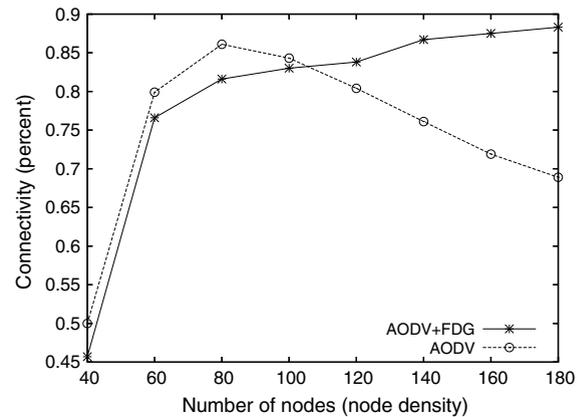


Fig. 8. Connectivity vs. number of nodes.

dom seeds. The average of those simulations is shown in Fig. 8. Disconnectivity is expected in low node density regardless of the routing protocol (e.g. 40 nodes). Connectivity in network with FDG was close to the one with AODV in moderate node densities (60–100 nodes). Surprisingly, connectivity in the network with AODV dropped when the number of nodes in the network increased more than 80 nodes. This is related to the broadcast storm problem discussed previously. Our investigation showed that AODV with FDG not only matches the connectivity achieved by AODV alone, but also improves connectivity in moderate to high node densities.

5.2. Performance evaluation

Previously, we claimed that implementing FDG in AODV improves the performance of the routing protocol. We conducted NS-2 simulations to verify our claim. In the simulations, the traffic sources were generated by constant bit rate (CBR) sources with 512 bytes per packet, which were started randomly during the simulations and continued until the data packets were transferred. Source and sink nodes were chosen based on a uniform distribution at the beginning of each simulation. All the sources had a certain amount of data that needed to be transferred to the sinks. Nodes were randomly distributed in the area in each simulation, therefore their locations were different in every simulation. Five NS-2 simulations were run for every scenario, and the reported results are the average of these simulation runs.

In order to show if FDG enhances the performance of the network at different node densities compared to AODV alone, the number of nodes in a 1000 by 1000 m area were varied. The nodes were uniformly distributed to that area randomly. The 60 communication pairs remained the same for all scenarios. Therefore the results only reflected the change due to the increasing number of nodes or node densities. The simulation time was 200 s, and the data packet rate of the CBR was 1 packet per second for all scenarios. The number of wireless nodes varied between 130 and 250. Figs. 9–11 show normalized overhead, packet delivery ratio, and average end-to-end delay per packet versus the number of nodes in the network, respectively. The routing

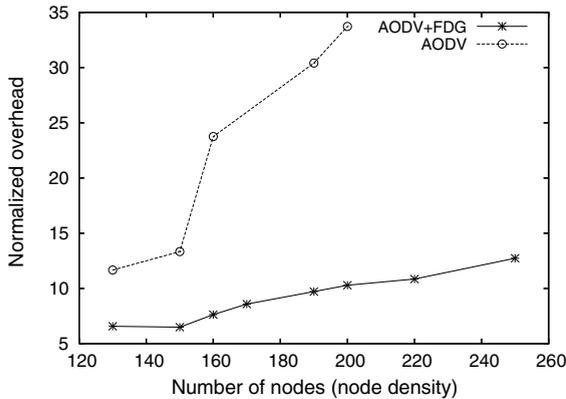


Fig. 9. Normalized overhead vs. number of nodes.

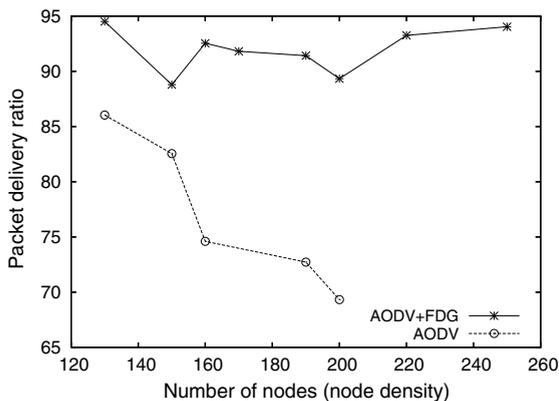


Fig. 10. Packet delivery ratio vs. number of nodes.

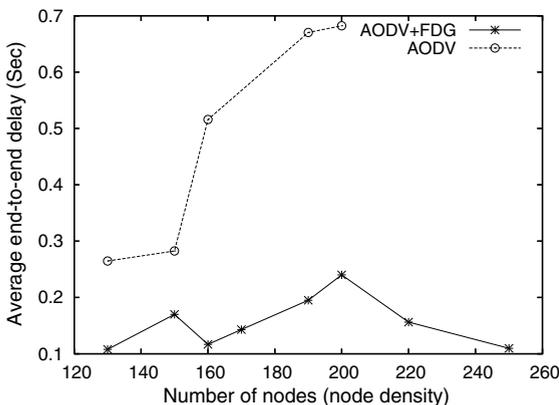


Fig. 11. Average end-to-end delay vs. number of nodes.

overhead was lower in networks that employed AODV with FDG than AODV alone, because AODV with FDG selectively eliminated RREQ packets. The result reported in Fig. 9 confirms the fact that the normalized routing overhead was 2–3 times lower in AODV with FDG. Fig. 10 shows the packet delivery ratios of the network with two competing protocols. As shown in the figure, the delivery

ratio of the modified routing protocol outperforms the AODV protocol alone. The difference was significant (3–5 times higher) especially at higher node densities. The modified protocol performed and delivered close to 95% of the data packets; whereas the non-modified protocol did not work at all. Reduction in routing overhead also helped reduce the average delay. Fig. 11 compares the average end-to-end delay in using AODV with FDG, versus using AODV alone with all other network parameters held the same. The network with the FDG was not sensitive to the increasing node densities, whereas the network with AODV showed a sharp increase in packet delay with increasing node densities.

6. Conclusions

This paper introduced a game theoretic approach, called forwarding dilemma game (FDG), for forwarding the flooding packets in wireless ad hoc networks. The FDG provides nodes the use of a strategy set $S = \{Forward, NotForward\}$. The probability of the selected strategy is then calculated based on the mixed strategy Nash equilibrium of the game. This limits the number of redundant broadcasts in dense networks while still allowing connectivity. This approach has two advantages over previously proposed methods used to control flooding. Firstly, nodes employ FDG to calculate the probability of forwarding adaptively. Secondly, unlike hierarchical or clustering methods, the proposed modification does not cause extra routing overhead. Simulation results show that AODV with FDG outperforms the AODV routing protocol, especially in dense network scenarios where routing overhead is a dominant factor degrading the network performance. This game can be applied to a large class of routing protocols that have flooding as a preliminary method of route discovery. In addition to the FDG, a neighbor discovery algorithm that enables nodes to discover the number of their neighbors was integrated in AODV to allow FDG to work properly.

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