An Efficient Pricing Based Protocol for Broadcasting in Wireless Ad hoc Networks

N. Rama Suri Y. Narahari D. Manjunath

Abstract—In many applications of wireless ad hoc networks, wireless nodes are owned by rational and intelligent users. In this paper, we call nodes selfish if they are owned by independent users and their only objective is to maximize their individual goals. In such situations, it may not be possible to use the existing protocols for wireless ad hoc networks as these protocols assume that nodes follow the prescribed protocol without deviation. Stimulating cooperation among these nodes is an interesting and challenging problem. Providing incentives and pricing the transactions are well known approaches to stimulate cooperation.

In this paper, we present a game theoretic framework for truthful broadcast protocol and strategy proof pricing mechanism called Immediate Predecessor Node Pricing Mechanism (IPNPM). The phrase strategy proof here means that truth revelation of cost is a weakly dominant-strategy (in game theoretic terms) for each node. In order to steer our mechanism-design approach towards practical implementation, we compute the payments to nodes using a distributed algorithm. We also propose a new protocol for broadcast in wireless ad hoc network with selfish nodes based on IPNPM. The features of the proposed broadcast protocol are reliability and a significantly reduced number of packet forwards compared to the number of network nodes, which in turn leads to less system-wide power consumption to broadcast a single packet. Our simulation results show the efficacy of the proposed broadcast protocol.

I. INTRODUCTION

A wireless ad hoc network is a collection of wireless nodes forming a temporary network without the aid of any centralized administration or standard support services. These networks are useful in areas where there is little or no communication infrastructure or the existing infrastructure is inconvenient to use. So, the potential applications of wireless ad hoc networks are such as battlefield, emergency relief, and environmental monitoring, etc. Due to the infrastructureless property of wireless ad hoc networks, all networking functions must be performed by the nodes themselves. Thus each node acts not only as a host but also a router. For details on architecture and protocols in wireless ad hoc networks, see [1] and [2].

In a broadcasting task for wireless ad hoc networks, a source node sends the same message to all the nodes in the network. Broadcast is useful in route discovery, for example [3], and paging a particular host or sending an alarm signal. So, it is interesting to study broadcast in which to consider incentives because wireless nodes are belonging to independent, self-interested users in many recent applications of wireless ad hoc networks. We call wireless nodes selfish if they are owned by independent users and their objective is to maximize their individual goals. Most of the existing protocols for broadcast assume that nodes voluntarily follow the prescribed protocols without deviation. These protocols will not work if the nodes exhibit selfish behavior. Thus there is a need for truthful computing in this context. Truthful computing refers to a stimulation mechanism to make selfish nodes cooperate with each other.

In our formulation of the truthful broadcast problem, each wireless node incurs a per-packet cost for forwarding packets. To compensate for these incurred costs, each wireless node is paid a price. Our goal is to maximize the network efficiency by making the broadcast packets follow the least cost paths (LCPs). Given the announced costs of the wireless nodes, the LCPs can be computed using some existing algorithms.

However, under many pricing schemes, a wireless node could better off by lying its cost. Then it would cause the traffic to take non-optimal paths and therefore reducing overall network efficiency. To avoid such situations, we require a strategy proof pricing mechanism for solving truthful broadcast problem. In a strategy proof pricing mechanism, it is the situation that truth revelation of cost is a weakly dominant-strategy (in game theoretic terms) for each node. We refer the reader to [4] and [5] for more details about strategy proof mechanisms.

The truthful broadcasting problem for wireless ad hoc networks is not well studied in the literature. In this paper, we try to answer some of the important issues in this context. In [6], a strategy proof pricing mechanism is developed for multicast in wireless ad hoc networks with
selfish nodes. The authors make a strong assumption that any receiver node will relay the data packets for any other receiver nodes for free if it is chosen as relay node. This assumption restricts the applicability of the model in civilian and real world applications of wireless ad hoc networks. So, we can not simply use and extend that approach to solve the truthful broadcast problem. We relax this assumption in this paper by saying that nodes charge for forwarding packets. In the rest of the paper, we explain the design of a strategy proof pricing mechanism for broadcast in wireless ad hoc networks with selfish nodes. In order to steer our strategy proof pricing mechanism towards practical implementation, we compute the least cost paths and prices in distributed fashion. For this, we also present an implementation model to capture these requirements and seek to compute the least cost paths and prices in our pricing mechanism.

A. Contributions of the Paper

The following are the main contributions of our paper:

1) We present a game theoretic framework for truthful broadcast

2) We also present a strategy proof pricing mechanism which we call Immediate Predecessor Node Pricing Mechanism (IPNPM) for broadcast in wireless ad hoc networks with selfish nodes

3) We propose a new protocol for broadcast based on IPNPM

4) We carry out simulation experiments to show the efficacy of the proposed broadcast protocol. In particular, our simulation results show that the proposed broadcast protocol achieves a considerably small number of packet forwards compared to the number of network nodes, which in turn leads to less system-wide power consumption to broadcast a single packet.

B. Organization of the Paper

The rest of this paper is organized as follows. In Section 2, we present a framework for a game theory and mechanism design for truthful broadcast problem. Section 3 presents our strategy proof pricing mechanism for truthful broadcast. In Section 4, we present a new approach to broadcast in wireless ad hoc networks with selfish nodes and also present the simulation results to show its efficacy. We conclude the paper in Section 5.

II. A GAME THEORETIC MODEL AND MECHANISM DESIGN FOR TRUTHFUL BROADCAST

The purpose of this section is to develop the framework for a game theoretic modelling and mechanism design for truthful broadcast problem. It is useful for the design and analysis of our strategy proof pricing mechanism presented in Section 3. The notation and the framework used in our analysis is taken from [5] and [7].

Consider a wireless ad hoc network with a set of \( n \) nodes represented by \( N = \{1, 2, \ldots, n\} \). Each node \( i \) holds private information \( \theta_i \) regarding the cost to forward a packet. We often refer to \( \theta_i \) as agent \( i \)'s type. Here the two terms, type and cost, are the same and we often use them interchangeably in this paper. The set of all possible types of agent \( i \) is denoted by \( \Theta_i \). The following are some symbols used later in our analysis.

\[
\begin{align*}
\Theta &= \text{Set of type profiles or cost profiles of the wireless nodes} \\
\theta &= \text{A type profile of the wireless nodes} \\
\Theta_{-i} &= \text{Set of type profiles of nodes excluding } \Theta_i \\
\theta_{-i} &= \text{A type profile of nodes excluding } \theta_i \\
\Delta \Theta &= \text{Set of all probability distributions over } \Theta_i \\
\Delta \theta_{-i} &= \text{Set of all probability distributions over } \Theta_{-i}.
\end{align*}
\]

In this setting, wireless nodes must make a collective choice from a set \( X \) of possible alternatives for broadcast. Each alternative in the set \( X \) specifies which nodes to forward the broadcast packets and payments to those nodes for forwarding packets. We represent \( x \) be an element of \( X \). We assume that \( x \in X \) takes the following quasilinear form:

\[
x = (k, t_1, \ldots, t_n)
\]

where \( k \) is an element of a finite set \( K \), to be called the finite set of allocations and \( t_i \in \mathbb{R} \) is a transfer of money to node \( i \). As we are going to elaborate more on the structure of the allocation \( k \) and payment vector \( t = (t_1, \ldots, t_n) \) in the following sections, we give a brief intuition here. An allocation \( k \in K \) represents the nodes that forward the packets. For each \( i \in N, t_i \in \mathbb{R} \) is the payment to node \( i \) when \( i \) forwards packets.

Each wireless node \( i \) is an expected utility maximizer. Node \( i \)'s utility function, in quasilinear environments, takes the following form:

\[
u_i(x, \theta_i) = v_i(k, \theta_i) + t_i + m_i
\]

where \( m_i \) is node \( i \)'s initial endowment. We assume \( m_i = 0 \) in our model. \( v_i(k, \theta_i) \) is the valuation function of the node \( i \). Because nodes' utilities depend on the cost profile \( \theta = (\theta_1, \ldots, \theta_n) \), the nodes expect the collective decision to depend on \( \theta \). To capture this dependency, we define a social choice function. A social choice function
is a function \( f : \Theta_1 \times \ldots \times \Theta_n \rightarrow X \) that, for each possible profile of the nodes’ types \((\theta_1, \ldots, \theta_n)\), assigns a collective choice \( f(\theta_1, \ldots, \theta_n) \in X \).

A mechanism \( M = (S_1, \ldots, S_n, g(.)) \) is a collection of \( n \) strategy sets \( S_1, \ldots, S_n \) for the wireless nodes and an outcome function \( g : S_1 \times \ldots \times S_n \rightarrow X \). The mechanism \( M \) can be viewed as an institution with rules governing the procedure for making the collective choice. The allowed actions of each node \( i \) are summarized by the strategy set \( S_i \), and the rule for how nodes’ actions get tuned into a social choice is given by the outcome function \( g(.) \). In a direct revelation mechanism, nodes reveal their costs directly. So, we call a mechanism as a direct revelation mechanism if \( S_i = \Theta_i \), \( \forall i \in N \) and the function \( g=f \).

A direct revelation mechanism induces a game in which nodes are strategic players and each node plays the game by reporting a cost \( \theta_i \) to forward a packet. Because cost \( \theta_i \) is known only to node \( i \), we are in a setting characterized by incomplete information. Such games are called Bayesian games. We now formally define the induced Bayesian game.

Let \( N = \{1, \ldots, n\} \) be the set of wireless nodes. Let \( \Theta_i \) represent the set of types or costs of agent \( i \). The strategy sets of nodes are represented by \((S_i)_{i \in N} \). In the direct revelation mechanism, strategies of nodes are nothing but announcing their costs. So, \( S_i = \Theta_i \), \( \forall i \in N \). We assume that node \( i \) has a belief function \( p_i : \Theta_i \rightarrow \Delta \Theta_{-i} \). That is, for any possible cost \( \theta_i \) of the node \( i \), the belief function specifies the probability distribution over the set \( \Theta_{-i} \), representing what node \( i \) would believe about the other nodes cost if its own cost were \( \theta_i \). Thus for any \( \theta_i \in \Theta_i \), \( p_i(\theta_{-i}|\theta_i) \) denotes the subjective probability to the event that \( \theta_{-i} \) is the actual profile of the rest all nodes’ cost, if its own cost were \( \theta_i \). The beliefs \((p_i)_{i \in N} \) are said to be consistent [7] iff there is some common prior distribution over the set of cost profiles \( \Theta \) such that each node’s belief given its cost is just the conditional probability distribution that can be computed from the prior distribution by Bayes formula. That is, beliefs are consistent iff there exists some probability distribution \( P \in \Delta \Theta \) such that,

\[
p_i(\theta_{-i}|\theta_i) = \frac{P(\theta_{-i} \cap \Theta_i)}{\sum_{\tau_{-i} \in \Theta_{-i}} P(\tau_{-i} \cap \Theta_i)}; \forall i \in N \quad (3)
\]

The utility function of node \( i \) is \( u_i(f(\theta), \theta_i) = v_i(k, \theta_i) + t_i(\theta) \), \( \forall i \in N \). This is the quantity nodes want to maximize. Here \( k \) is the allocation chosen by the outcome \( f(\theta) = (k, t_1(\theta), \ldots, t_n(\theta)) \). The above model describes a Bayesian game, denoted by

\[
\Gamma^b = \{ (N), (\Theta_i)_{i \in N}, (S_i)_{i \in N}, (p_i)_{i \in N}, (u_i)_{i \in N} \}.
\]

### A. Strategy Proof Mechanisms

A strategy proof pricing mechanism is one in which types are part of the strategy space \( S_i \) and there exists a weakly dominant strategy for each node in game theoretic sense. That is, each node maximizes its utility by announcing its cost \( \theta_i \) as input regardless of what other nodes do. In other words, \( \forall i \in N \) and \( \forall \theta_i \in \Theta_i \),

\[
u_i(f(\theta_i, \theta_{-i}), \theta_i) \geq u_i(f(a_i, \theta_{-i}), \theta_i), \forall \theta_{-i} \in \Theta_{-i} \forall a_i \in \Theta_i \quad (4)
\]

with strict inequality holding for some \( i \in N \) and for some \( \theta_{-i} \in \Theta_{-i} \). Thus, the mechanism makes each node to report its cost truthfully, and it is required to provide incentives in the form of payments to stimulate them to do so.

In Section 3, we design a strategy proof mechanism that belongs to a well known class of strategy proof mechanisms called the VCG (Vickrey-Clarke-Groves) mechanisms. These are mechanisms which provide allocation and payment rules which, if followed, will make truth revelation of cost as a weakly dominant strategy in the game theoretic sense. For more technical details regarding the VCG family of mechanisms, we refer to [4] and [5]. The following is the payment rule in VCG mechanisms,

\[
t_i(\theta) = \sum_{j \neq i} v_j(k^*(\theta), \theta_j) - \sum_{j \neq i} v_j(k^*_j(\theta_{-i}), \theta_j) \quad (5)
\]

where \( k^*(\theta) \in \max_{k \in K} \sum_{j=1}^n v_j(k(\theta), \theta_j) \) is allocative efficient function with node \( i \) in the scene and \( k^*_j(\theta_{-i}) \in \max_{k \in K} \sum_{j \neq i} v_j(k(\theta_{-i}), \theta_j) \) is an allocative efficient function without the node \( i \) in the scene.

The appeal behind using a strategy proof mechanism is as follows. Such a mechanism will make revealing true costs as a best response strategy for every node regardless of the strategies adapted by the other nodes. Also, the complexity of bidding logic for each node is trivial since it does not have to do complex computations to come up with a bidding strategy. Such a mechanism is also very robust since no assumptions need to be made about strategic behavior of the selfish nodes.

### III. A STRATEGY PROOF PRICING MECHANISM FOR TRUTHFUL BROADCAST

#### A. Statement of The Problem

The wireless ad hoc network under consideration is represented by a directed graph \( G = (N, E) \), where \( N = \{1,2,\ldots,n\} \) is the set of wireless nodes and \( E \) is the set of links between the nodes. If a node \( v \) is reachable from node \( u \), we assume that node \( u \) is also reachable from node \( v \). So, there exists an undirected link in the graph between nodes corresponding to \( u \) and \( v \). We assume each wireless node has an omnidirectional antenna and a
single transmission of a node can be received by any node within its vicinity, i.e. all its neighbors in G. We assume the graph G is biconnected. This assumption guarantees that the graph that remains after removing any node and its incident links from the graph still remains connected. Thus, biconnectivity of the graph prevents monopoly on the network by the cut vertices. We also assume that wireless nodes do not collude with one another to improve their utility. This assumption is a standard one in all economic based approaches.

We assume node s ∈ N is the source of broadcast in the wireless ad hoc network with selfish nodes. Node i incurs a cost θ_i to forward a packet. For simplicity, we assume that this cost is independent of the neighbor from which the packet is received and the neighbor to which the packet is destined. Each node i is given a payment t_i to compensate it for forwarding the packets. In general, the payment depends on cost profile θ = (θ_1, . . . , θ_n) and the matrix [D_i] representing the number of packets forwarded by node i, ∀i ∈ N. We also want nodes that forward no packets receive no payment.

Our aim is to send the packets along the LCP, according to the true cost vector. Using some algorithms, given the cost profile θ, LCPs can be computed. Ties in LCPs between a particular source and destination pair are resolved appropriately. Let I_m(θ, s, j) be the indicator function for the LCP from s to j; i.e., I_m(θ, s, j) = 1, if node m is an intermediate node on the LCP from s to j, and I_m(θ, s, j) = 0 otherwise. Note that I_s(θ, s, j) = I_j(θ, s, j) = 0. Now consider the LCPs specified by the indicator functions \{I_m(θ, s, j)\}_m∈N. When the packets are broadcasted along these paths, each node that forwards the packet incurs a cost. We need a pricing mechanism for service reimbursement to the nodes that forward the broadcast packets.

We treat the truthful broadcast problem as a game in which wireless nodes are the strategic players. Each node plays the game by reporting a cost to forward the packet. A wireless node’s cost is private information to that node. But, LCPs are defined using the true costs of the nodes. So, we require nodes to announce their actual costs to compute the LCPs to broadcast packets over the wireless ad hoc network.

To do so, we propose an algorithmic mechanism as described in Section 2. The mechanism takes as input the graph that represents the wireless ad hoc network under consideration and a cost profile θ = (θ_1, . . . , θ_n) and produces as output the set of prices to nodes. The pricing mechanism must be strategy proof so that nodes have no incentive to lie about their costs.

B. The Pricing Mechanism

1) An Illustrative Example: We illustrate our pricing mechanism for the graph shown in Figure 1(i). For computational simplicity, we assume that the cost to forward a packet is same for each node in the network. So, the cost profile is θ = (c, . . . , c).

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{example.png}
\caption{(i) An illustrative example, (ii) Sink tree rooted at node 1 for the graph in 1.(i)}
\end{figure}

Assume node 1 is the source of broadcast. We want the packets to be broadcasted along the least cost paths computed using some algorithms, for example one presented in Section 3.2.3. For this graph, the least cost paths are shown in Figure 1(ii). We call the tree in Figure 1(ii) as sink tree. For example the least cost path from node 1 to node 8 is represented by LCP(θ, 1, 8) = (1, 3, 6, 8).

Now consider the situation at node 6. When node 6 receives the packet along LCP(θ, 1, 6), according to our pricing mechanism, node 6 pays an amount, call it, p^6_{6,1}, to node 3. Here node 3 is the immediate predecessor of node 6 in the sink tree. The value of p^6_{6,1} is computed using VCG pricing rule in the following way.

\[ p^3_{6,1} = \text{(cost of 3 to forward a packet)} + \text{(cost of LCP(θ, 1, 6) in the absence node 3)} - \text{(cost of LCP(θ, 1, 6) in the presence node 3)} \]
\[ = c + 3c - 2c \]
\[ = 2c. \]

Similarly when node 6 forwards the packet, node 8 receives and pays an amount, p^6_{8,1}, to node 6 because node 6 is the immediate predecessor of node 8 in the sink tree. Node 8 does not pay to other intermediate node 3, on LCP(θ, 1, 8), because node 3 is the immediate predecessor for node 6 in the sink tree and node 6 has already paid to node 3 before node 8 receives packet. The reason is that node 6 is also an intended recipient of the packet.

From this example, we summarize the main idea behind the pricing mechanism in the following way. When a node receives a packet along the least cost path, it pays only to its immediate predecessor in the sink tree.
rooted at the source of the broadcast. Hence we call our mechanism as Immediate Predecessor Node Payment Mechanism (IPNPM).

2) IPNPM: Using the algorithm in Section 3.2.3, for the biconnected graph given the profile of declared costs \( \theta \), we compute the set of LCPs breaking the ties appropriately. We represent the LCPs by the indicator functions \( \{I_m(\theta,s,j)\}_{m \in N} \). If \( LCP(\theta,s,j) = \{s,e_1,\ldots,e_x,j\} \) be the least cost path corresponding to \( \{I_m(\theta,s,j)\}_{m \in N} \), then \( k_{\theta}(\theta,s,j) = 1 \). Thus, for each \( i \in N \), the allocation function \( k_{\theta}(\cdot) \) is defined as \( k_{\theta}: \{\theta,s,\{1,\ldots,n\} \} \rightarrow \{0,1\} \). We want the pricing mechanism be strategy proof and nodes that do not forward the packets receive no payment.

**Theorem 1:** If the wireless ad hoc network with selfish nodes is biconnected and packets follow the least cost paths in broadcast, there is a strategy proof pricing mechanism that gives no payments to nodes that do not forward the packets. The payments to the nodes that forward the packets are of the form \( t_{i}(\theta) = D_{i}\{\sum_{j \in N} k_{i}(\theta,s,j)p_{i,s,j}^{\theta}\} \), where

\[
p_{i,s,j} = I_{i}(\theta,s,j)\theta_{i} + \left(\sum_{m \in N} I_{m}(\theta|\infty,s,j)\theta_{m} - \sum_{m \in N} I_{m}(\theta,s,j)\theta_{m}\right).
\]

In the theorem, \( D_{i} \) represents the total number packets forwarded by node \( i \) when node \( s \) is the source of broadcast. \( \{I_m(\theta,s,j)\}_{m \in N} \) is the least cost path from \( s \) to \( j \) with node \( i \) present in the network and \( \{I_m(\theta|\infty,s,j)\}_{m \in N} \) is the least cost path from \( s \) to \( j \) without node \( i \) present in the network. For each \( i,j \in N \), \( p_{i,s,j}^{\theta} \) are computed using VCG pricing rule as shown in equation (5). So our mechanism, IPNPM, belongs to the VCG family of mechanisms.

**Proposition 1:** Our pricing mechanism IPNPM belongs to VCG family of mechanisms or IPNPM is a strategy proof mechanism.

3) Algorithms to Implement The Pricing Mechanism: We now present a method to compute the least cost paths, the prices \( p_{i,s,j}^{\theta} \), \( \forall i,j \in N \), and the functions \( k_{i}(\cdot) \), \( \forall i \in N \). We follow a two stage approach to develop a distributed algorithm for IPNPM.

**STAGE-1:**

We use the algorithm in [8] to find least cost paths and payments to nodes. If there are multiple least cost paths from node \( i \) to other node, then node \( i \) selects one least cost path arbitrarily. For truthful implementation of the algorithm [8], we can use the technique given in [8] itself or [9].

**STAGE-2:**

\( LCP(\theta,s,j) = \{s,e_1,\ldots,e_x,j\} \) is the least cost path corresponding to \( \{I_m(\theta,s,j)\}_{m \in N} \). Node \( j \) sends a control message \( SEND\_CTRL\_MSG(s,j,p_{s,j}^{\theta}) \) to its immediate predecessor, \( e_x \), in the sink tree rooted at \( s \). On receiving this control message, node \( e_x \) executes the procedure \( RECV\_CTRL\_MSG() \) to create an entry \( ((s),(j,p_{s,j}^{\theta})) \) in its internal table, \( INT\_TAB_{e_x} \). This internal table contains two fields: source and \( (Node,Price) \). The meaning of the entry \( ((s),(j,p_{s,j}^{\theta})) \) in the table \( INT\_TAB_{e_x} \) can be interpreted in the following way. If node \( s \) is source of broadcast and when node \( e_x \) forwards the packet, then node \( j \) receives the packet and pays an amount equivalent to \( p_{s,j}^{\theta} \) to node \( e_x \).

Each node \( j \in N \) uses Algorithm 1 for sending the \( SEND\_CTRL\_MSG() \) and Algorithm 2 for the processing of \( RECV\_CTRL\_MSG() \).

**Algorithm 1:**

BEGIN SELECT_FORWARDER()

**STEP-1** FOR \( s = 1,2,\ldots,n \) and \( s \neq j \)

i) \( j \) knows \( LCP(\theta,s,j) = \{s,e_1,\ldots,e_x,j\} \) and payment \( p_{s,j}^{\theta} \).

ii) \( SEND\_CTRL\_MSG(s,j,p_{s,j}^{\theta}) \);

END FOR.

END SELECT_FORWARDER()

**Algorithm 2:**

BEGIN RECV_CTRL_MSG(s,k,p)

**Step-1** FOR \( s = 1,2,\ldots,n \) DO

IF \( INT\_TAB_{j}[source] = s \) THEN

i) Append \((k,p)\) pair to the entry in \( INT\_TAB_{j}[s][\{Node,Price\}] \)

END IF

END FOR

**Step-2** IF there is no entry with \( s \) as source in \( INT\_TAB_{j} \), THEN

i) \( INT\_TAB_{j}[source] = s \),

ii) \( INT\_TAB_{j}[s][\{Node,Price\}]=(k,p) \).

END IF

END RECV_CTRL_MSG()
IV. A NEW BROADCAST PROTOCOL BASED ON IPNPM

We first present a new broadcast protocol based on IPNPM in the following way.

If a node receives a broadcast packet, it checks its $INT\_TAB$ entry corresponding to the source of broadcast. If the (Node, Price) field in that table entry is empty, the node does not forward the packet. Otherwise, it forwards the packet.

We explain this protocol with graph in Figure 1. Consider the $INT\_TAB_7$ of node 7 in Table 1. If node 1 broadcasts a packet, node 7 does not forward the packet after receiving it since the field (Node, Price) is empty in the entry with source 1 in $INT\_TAB_7$. For similar reasons, node 7 does not forward packets when one of node 3, node 4, node 5, and node 6 is the source of broadcast. On the other hand, if node 2 is the source of broadcast, node 7 forwards packets since the field (Node, Price) is non-empty in the entry with source 2 in $INT\_TAB_7$. Similarly, node 7 also forwards packets if the source of broadcast is node 8.

<table>
<thead>
<tr>
<th>Source</th>
<th>(Node, Price)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>(8,2c)</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>—</td>
</tr>
<tr>
<td>8</td>
<td>(2,2c)</td>
</tr>
</tbody>
</table>

Table 1: Contents of $INT\_TAB_7$

A. Simulation Experiments

In this section, we show the efficacy of the proposed broadcast protocol using simulation experiments. In our simulation experiments, we compared our protocol with the connected dominating set based broadcast protocol [10].

1) Simulation Model: The protocol is implemented as a TinyOS application in order to analyze its performance using PowerTOSSIM. PowerTOSSIM, a power modelling extension to TOSSIM, is a TinyOS simulator. PowerTOSSIM accurately models the power consumed by TinyOS applications. The central components assumed by PowerTOSSIM on each wireless node are CPU of 4MHz frequency, CC1000RF transceiver of 433MHz band, CSMA based B-MAC, and battery of voltage 3v.

We conducted all our simulation experiments on randomly generated graphs with $n = 5, 10, 15, 20, 25$, and 30 nodes. We set the transmission range of each node as 200 m. The cost $c_{i,j}$ of a node $q_i$ to send a packet to another node $q_j$ within its transmission range is $c_1 + c_2 \| q_i q_j \| i$, where $c_1$ takes values from 300 to 500, $c_2$ takes values from 10 to 50, and $i$ takes values 2 and 2.5 in our experiments. The ranges of $c_1$ and $c_2$ used here reflect the actual power cost of a node to send data at 2 Mbps. When node $q_j$ is not within the transmission range of node $q_i$, cost $c_{i,j}$ is set to $\infty$. The parameters are essentially the same as in [9].

![Fig. 2. Number of nodes vs number of routers with $i = 2$](image1)

![Fig. 3. Number of nodes vs number of routers with $i = 2.5$](image2)

![Fig. 4. Energy required for forwarding a single packet with $i = 2$](image3)

2) Analysis on Simulation Results: Figure 2(i) and Figure 2(ii) show the number of routers selected with our broadcast protocol and with the dominating set based broadcast protocol on the random graphs with $n = 5, 10, 15, 20, 25$, and 30 nodes. Figure 2(i) corresponds to the scenario with $i = 2$ and Figure 2(ii) corresponds to $i = 2.5$. The declining curve in both the graphs is associated with our protocol. It shows that the number of nodes.
routers is small with our protocol. This is an important objective by the broadcast protocol proposed in this paper. An immediate consequence of this is increased network life time.

If the number of routers is less, the total energy spent by the routers to forward the packet will be correspondingly less. This leads to less system wide power consumption to broadcast a single packet. Figure 2(iii) and Figure 2(iv) show the energy consumed by the routers for broadcasting a single packet. Figure 2(iii) corresponds to the scenario with \( i = 2 \) and Figure 2(iv) corresponds to \( i = 2.5 \). From the graphs, it is clear that our protocol achieves the objective of reducing system wide power consumption to broadcast a single packet over the wireless ad hoc network.

V. CONCLUSIONS AND FUTURE WORK

We have proposed a strategy proof pricing scheme, IPNPM, for broadcast in wireless ad hoc networks with selfish nodes. We have also presented a new broadcast protocol based on IPNPM. The proposed broadcast protocol leads to reduced number of forwards and less system wide power consumption compared to existing broadcast protocols such as [10]. An implementation our protocol on synthetically generated ad hoc networks of resource constrained MICA2 motes reveals that the proposed protocol based on IPNPM could be easily implemented asynchronously.

Since Bayesian incentive compatible mechanisms implement a wider class of mechanisms than that of strategy proof mechanisms, it is natural to extend our work to Bayesian implementations.

REFERENCES