# SMM: A Truthful Mechanism for Maximum Lifetime Routing in Wireless Ad Hoc Networks

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**Abstract.** As an important metric for wireless ad hoc networks, network lifetime has received great attentions in recent years. Existing lifetime-aware algorithms have an implicit assumption that nodes are cooperative and truthful, and they cannot work properly when the network contains selfish nodes. To make these algorithms achieve their design objectives even in the presence of selfish nodes, in this paper, we propose a truthful mechanism Second-Max-Min (SMM) based on the analysis of current algorithms as well as a DSR-like routing protocol for the mechanism implementation. In SMM mechanism, the source node gives appropriate payments to relay nodes, and the payments are related to the path which has the second maximum lifetime in all possible paths. We show that the payment ratio is relatively small due to the nature of lifetime-aware routing algorithms, which is confirmed by experiments.

## 1 Introduction

Power-aware routing is a key concern for wireless ad hoc networks due to the limited battery power of nodes. Current research on power-aware routing mainly focuses on two aspects: minimizing the consumed energy of communication (i.e. energy-efficiency) [8] and maximizing the lifetime of whole network (i.e. lifetime-aware) [4–6]. An energy-efficient routing protocol tries to find a path which has the minimal consumed energy. However, the nodes in the minimal energy path will be drain-out of energy quickly if all the packets are routed along this path. Therefore, it would be better to route along nodes which have a higher residual energy, which is discussed by lifetime-aware routing protocols.

Most previous works on power-aware routing have implicitly assumed that nodes are cooperative and truthful. A cooperative node means the node is willing to relay packets for other nodes. A truthful node means the node will reveal its private information, such as its residual energy etc. However, this assumption cannot be taken for granted from the view of an individual node. A node may tend to be selfish, refuse to relay packets for other nodes, or do not tell the truth for its own benefit.

Several protocols have been proposed to stimulate the cooperation of nodes (see [9] for a survey). Further, [2] proposed Ad hoc–VCG, an reactive routing

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protocol coping with the selfish nodes while also achieving the desirable goal of truthfulness and energy-efficiency. However, as we have pointed out, lifetime is also an import metric for network. In the face of selfish nodes, how to make existing lifetime-aware routing algorithms achieve their design objectives is an imperative problem to be solved. But to the best of our knowledge, few works have addressed this problem.

In this paper, we study existing lifetime-aware routing algorithms, and propose a truthful mechanism SMM based on the analysis of current algorithms. Our mechanism deals with selfish node within the framework of algorithmic mechanism design [3]. By giving appropriate payments to relay nodes, the mechanism ensures existing algorithms work properly even the nodes in network are selfish. We also present a DSR-like routing protocol to implement SMM mechanism.

The rest of the paper is organized as follows. Section 2 reviews some related works. Section 3 presents our problem, and analyzes existing solutions. Section 4 proposes the SMM mechanism and presents a DSR-like protocol for the implementation of our mechanism. Section 5 proves the truthfulness of SMM mechanism. Section 6 conducts experiments to examine the performance of payment ratio. We conclude our work in sect. 7.

## 2 Related Work

Several lifetime-aware routing algorithms which do not consider the effect of selfish nodes have been proposed. MMBCR [4] tries to avoid the path with nodes having the least battery power among all nodes in all possible paths. MRPC [5] identifies the capacity of a node not only by its residual battery power, but also by the expected energy spent in reliably forwarding a packet over a specific link. It selects the path which has the largest packet capacity at the critical node. LPR [6] minimizes the variance in the remaining power of all the nodes and thereby prolong the network lifetime. Other algorithms like CMMBCR [4] and CMRPC [5] can be viewed as a conditional variant of algorithms mentioned above.

To make existing algorithms continue to work when the nodes in network are selfish, we adopt the framework of algorithmic mechanism design. Algorithmic mechanism design considers the problems in a distributed environment where the participants cannot be assumed to follow the algorithm but rather their own self-interest. [3] proposed a formal model for such problems. It can be described as following:

In a distributed environment, there are $n$ agents. Each agent $i$ has some private information $t^i$, called its *type*. For a mechanism design problem, there is an *output specification* that maps each type vector to a set of allowed outputs $o \in O$. Agent $i$'s preferences are given by a *valuation function* $v(o, t^i)$. A *mechanism* defines a family of *strategies* $A^i$ for each agent $i$. For each strategy vector $(a^1, \ldots, a^n)$, $a^i \in A^i$, the mechanism computes an *output* $o = o(a^1, \ldots, a^n)$, and a *payment* vector $p = p(p^1, \ldots, p^n)$. Agent $i$'s *utility* is $u^i = p^i - v(o, t^i)$. It is $i$'s goal to maximize its utility. A mechanism is called *truthful* if for every agent $i$ of type $t^i$ and for every strategies $a^{-i}$ of the other agents, $i$'s utility is maximized when it declares its type $t^i$.

Several standard problems have been studied as the mechanism design problem [3]. In the context of wireless ad hoc network, [2] applies the mechanism design theory to ad hoc energy-efficient routing problem. They proposed a reactive routing protocol Ad hoc–VCG, which achieves the design objectives of truthfulness and energy-efficiency by paying to the intermediate nodes a premium over their actual costs for forwarding packets.

## 3 Problem Statement and Analysis

In this section, we present the mechanism design problem for lifetime-aware routing in wireless ad hoc networks by considering the selfish nodes.

In a wireless ad hoc network, there are $m$ mobile nodes, each of which has a unique identification and belongs to different users. From the view of a node, it is selfish but economically rational, and its objective is to maximize its own benefit. A rational node means the node is willing to forward packets for others only when it can get payments equal or greater than what it desires. Now, a source node $S$ wants to send a message to a destination node $D$. There are $n$ possible paths can be found between $S$ and $D$. Our problem is to select a path from these $n$ possible paths to maximize the lifetime of network and ensure the truthfulness of this selected path.

Section 2 has reviewed some solutions that do not consider the impact of selfish nodes. After pondering existing algorithms, we find these algorithms can be represented by a common form as following:

Let function $g()$ be the common representation of lifetime of all nodes. The factors, such as the residual battery power of node and the transmission power between nodes, can be used as the parameters of $g()$. We treat the minimal lifetime of nodes in a path as the lifetime of the path, and select the path which has the maximal lifetime as the output path, i.e. the output path $o$ can be obtained from the equation:

$$o = \underset{j \in A}{Max}(\underset{i \in j}{Min}(g(R_j^i, \ldots))), \tag{1}$$

where $R_j^i$ is the residual battery power of node $i$ in path $j$, and $A$ is the set of all possible paths.

As we have pointed out, a node may tend to be selfish. To prevent its battery power is consumed for other nodes, a node may refuse to relay packets, or declare a very low lifetime so that it cannot be selected as the relay node. In this case, existing algorithms will fail to work. Our objective is just to design a mechanism which ensures to route along the path selected by (1), and the path is truthful.

## 4 SMM Mechanism and Protocol

In this section, we propose SMM mechanism to cope with the selfish nodes. We also present a DSR-like protocol to implement our mechanism.

### 4.1 SMM Mechanism

To design a mechanism, we provide the output function of mechanism, define practical valuation function of nodes, and present appropriate payment function.

The output function $o()$ is given first. According to the lifetime declaration of each node (a node can declare its lifetime at will), the output function $o()$ selects a path from all possible paths by using (1). It can be represented as following:

$$o(a^1, \ldots, a^m) = \underset{j \in A}{Max}(\underset{i \in j}{Min}(a_j^i)), \tag{2}$$

where $a^i$ is the lifetime declaration of node $i$, $a_j^i$ is the lifetime declaration of node $i$ in path $j$.

The valuation function of nodes is defined as following:

$$v(o, t^i) = \begin{cases} 0 & : \quad i \notin o \\ \frac{c}{t^i} & : \quad i \in o \end{cases}, \tag{3}$$

where $t^i$ is the lifetime of node $i$, and $o$ is the output path.

It means that $i$'s evaluation is zero if $i$ does not belong to $o$, and $i$'s evaluation is inversely proportion to its lifetime if $i$ is one of the node in $o$. Intuitively, the shorter lifetime $i$ has, the more likely that $i$ is not willing to forward packets for other nodes. Therefore, $i$ would expect more payments.

The goal of a node is to maximize its utility, so it tends to choose favorable strategy and become truthless. If a node declares false lifetime, $o()$ may select an improper path. We have to design an appropriate payment function which can meet the needs of nodes while compatible with the output of algorithm.

We treat the minimal lifetime declaration of nodes in path $j$ as $j$'s lifetime declaration. Assume that the nodes whose lifetime declaration is minimal in all $n$ possible paths are $q_1, \ldots, q_n$, then the lifetime declarations of these $n$ paths are $a_1^{q_1}, \ldots, a_{n-1}^{q_{n-1}}, a_n^{q_n}$. We can simply denote them as $a_1, \ldots, a_{n-1}, a_n$. Without losing generality, we assume $a_1 \leq \ldots \leq a_{n-1} \leq a_n$. The output would be the path $n$. The payment function $p()$ is defined as following:

$$p(a_j^i) = \begin{cases} 0 & : \quad \forall j \neq n, i \in j \\ \frac{c}{a_{n-1}} & : \quad j = n, i \in n \end{cases}, \tag{4}$$

where c is a constant.

It means that the payments to nodes which do not belong to the output path would be zero, and the payments to nodes in the output path are related to the path which has the second maximum lifetime declaration in all possible paths.

We call our mechanism the Second-Max-Min (SMM) mechanism and will prove the truthfulness of SMM mechanism in the next section.

### 4.2 Protocol

DSR [7] protocol is an reactive routing protocol which is used to find the shortest hop path between source and destination. To meet the need of the implementation of our SMM mechanism, we make some modifications to DSR protocol.

First, the lifetime declaration of each intermediate node, which is equal to its type through SMM mechanism, is recorded in the request packet. Type is private information for each node. To prevent a node's type information from being known or altered by other nodes, we adopt a PKI-based security model. In this model, the keyed *encryption algorithm* is known to all the nodes in the network, the *encryption* and *decryption keys* are generated by $S$. When $S$ starts the route discovery phase, it puts the encryption key in the route request packet. Every intermediate node uses the encryption key in the received route request packet and the public encryption algorithm to encrypt its private lifetime declaration. After receiving the route reply packet, $S$ uses the decryption key to decrypt the lifetime declaration of each intermediate node in the packet.

Second, instead of selecting the shortest hop path, we try to choose a path which can maximize the lifetime of network. When $S$ wants to send a packet to $D$, it starts a timer and launches the route discovery phase. During a period of time $T$, $S$ may receive several possible paths from the destination. Each path has the information of lifetime declaration of nodes in the path. $S$ can choose a path from these paths by using the output function $o()$ and calculate the payments to each node in the selected path by using the payment function $p()$.

Third, we avoid the route cache optimization techniques used in DSR. The cached routes cannot represent the current state of nodes because every node's type keeps changing. In our implementation, the source node periodically refreshes its cache and triggers a new route discovery process, the intermediate node does not respond to the route requests with cached routes.

Last, unlike DSR, a node processes the route request packet even it has seen the request before. We cannot simply discard the packet because the later arrived packet may have longer minimal lifetime declaration. Therefore, we ignore the judgment whether the node has seen the request before. To prevent heavy traffic, node will discard a packet if it has seen the request more than several times.

## 5 SMM Mechanism Analysis

In this section, we will show that the design of SMM mechanism can ensure the routing algorithm get its desired output in the presence of selfish nodes.

First, our mechanism guarantees the voluntary participation of all nodes. If a node can get payments equal to or greater than its valuation, it is willing to participate in the protocols. It can be shown that no matter a node belongs to the output path or not, its utility is non-negative in our mechanism.

Second, our mechanism is truthful. It is clear that if all nodes declare their type ($a_j^i = t_j^i$), our mechanism will guarantee the source node chooses algorithm desired path. Here, we prove that SMM mechanism is truthful.

**Theorem 1.** *SMM mechanism is truthful.*

*Proof.* To prove our mechanism is truthful, we need to show that every node cannot get more utility than what it gets when declaring its true lifetime, that is cheating cannot increase the utility of a node. We get it in two steps:

First, the lifetime declaration of each path is truthful. We treat the nodes in a path as an entity, and consider the behavior of the path. Assume that there are $n$ possible paths between $S$ and $D$, and the lifetime of these $n$ paths are $a_1, \ldots, a_{n-1}, a_n$ $(a_1 \leq \ldots \leq a_{n-1} \leq a_n)$.

- The path $n$ can be selected as the output path if it declares its true lifetime, its utility $u$ is $\frac{l_n \cdot c}{a_{n-1}} - \sum_{k=1}^{l_n} \frac{c}{a_n^{i_k}} \geq 0$, where $l_n$ is the number of nodes except $S$ and $D$ in path $n$. Now path $n$ declares a false lifetime $\overline{a_n}$. If $\overline{a_n} \geq a_{n-1}$, $n$ still can be selected as the output path, and its utility does not change. If $\overline{a_n} < a_{n-1}$, $n$ cannot be selected as the output path, and its utility is zero.
- The other paths cannot be selected as the output path if they declare their true lifetime, their utility are zero. Now a path $j$ declares a false lifetime $\overline{a_j}$. If $\overline{a_j} < a_n$, $j$ still cannot be selected as the output path, its utility will not change. If $\overline{a_j} \geq a_n$, $j$ can be selected as the output path, its utility $u'$ is $\frac{l_j \cdot c}{a_n} - \sum_{k=1}^{l_j} \frac{c}{a_j^{i_k}}$, but its expected utility $u$ is larger than $u'$ because $u \geq \frac{l_j \cdot c}{a_j} - \sum_{k=1}^{l_j} \frac{c}{a_j^{i_k}} > u'$. Therefore, there must exist some nodes in path $j$, such as the node with the minimal lifetime, their utility decrease.

Second, the lifetime declaration of each node in a path is truthful. We consider a node $i$ in path $j$. No matter $i$ is the node which has the minimal lifetime in path $j$ or not, $i$ cannot get more utility if it declares a false lifetime. The analysis is similar as the first one, we omit it here.

To measure the payment, we define *payment ratio*: Lets path $j$ be the output path, payment ratio is the ratio of payment for path $j$ to valuation of path $j$. We have following theorem for payment ratio.

**Theorem 2.** *For SMM mechanism, let path $j$ be the output path, which has the maximum lifetime in all possible paths from $S$ to $D$; and path $s$ has the second maximum lifetime. Let $Max(a_j^i)$ denote the maximal lifetime declaration of nodes in path $j$, $Min(a_j^i)$ denote the minimal lifetime declaration of nodes in path $j$, and $Min(a_s^i)$ denote the minimal lifetime declaration of nodes in path $s$, then:*

$$\frac{Min(a_j^i)}{Min(a_s^i)} \leq \beta \leq \frac{Max(a_j^i)}{Min(a_s^i)} \tag{5}$$

*Proof.* We omit the proof due to limitations of space.

The payment ratio $\beta$ can be used as an important metric to the performance of mechanism. If $\beta$ is close to 1, the premium that the source node pays to intermediate nodes is low. It means that the mechanism achieves the design objective of algorithm at little additional cost. While $\beta$ is far more than 1, the premium that the source node pays to intermediate nodes is high. It means that the mechanism achieves the design objective of algorithm at high additional cost. The essence of a lifetime-aware routing algorithm is to distribute the power consumption evenly among nodes, which leads to the result that the lifetime of nodes has the tendency of closing to each other. From Theorem 2, we can conclude that $\beta$ is close to 1 when the maximal lifetime of nodes in the output path is close to the minimal lifetime of nodes in path which has the second maximum lifetime. Therefore, we can infer that SMM mechanism has excellent payment ratio, which is relatively small and stable.

## 6 Experiment

We conducted experiments to evaluate the payment ratio of SMM mechanism. The simulation consisted of a network of 50 nodes randomly distributed over a $700 \times 700m^2$ area. We used the CBR traffic at 4 packets per second, and the packet size was 512 bytes. Random connections were established. The source node refreshed its cache every other 10 sec. Each node was given enough battery power to finish the experiments. The initial values of battery power in all nodes are same. A node could dynamically adjust its transmission power based on the link distance $d$, and the transmission cost $h$ is $K \cdot d^{\alpha}$, where $\alpha$ is the signal loss exponent. Two lifetime-aware routing algorithms, MMBCR and MRPC, were implemented. We try to find the influence of different parameters (such as the link distance $d$, the signal loss exponent $\alpha$) on payment ratio.

In Fig.1, we present the payment ratio in MMBCR when $\alpha = 2$. It can be observed that the ratio payment is very small and close to 1. We compare the situations when the maximum transmission range $R$ of nodes is $150m$, $200m$ and $250m$ respectively. The effect of transmission range increment lies in two aspects: (1) Each node covers more nodes, so there are more possible paths between the source node and the destination node. It will increase the balance of traffic on nodes and reduce the lifetime variance between nodes; (2) The range of transmission cost will increase due to $h = K \cdot d^{\alpha}$, which increases the lifetime variance between nodes. In Fig.1, we can find that the payment ratio for $R = 150m$ is higher than the payment ratio for $R = 200m$ and $R = 250m$. This result can be viewed as the effect of the first aspect. The payment ratio for $R = 200m$ is close to the payment ratio for $R = 250m$, which can be viewed as the balance between these two aspects.

In Fig.2, we present the payment ratio in MRPC when $R = 150$. In MRPC, the lifetime of a node is the ratio of its residual battery power to its transmission cost (we does not consider the link's packet error probability). Though the initial battery power of all nodes is same, the transmission cost of nodes is different because the transmission cost relates to the link distance. This experiment can be viewed as a simulation of the initial lifetime of all nodes is different. From Fig.2, we see that the payment ratio increases with the increment of $\alpha$. It is because that the higher $\alpha$, the higher the difference between initial lifetime of nodes. As we have pointed out, a lifetime-aware routing algorithm tries to minimize the variance of lifetime between nodes to increase the lifetime of network. It can be observed in Fig.2 that the payment ratio decreases with time.

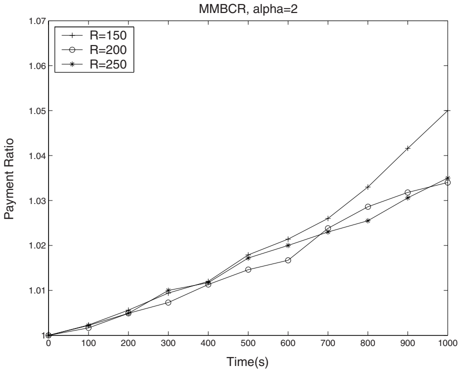

Fig. 1. $\beta$ vs. $R$ in MMBCR

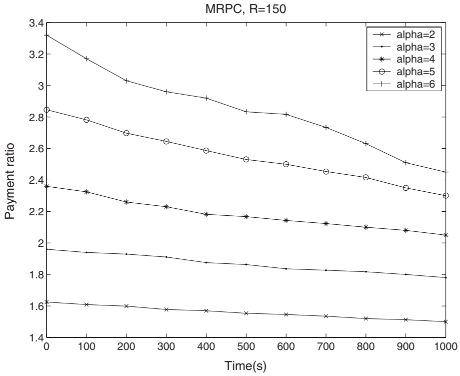

Fig. 2. $\beta$ vs. $\alpha$ in MRPC

# 7 Conclusion

In this paper, we dealt with the problem of maximum lifetime routing in ad hoc network with selfish nodes. By applying the framework of algorithm mechanism design, we designed a mechanism SMM. The basic idea of our mechanism is giving appropriate payments to stimulate the cooperation of nodes, and cheating can not increase or even lose the utility. In SMM mechanism, the payments to nodes in the output path are related to the path which has the second maximum lifetime in all possible paths. We proved that SMM mechanism is truthful, and purposed a routing algorithm to implement SMM mechanism. Finally, we conducted experiments to evaluate the performance of our mechanism.

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