Fair Route Selection in Multi-Domain WSNs using Non-Cooperative Game Theory in Separate Sink Scenario

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ABSTRACT

An important use of multi-domain wireless sensor networks (WSNs) is resource sharing between different networks co-existing in the same area to prolong the network lifetime. The challenge of resource allocation in such scenario is how to determine packet forwarding strategies which are beneficial to all networks under constrained resources in non-cooperative multi-domain WSNs. Therefore, this paper proposes the Non-cooperative game algorithm based on Lemke Howson method (NCG-LH) for a packet forwarding game in non-cooperative multi-domain WSNs. The objective is to achieve the best mutual strategy and improve the network performance between two different network authorities in non-cooperative multi-domain WSNs in separate sink scenario. Results show that NCG-LH can obtain longer network lifetime than the existing routing algorithms particularly in presence of failed nodes and high path loss exponent. NCG-LH also outperforms the other routing algorithms in terms of fair route selection by attaining the lowest average difference in energy consumption.

Keywords: Multi-Domain Wireless Sensor Networks, Non-Cooperative Game, Nash Equilibrium, Lemke-Howson Method

1. INTRODUCTION

In recent years, multiple WSNs have been deployed within the same region of interest [1]-[2]. For such scenarios, researchers have been investigating cooperation among sensor nodes belonging different network authorities which could potentially gain certain benefits. Such benefits include alternative routes and reduced energy consumption, which can prolong their network lifetime.

Most existing works focus on full cooperation in multi-domain WSNs, meaning that, network authorities have to agree on sharing or providing a common resource in order to increase the benefit of their networks. In [3] the potential benefits of cooperation in multiple WSNs are investigated. Linear programming is employed to find energy efficient paths in order to prolong their network lifetime. However, routes with low energy consumption do not always guarantee a prolonged network lifetime. Sensor nodes belonging to such paths tend to have higher traffic load and consume more energy than other nodes. As a result, such nodes tend to die earlier. In order to avoid heavy traffic load situations, [4] proposed a fair cooperative routing scheme for heterogeneous overlapped WSNs called pool-based selecting method. An energy pool was introduced to maintain the total amount of energy consumption by cooperative packet forwarding. Their simulation results showed that the proposed scheme was able to balance the energy consumption and prolong the network lifetime. Ref. [5]-[7] showed benefits of node collaboration in multi-domain WSNs under practical implementation. The results showed that cooperation with co-located sensor devices in different networks can increase the network lifetime. However, [8] and [9] showed that cooperation between sensor nodes belonging to different authorities may not always beneficial to any WSN. It is possible that some WSNs can prolong their network lifetime but other WSNs may have their network lifetime shortened, depending on the configuration of each network, network connectivity and how hostile the environment is. Therefore, multi-domain WSNs require fair cooperative control methods for each network authority to efficiently decide whether to cooperate with each other or not under a given condition, in a non-cooperative environment in order to provide mutual benefits to all networks coexisting in the area.

In this paper, we introduce a game theory framework to address the non-cooperative distributed resource allocation problem in multi-domain WSNs [10]. Game theory has become a common framework to analyze the interaction between rational agents and to determine a set of strategies among them, where each agent uses available information to decide its behavior. Nash equilibrium (NE) is a solution to the non-cooperative game theory framework which is used to determine a suitable and fair strategy for all agents. Ref. [11] applied game theory to a packet forwarding problem in multi-domain WSNs by using incentive mechanisms to motivate cooperation between sensor nodes in a common sink scenario. The sink node (i.e. base station) is located at the center of the area and shared by multiple networks.

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On the other hand, [12] applied the Non-cooperative game algorithm into a packet forwarding game problem to describe such a situation that cooperation can exist in multi-domain WSNs without any incentive mechanisms under common and separate sink scenario. They showed that the Non-cooperative game algorithm is a suitable framework to determine an equilibrium strategy for their problem. However, this algorithm requires a centralized operation, which was impractical for storage and computing ability of sensor nodes. A two-agent relaying game was analyzed in a distributed non-cooperative game framework under separate sink scenario was proposed in [13]. However, their experiment investigated a small network with two sensors and two separate sinks.

This paper therefore studies cooperative packet forwarding problem in multi-domain WSNs under a separate sink scenario. The objective of this paper is to propose a routing algorithm to 1) deal with non-cooperative behaviors of sensor nodes and dynamic environment factors that affect cooperation between multidomain WSNs; 2) to select fair packet forwarding route that can prolong network lifetime for all multi-domain WSNs with separate sinks. For this purpose, we propose the Non-cooperative game algorithm based on Lemke Howson method (NCG-LH) to achieve a fair packet forwarding strategy and improve the network performance for all nodes belonging to multi-domain WSNs. Moreover, this paper considers a distributed localized approach to reduce the amount of communication overhead and achieve scalability.

The main contributions of this paper are threefold: 1) The NCG-LH algorithm is applied to a non-cooperative multi-domain WSN under a separate sink scenario; 2) Fair cooperative routing comparison is made between routing algorithm based on game theoretic method and an existing non-game theoretic (load balancing) method; 3) Identification of parameters that affect fairness and cooperation between multiple co-located networks.

2. PACKET FORWARDING GAME USING NON-COOPERATIVE GAME APPROACH

Game theory has gained attention for wireless network applications as it is a powerful tool to analyze the behavior of rational agents (or players) [14]. Game theory has been successfully applied to a wide range of problems such as routing [15], power control [16], wireless security system [17] and intrusion detection [18]. Non-cooperative game theory is a branch of game theory which involves interactive decisions in situations which multiple decision makers, each with its own objectives, jointly determine the outcome.

In this paper, Non-cooperative game theory has been applied in a distributed packet forwarding game for multidomain WSNs under separate sink scenario. The motivation for using non-cooperative game theory in routing area is that the agents, e.g., the sensor nodes in WSNs, which have rational selfish behavior, attempt to gain benefit themselves first when they are deciding their routing strategies. Thus, such selfish sensor nodes may prefer to drop packets from other different network domains rather than to help forward the packets in order to conserve their limited energy resources. This is because each packet transmission has an energy cost for each participating sensor node to transmit along the cooperative route. If nodes belonging to different domains adopt this strategy, cooperative routing between multiple domains would not be achieved. Therefore, each agent needs to consider other agents' benefits as well while optimizing its own benefit in order to achieve cooperation. Thus, non-cooperative game theory is a suitable framework to analyze such complex interactions among rational selfish agents such as the packet forwarding game in multi-domain WSNs.

2.1 Game Strategic Form

Strategic form (or normal form) is a basic component in game theory, which is defined by the tuple (I, iA, u_i), where

- I denotes the set of agents, $i \epsilon I$,
- $A_i$denotes the set of actions available to agent i.
- $u_i$denotes the real-valued payoff function for agent i.

To determine suitable strategies for agents to adopt in a non-cooperative game, the most widely used solution is Nash Equilibrium (NE) which is described in the next section.

2.2 Nash Equilibrium Concept

In non-cooperative game theory, the Nash equilibrium (NE) is a solution concept which is used to determine a fair strategy for all agents. NE is a set of strategies for each of agent such that each agent can correctly expect about of the other agent's behaviors, and acts rationally according to this expectation. Acting rationally implies that the agent's strategy is the best response with respect to the other agent's strategy. For any game, at least one NE exists in either pure or mixed strategies [14].

In pure strategy NE, an agent can choose with certainty an action which achieves the best response to the other agent's choice. However, the existence of a pure strategy NE for the game cannot be guaranteed [10]. In a game which a pure strategy NE does not exist, the agents need to select their strategies randomly according to some probability calculated from the Lemke-Howson (LH) method [10] to achieve a mixed-strategy NE. The LH method is the best known method to solve for mixedstrategy NE for two agents. The advantage of LH method is that it is guaranteed to find at least one NE point. We thus employ the LH method in the proposed existing noncooperative game framework.

3. PROBLEM FORMULATION

In this section, NCG-LH algorithm is formally introduced in order to find the best mutual policy for a packet forwarding game in multi-domain WSNs.

3.1 Network Model

Consider two different WSNs, N_i , i=1,2, deployed in a multi-domain WSN. Each WSN domain consists of v sensor nodes,$N_i = n_i^1, n_i^2, ..., n_i^v$ and one sink. Our model divides the time into discrete time units called time steps. In each time step, a source node is randomly selected in each domain to generate a data packet and send it to its sink. The source node acts as an agent that decides which route to send the packet by using the proposed route selection scheme. This paper assumes the following characteristics for each sensor node in the multi-domain WSNs:

- Two sensor nodes are able to communicate with each other if they are within transmission range.
- Each sensor node must be aware of its location, neighbor's location, its sink location and also its neighbor's sink location using an on-board GPS receiver.
- Each sensor node uses a pre-established routing structure based on the ad hoc on demand distance vector (AODV) routing protocol.
- A source node is able to calculate the cost the endto-end energy required for relaying a packet from the source node to the sink.
- The energy consumption of each sensor node are dissipated only for data transmission and reception. Node processing energy is assumed negligible.

The energy consumption required for packet forwarding is computed from the radio model in [19]. The energy cost for receiving a packet at each sensor node is given by,$E_{RX}(b) = E_{elec} \times b$, where E_{elec}= 50 nJ/bit is the cost in the radio electronics and we assume that b is the size of the transmitted packet in bits. Each transmission of packet consumes energy which is considered a transmission cost given by

$E_{TX}(b, d) = (E_{elec} \times b) + (\varepsilon_{amp} \times b \times d^{\sigma})$,

where σ is the path loss exponent and ε_{amp}=10pJ / bit / amp m^{σ} is the energy consumed at the output transmitter antenna for transmission range of one meter.

A pre-established routing process, AODV routing protocol which used in IEEE standard 802.15.4 ZigBee protocol stack [20] is employed to determine available packet forwarding routes to be selected. In the AODV route discovery process, the source node broadcasts a Route Request (RREQ) packet to its neighboring nodes from the same domain and also to neighboring nodes from a different network domain. The source node then establishes two different routes with two different routing tables, one for routing within the source node's own network (refered as non-cooperative route, which is a regular route to forward its packet to sink) and the other for coordinating routes with the other network domain (refered as cooperative route which is an alternative route). This is illustrated in Fig. 1 where sensor node from network domain 1 is a source node taking a role as an agent in the game. Let the source node be denoted by n_1^{src} . From the figure, when n_1^{src} has a packet to send to its sink1, n_1^{src} must decide whether to use the non-cooperative route in its own domain or the cooperative route that consists of nodes from the other domain. To make a decision, n_1^{src} calculates the following energy, including: 1) the end-to-end energy cost along non-cooperative route, $\varepsilon_1^{nc} = \varepsilon_1^{nc_1} + \varepsilon_1^{nc_2}$; 2) the energy required at n_1^{src} to forward its packet to nodes from domain2 to forward their packets to sink1,ε_1^s ; and 3) the end-to-end energy used by nodes in domain 1 required to help domain 2 forward their packets to sink2, ε_1^c . These energy values are used to estimate a payoff value that an agent receives in order to decide which packet forwarding route to choose. The optimal packet forwarding route will be chosen by the source node depending on strategy decision through NCH-LH routing algorithm described next.

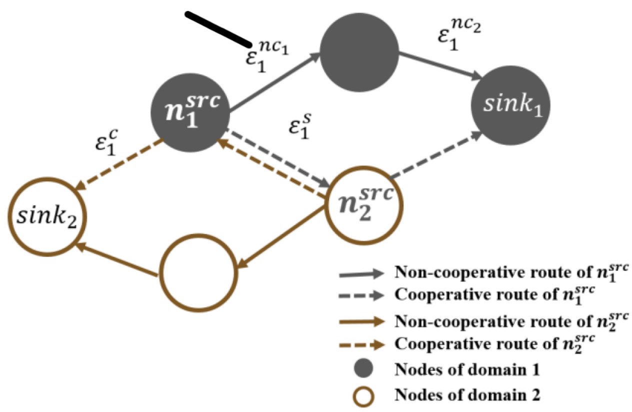

Fig.1: *System model.*

3.2 Strategy Decision

In each game, each agent can independently decide its own action whether or not to cooperate with the other agent. Let A be a set of strategies, which includes all the possible joint actions available in the game. Let a set of strategies for agent i be defined by $A_i = D, F$, i=1,2, where D and F refer to the following:

D: Agent *drops* all packets from the other network if it is asked to help forward the packets.

F: Agent *forwards* all packets from the other networks if it is asked to help forward the packets.

We propose a payoff function according to the payoff matrix in Table 1 to select a fair forwarding route based on the PRR and energy gain. It is assumed that when a forwarding route with the best link quality and energy efficiency is chosen, the reliability and network lifetime should be improved. It should be noted that such linear combination of payoffs of different units have been used in the game theoretic framework for CDMA power control [22] and routing in WSNs [23]. In game theory, given the same set of players and the same set of strategy, a linear combination of payoff functions is still a potential game with Nash Equilibrium [22]. From Table 1, $\mu_i$is the

Table 1: *Payoff matrix of interaction between sensor nodes in different network domain*

$n_1^{src} \setminus n_2^{src}$	$a_2 = D$	$a_2 = F$
$a_1 = D$	μ_1, μ_2	$0, -\eta_2$
$a_1 = F$	$-\eta_1, 0$	$\mu_1(\gamma_1 - \eta_1), \mu_2 + (\gamma_2 - \eta_2)$

packet received rate (PRR) [21], which estimates the probability of successfully receiving a packet from the source node to the sink, and i= 1,2 is the network domain index. PRR is used to estimate the link quality of the forwarding route. The higher PRR is, the higher the link quality is. The PRR can be calculated from the bit error rate (BER) as

$$PRR = (1 - P_b)^b \tag{1}$$

where P_b is the BER for OQPSK (Offset Quadrature Phase Shift Keying) modulation used in IEEE standard 802.15.4 ZigBee protocol stack at frequency 2.4 GHz. The quantity $\gamma_i = \varepsilon_i^{nc} - \varepsilon_i^s$ denotes the energy reduction obtained from changing from noncooperative route to cooperative route. The quantity $\eta_i = \varepsilon_i^c$ is the cooperative energy required for cooperation. Finally, the quantity $\gamma_i - \eta_i$ is the net energy gain if the source node chooses the cooperate route. If $\gamma_i - \eta_i$ is a positive value, it means that the cooperative route consumes less energy than the noncooperative route. Otherwise, cooperative route consumes more energy.

It can be seen from the table that each joint strategy provides a different payoff value. The joint action D, D refers to an action which each domain chooses a regular route. Hence, there is no need to calculate energy cost, so the payoff takes account of only the link quality (μ_i) . As for joint action F, F, the payoff is the PRR and the energy gain obtained from the cooperation between domains ($\gamma_i - \eta_i$). For joint action D, F or F, D refers to the joint action which either agent decides to help the other domain forward its packets, while the other domain declines to cooperate. In this case, the cost of cooperation would be the energy which domain i uses to help forward the other domainâĂŹs packets to the sink ($-\eta_i$). The minus sign depicts the energy consumed which is perceived as a cost of cooperation. The other domainâĂŹs cost is zero since it does not incur any energy consumption (as it refuses to cooperate) but does not enjoy any benefit of increased PRR.

The payoff matrix is determined by the source node based on the two routes discovered by the AODV route discovery process (one cooperative route using nodes from both domains, and another non- cooperative route using nodes from the same domain as the source node). To avoid unfair improvement in only a particular network, the decision to select a fair optimal strategy in NCG- LH algorithm depends on the NE with respect to the payoff matrix in Table I. Let (a_1, a_2) be a joint action of agents in both domains where $a_i \epsilon A_i.A$ joint action (a_1^*, a_2^*) is said to be a NE if an agent from domain i selects an action $a_i \epsilon A_i . i = 1, 2$, which provides the highest payoff when its opponent selects its best action a_{-i}^* where $a_{-i}^* \epsilon A_{-i}$ is the action selected by domain i's opponent $(-i)$. NE can be expressed as

$$u_i(a_i^*, a_{-i}^*) \geq u_i(a_i, a_{-i}^*), \tag{2}$$

where u_i is a payoff function for agent in domain i. If all agents follow NE strategy, a fair mutual benefit is obtained. A joint strategy of a stage game is a pure-strategy NE point if every agent receives its highest payoff at this point. The Lemke-Howson method (LH) is used to solve for a mixed-strategy NE if a pure strategy does not exist [10].

3.3 Compared Algorithms

In order to evaluate the performance of the proposed routing algorithm, we compare it with 3 routing algorithms which include: 1) Pool- based routing algorithm (Poolbased) [4] which is a load balancing routing algorithm for multi- domain WSNs which spreads out the traffic load between the cooperative route and regular route to the destination. Thus, this algorithm promotes fair routing in multi- domain WSNs, similar to our work; 2) an AODV routing scheme which discovers routes that consist of nodes within the same domain only (No cooperation) ; and 3) an AODV routing scheme which discovers routes that consist of nodes from both domains (All cooperation). The last two algorithms are considered in our comparison to show how multiple networks would perform if they always never cooperate or always cooperate, respectively.

4. EXPERIMENT RESULTS

In this section, we provided the simulation results of the proposed NCG-LH algorithm performed in Visual C++ environment and investigate the cooperative conditions of the packet forwarding strategies in multi-domain WSNs under separate sink scenario.

The simulation results are carried out under varying number of nodes, number of failed nodes and path loss exponent as well as network connectivity (i.e.

unguaranteed and guaranteed connectivity). This is because these factors can cause connectivity problems which cause failure in the forwarding routes

Table 2: *Parameter setting*

Parameter	Value	
	Scenario A	Scenario B
Area size	500x500m^2	
Number of domains	2	
Number of sensors perdomain	80-240	
N_1 sink position	[125,250]	[0,0]
N_2 sink position	[375,250]	[500,500]
Distribution of thesensors	Uniform random	
Number of maximumhop in a route	5 hops	
Transmission range	100 m	
Data load per packet, b	100 bytes	
Path loss exponent, ÏČ	2, 4	
Number of failed nodes	4-48	
Routing protocol	AODV routing	

```
BEGIN
 for topology 1:100
     Random sensor nodes for two WSNs to area
     Initialize energy 0.5J for each node
     Let t=0
     do
       Random source node to create data packet
       Establish two routing tables using AODV routing protocol
        (one table for paths in own network and another one
         for paths in cooperative networks)
       Calculate payoff value for all available action
       Determine strategy using NE and LH method
       Sent data packet to sink following its strategy
       Evaluate network performance
       Let t=t+1
     while (at least one node run out of battery )
 endfor
END
```

Fig.2: *Pseudo code of the simulation.*

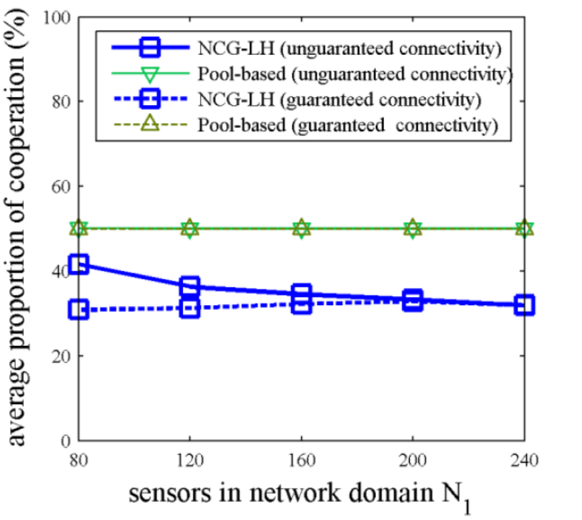

Fig.3: *Average proportion of cooperation at different node density of network N_1.*

thereby reducing the reliability of WSN. Under such scenarios, NCG-LH exhibits the ability to allocate resource between multiple network domains and enable fair routing to eliminate any connectivity weakness and prolong network lifetime.

We compare the proposed NCG-LH algorithm with the aforementioned 3 existing algorithms by evaluating 3 metrics including:

- Proportion of cooperation: the ratio of the number of cooperative routes to the total number of routes discovered.
- Network lifetime: Since each time step, a packet is transmitted, this paper thus measures the network lifetime in terms of the total number of time steps until the first node dies.
- Fairness: the difference in average energy consumed along a forwarding route between network domain N_1 and N_2 . From a fairness point-of-view, a fair routing strategy should enable each network domain to consume energy equally. If one domain uses more energy than the other domain, there will be discrepancy in energy consumption between domains, thus causing unfairness.

The simulation results are divided into 2 scenarios. The simulation parameters are shown in Table 2. Simulation results are carried out over 100 randomly generated topologies. The experimental results shown in this section are obtained from average results. The pseudo code of NCG-LH is shown in Fig. 2.

4.1 Effect of Node Density

In real world WSN applications, it is difficult to control equal node density in each network domain. In some regions, small- scale WSN may be deployed in the same area with a large- scale WSN. The objective of this scenario is to show the resource allocation ability of NCGLH in presence of different node densities in multi- domain WSNs. To deal with this issue, simulation is conducted by varying the density of network N_1 from 80 to 240 nodes and fixing density of network N_2 at 80 nodes.

Fig. 3 shows the average proportion of cooperation with varying number of sensor nodes in N_1 . In the case of unguaranteed connectivity, it can be seen that NCG- LH reduces the proportion of cooperation between the two networks as the network size of network domain N_1 increases. This is due to high availability of nodes and routes in domain N_1 alone, therefore, there is no need to cooperate with domain N_2. In the case of guaranteed connectivity, it can be seen that the average proportion of cooperation of NCG-LH is relatively constant at 30- 35% . This because each network has strong connectivity, thus cooperation is not required as the network density of N_1 increases. This suggests that cooperation between multiple domains is needed in presence of low network density which corresponds to weak connectivity. However, Poolbased algorithm shows a constant average proportion of cooperation at 50% on average for both unguaranteed and guaranteed connectivity cases. This is because high density in each domain implies strong connectivity, Pool- based only balances the load by equally using both cooperative route and non-cooperative route.

Fig. 4a depicts results unguaranteed connectivity. The figure shows that NCG- LH has longer network lifetime than Pool- based, All cooperation and No cooperation routing algorithms by 6.2% , 26.6% and 34% on average, respectively. Similarly, in the case of guaranteed connectivity in Fig. 4b, NCG- LH also attains longer network lifetime than Pool- based, All cooperation and No cooperation routing algorithms by 10% , 34. 8% and 22% on average, respectively.

Another parameter which affects routing algorithm efficiency is fairness of nodes energy consumption as shown in Fig. 5. From the figure, NCG-LH uses NE to determine fair packet forwarding strategies allowing it to achieve fair route selection in terms of energy consumption. NCG-LH outperforms All cooperation algorithms and attains a comparable energy consumption as Pool-based algorithm.

We then investigate the effect of hostile environment in terms of the number of failed nodes and path loss exponent (PLE) in multi- domain WSNs under separate sink scenario as shown in Fig. 6- 8. The experiment is conducted by fixing the density of network N_1 at 160 nodes and fixing density of network N_2 at 80 nodes. We vary only the number of failed nodes and PLE.

Fig. 6 illustrates the average proportion of cooperation with varying number of failed nodes per domain under PLE of 2 and 4. It can be seen that NCG-LH promotes more cooperation between two different domains with increased failed nodes and higher PLE. Meanwhile, that of Poolbased algorithm is kept constant at 50% on average. Note that NCG-LH attains

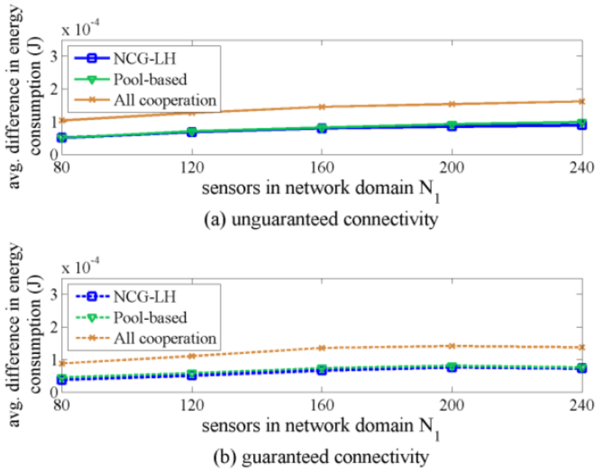

Fig.5: *Average difference in energy consumption at different node density of network N_1.*

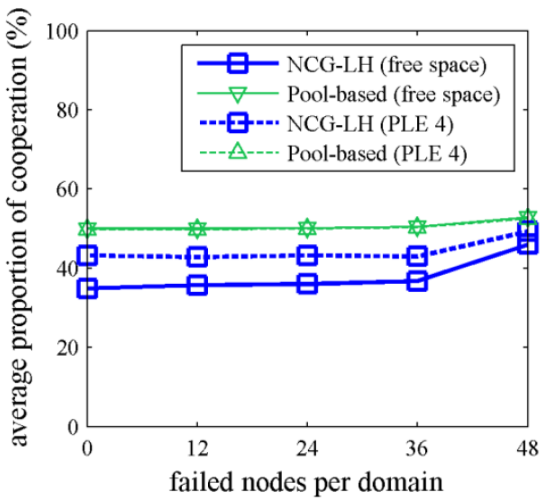

Fig.6: *Average proportion of cooperation in various node failures and different path loss exponents.*

less proportion of cooperation than Pool-based algorithm, yet achieves longer network lifetime than the other algorithm as shown in Fig. 7. From the figure, NCG-LH has longer network lifetime than Pool-based, All cooperation and No cooperation routing algorithms by 3. 3% , 22. 9% and 34. 1% on average, respectively, for free space case. Similarly, when PLE is 4, NCG- LH still has a longer network lifetime than Poolbased, All cooperation and No cooperation routing algorithms by 11. 8% , 29% and 37. 3% on average, respectively.

Fig. 8 shows the average difference in energy consumption with varying number of failed nodes under different path loss exponents. It can be seen that NCG-LH is still comparable to Pool-based algorithms in terms of the difference in average energy consumed between both networks. It is because both

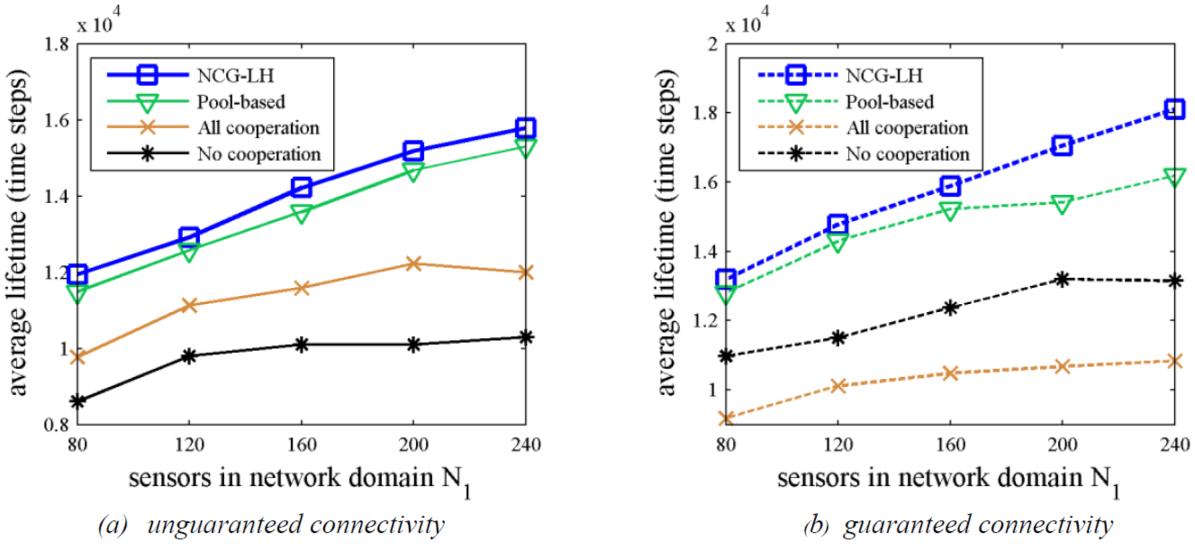

Fig.4: *Average proportion of cooperation at different node density of network* N_1*.*

algorithms take fair energy consumption into consideration. Thus, both algorithms outperform All cooperation. routing algorithm.

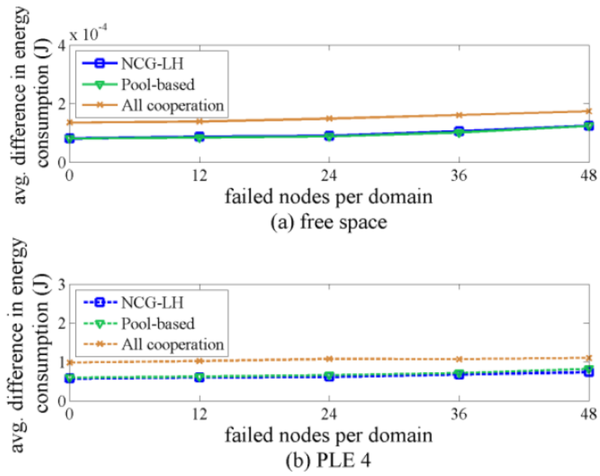

Fig.8: *Average difference in energy consumption in various node failures and different path loss exponents.*

4.2 Effect of Sink Position

This section studies the sink positions that affect cooperation between multi-domain WSNs. The experiment is still conducted with the same parameter setting as the previous scenario except for the sink positions. The sink positions are moved further away from each other by setting the sink node of network domain N_1 at (0,0) and N_2 at (500,500) over a square region with 500 m $\times$ 500 m^2.

Fig. 9 shows the average proportion of cooperation with varying number of sensor nodes of network

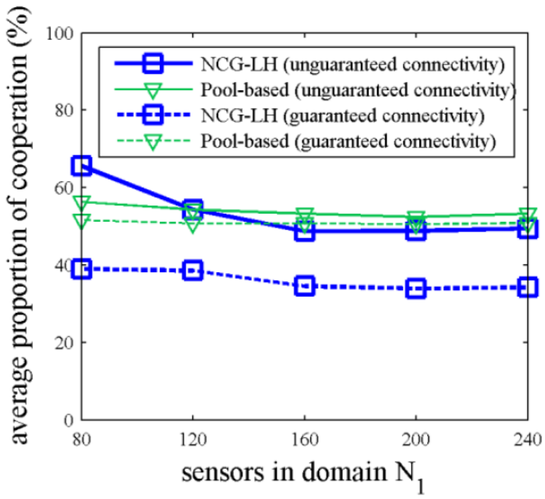

Fig.9: *Average proportion of cooperation at different node density of network* N_1*.*

N_1 . Unguaranteed connectivity, it can be seen that NCG-LH can reduce proportion of cooperation from 66% to 48% as the network size of network domain N_1 increases to 240 nodes. Interestingly, a higher proportion of cooperation for NCG-LH is attained when compared to the previous scenario which the sinks were closer (see Fig. 3). This suggests that when the sink positions are moved further away from other nodes, more cooperation is needed. In the case of guaranteed connectivity, the average proportion of cooperation of NCG-LH is almost constant as number of sensor nodes of network N_1 increases. This is due to the existing strong connectivity in the network which did not require additional cooperation among nodes.

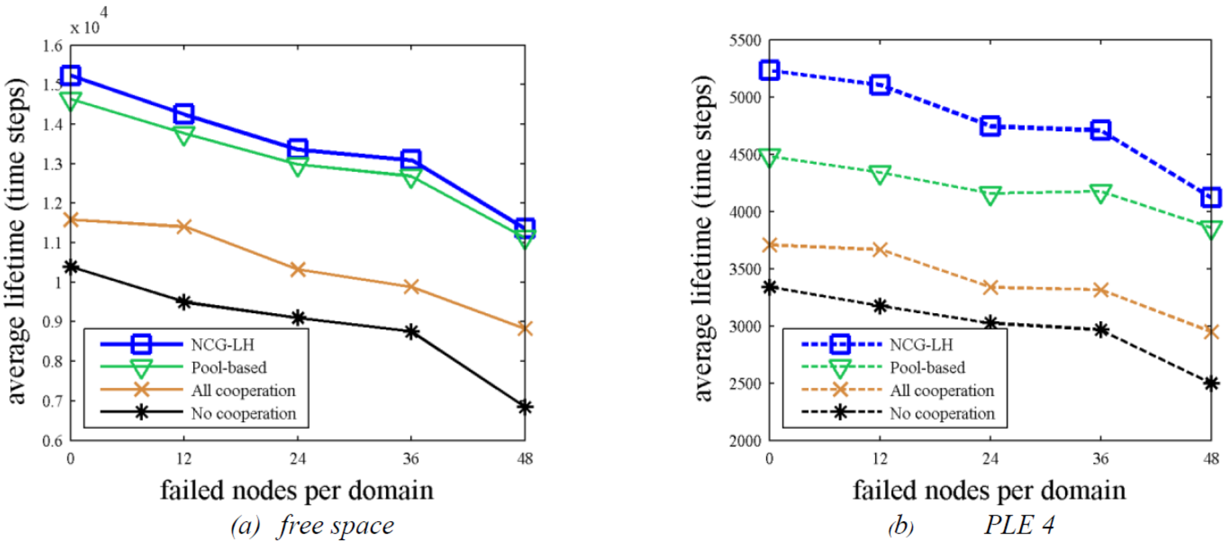

Fig.7: *Average network lifetime in various node failures and different path loss exponents.*

Fig. 10 presents the network lifetime performance. Unguaranteed connectivity, NCG- LH achieves longer network lifetime than Pool- based, All cooperation and No cooperation routing algorithms by 4.3% , 20.7% and 39.1% on average, respectively. Similarly, the guaranteed connectivity case shows that NCG-LH can achieve longer network lifetime than Pool-based, All cooperation and No cooperation routing algorithms by 3. 7% , 25. 6% and 17% on average, respectively.

Fig. 11 shows the average difference in energy consumption with varying number of sensor nodes in network N_1 . It can be seen that NCG-LH achieved the lowest difference followed by Pool- based and All cooperation. routing algorithms. Thus, it can be concluded that in terms of fairness, NCG- LH performs the best compared with the existing routing algorithms under both unguaranteed and guaranteed connectivity when sinks are positioned further apart.

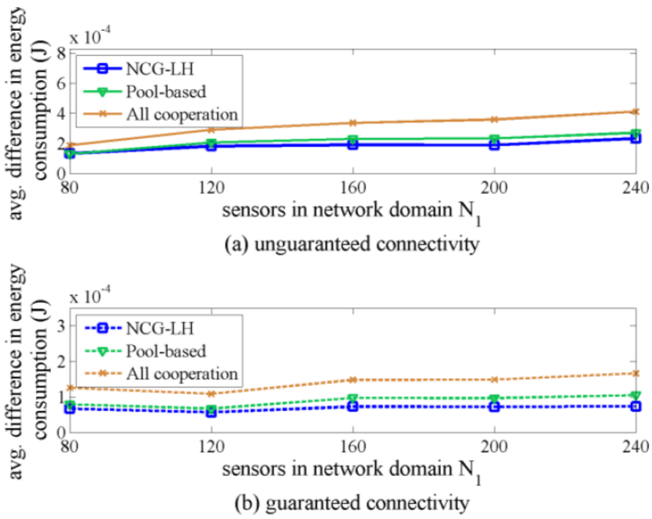

Fig.11: *Average difference in energy consumption at various different node density of network* N_1.

We investigate the effect of hostile environment in terms of the number of failed nodes and PLE in multidomain WSNs under separate sink scenario as shown in Fig. 12-14.

Fig. 12 indicates the average proportion of cooperation with varying number of failed nodes per domain under PLE of 2 to 4. As All cooperation and No cooperation have 100% and 0% proportion of cooperation, respectively, their results are not shown. It can be seen that both NCG-LH and Pool-based algorithms tend to promote cooperation between two different domains in presence of more failed nodes and higher PLE. Note that NCG-LH has higher proportion of cooperation than Pool-based algorithm. From Fig. 13, NCG-LH has longer network lifetime than Poolbased, All cooperation and No cooperation routing algorithms by 3.3%, 22.9% and 34.1% on average, respectively, for free space case. When PLE is 4, NCG-LH has an even longer network lifetime than Pool-based, All cooperation and No cooperation routing algorithms by 11.8%, 29% and 37.3% on average, respectively.

In Fig. 14, NCG- LH still shows attains the least difference in energy consumption between the two domains, thus outperforming Pool- based and All cooperation algorithms when the sinks are moved further away.

5. CONCLUSION

Multi-domain networks which cooperate in packet forwarding, under certain scenarios, may enjoy ben-

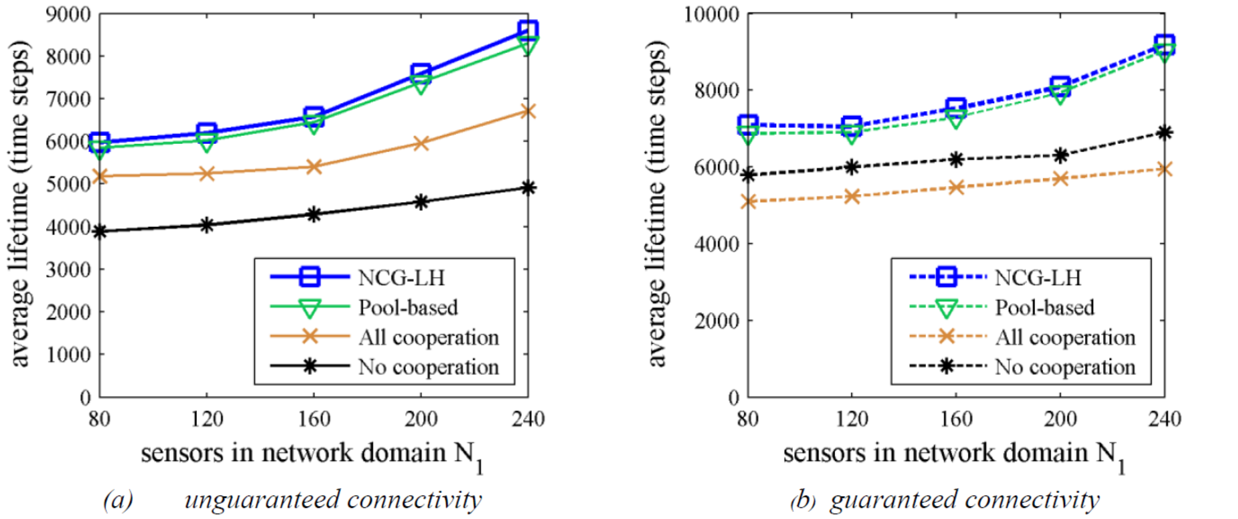

Fig.10: *Average network lifetime at different node density of network N_1.*

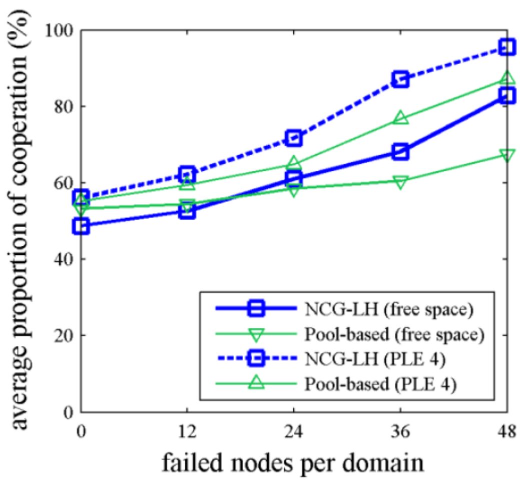

Fig.12: *Average proportion of cooperation in node failures and different path loss exponents.*

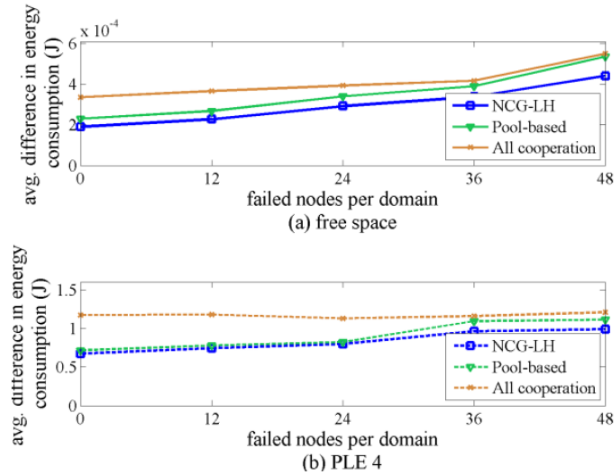

Fig.14: *Average difference in energy consumption in various node failures and different path loss.*

efits including alternative routes and reduced energy consumption, which can prolong their network lifetime. In this paper, we propose the Non-cooperative game algorithm based on Lemke Howson method (NCG-LH) algorithm and evaluate its routing performance in multidomain WSNs under separate sink scenario. The objective of this paper is to determine a fair packet forwarding strategy with the best mutual benefit for all agents and to investigate parameters that affect cooperation between multi-domain WSNs.

The main contributions of this paper is three fold: 1) the NCG-LH for packet forwarding in multidomain WSNs is proposed, 2) investigation of fairness in terms of the difference in energy consumption between domains and comparison between a game theoretic approach (NCG-LH) and the non-game theoretic approach (Pool-based method), 3) Identification of parameters that affect cooperation between multiple co-located networks i.e., network density, node failure, PLE, network connectivity and sink positions.

The simulation results are divided into two scenarios. The study in scenario 1 is to investigate effect of cooperation under different node density, i.e. when the number of sensors in domain N_1 are denser than domain N_2 . NCG-LH can demote cooperation between domains due to the high availability of nodes and routes in domain N_1. This in turn, helps prolong network lifetime in domain N_2 which has less node density. The results show that NCG-LH obtains 3.3%-37.3% longer network lifetime than the others as network density, PLE and the number of failed node increases. In scenario 2, the effect of sink position is

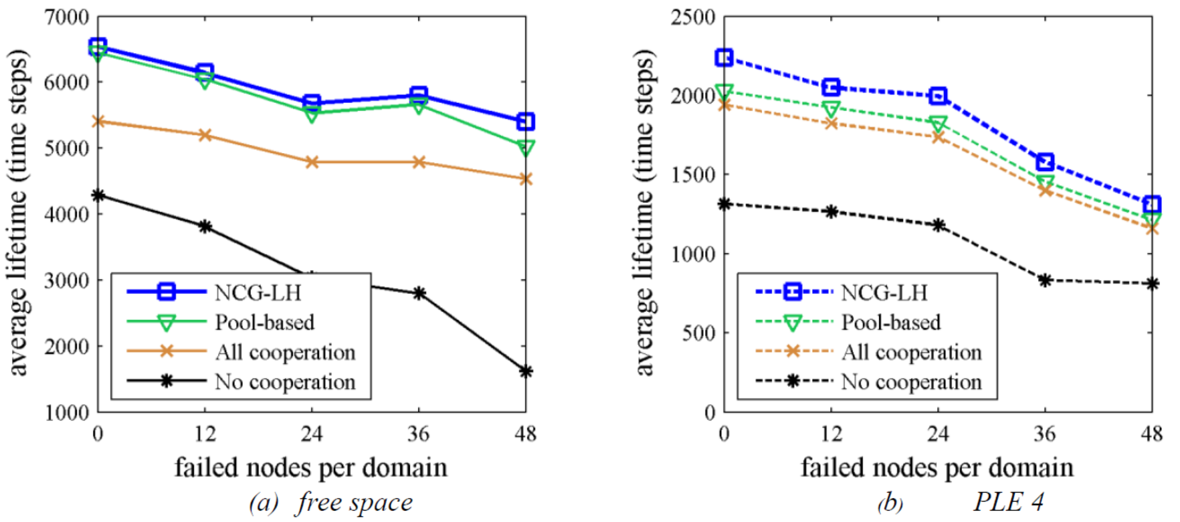

Fig.13: *Average network lifetime in various node failures and different path loss exponents.*

studied. When the sink positions are moved further away from each other, NCG-LH promotes cooperation between networks compared to the original position and obtains 2.6%-39.1% longer network lifetime than the other algorithms as network density, PLE and number of failed node increases. In addition, NCG-LH outperforms the other routing algorithms in terms of fair route selection by attaining the lowest average difference in energy consumption.

It is worth noting that this paper is limited to packet forwarding problem in two-domain WSNs only. However, with the recent advancements in WSN applications covering large areas, it is possible that multiple WSNs can coexist in the same area. A worthwhile extension of this paper is thus to support resource allocation in n -domain WSNs. Furthermore, instead of having the route selection decision made at the source node only, extensions can be made to perform decisions at each intermediate sensor node.

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