Lifetime Enhancement Techniques For MANET Routing In Space Exploration Applications

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Abstract—**Lifetime is a major concern when it comes to space applications such as Mars exploration missions. In such missions, rovers are set to rotate in circular orbits to sense useful data and transmit it to a mother ship in the center of the orbits. Rovers rely on the sun as a source of energy at day time and use their charged batteries for night work. With the energy being too scarce on Mars, further techniques need to be implemented to achieve the highest possible system lifetime. In this paper, the optimum initial position is determined to extend the lifetime of Mars exploration missions. Furthermore, a new more capable rover design is proposed and the best orbit in which it should be positioned, is determined. The results obtained from simulations showed that the proposed two techniques resulted in a higher lifetime of the mission.**

Keywords—Mars Exploration; Routing Protocol; Energy Efficiency; Network Lifetime.

I. INTRODUCTION

A Mobile Ad hoc Network (MANET) is a class of networks which is characterized by having no predefined infrastructure. Most of the time, such networks face critical issues with energy. Nodes in MANET networks are self-configurable which means that they require minimal administration. The topology in these networks is changing all the time since nodes keep moving in the network [1]. The sensor networks used in the space exploration missions follow this type of networks.

Exploration missions to Mars have witnessed huge changes since the year 1996 [2]. The main goal behind Mars exploration missions is to understand the nature of this planet [3]. Rovers are deployed in certain orbits with the aim of regularly gathering useful information about temperature, pressure, type of soil, water, etc. This information will then be sent by the rovers to a mother ship that has the ability to transmit this information back to Earth where it is received and analyzed. Since the system will only be functional as long as all the rovers have energy, the consumption of energy by the rovers is very critical to the mission [4]. Energy is drained in several ways during the mission including motion, sensing and communication. The routing protocol used will determine how much energy is consumed during the communication process which in turn will affect the lifetime of the whole system. Taking the criticality of energy consumption into consideration, rovers use synchronous transmission where they will only transmit their data during predefined periods of length τ, and they will be in sleep mode for the rest of the time. Rovers have batteries and solar cells to recharge them. As long as it is daylight, rovers will be functional without any problems, and moreover they will charge their batteries in order to use them during the night period. The energy consumed by the mother ship is not very crucial, because these ships are usually equipped with more sources of energy compared to the rotating rovers. The rovers are placed in circular orbits with the mother ship in the center of the orbits [5]. To balance between the different orbits, outer orbits, which have bigger radii, have more rovers than the orbits closer to the center. The path that the rovers follow while rotating in their orbits is assumed to be full of obstacles.

In [6], a routing protocol named Space Mission Routing (SMR) was proposed to efficiently exploit the energy of the rovers in the system to achieve a targeted lifetime. The proposed protocol was designed for the period when the rovers are completely relying on their batteries during the night. Through simulations, it was found that the proposed protocol, in contrast to other protocols, achieves a higher lifetime. Moreover, this proposed protocol enhances other important parameters like the fairness of the system, control to payload ratio, and finally the packet delivery fraction.

In this paper, design modifications are introduced in order to maximize the lifetime of the system proposed in [6]. The two modifications that will be presented in this paper are the initial position and the bottleneck orbit identification. The effect of these two modifications on system lifetime, will be studied. It will be shown that system lifetime can be significantly increased when the battery capacity of the rovers in the bottleneck orbit, is slightly increased. A similar increase in the batteries of rovers in other orbits will produce a much lower increase in lifetime. Furthermore, the optimum initial position for all rovers is determined and it is proven that this position also significantly increases system lifetime.

The rest of the paper is structured as follows: Section II contains the background information. In Section III, the proposed work is presented with a focus on the bottleneck orbit identification. Section IV discusses the effect of the initial position on the lifetime. Section V has the conclusions of this research.

II. BACKGROUND

Many routing protocols can be applied on such an architecture [7-15]. An example of the most widely used MANET protocols is the Ad hoc On-Demand Distance Vector (AODV). AODV is an on demand reactive routing protocol that finds routes only when needed. AODV is suitable for fast changing networks like MANETs, as routes keep changing quickly. The major disadvantage of the AODV protocol is that it struggles in energy consumption. The reason behind it is that it relies on control messages to find its routes, consuming too much energy [8].

In [6], a new more efficient routing protocol was proposed and designed specifically for such missions. The proposed protocol is characterized by being reactive, on demand, flat and distributed. Reactiveness in the protocol means that nodes will only search for a route if they need to send data unlike the proactive protocols. This reactiveness helps the system save energy. Being flat means that the level of fairness in the system will be high because of the absence of hierarchies. Finally, being distributed, the proposed protocol will guarantee that the targeted level of fairness will be achieved, because all the rovers will collaborate in order to deliver their packets to the mother ship.

The proposed protocol functions as follows: during each period τ, which will be predefined for the system, all the rovers will transmit control packets to their neighboring rovers. These control packets contain useful information about the sender's rank, residual energy and the number of packets it needs to send. The rank refers to the orbit of the rover (the sink has a rank of 0 whereas rover 1 has a rank of 1). These control packets will only be received by the rovers that are far from the sender by a distance that is smaller or equal to the maximum communication range specified in the system. When received, rovers will have enough information about their neighbors, and they will start selecting which rover should they forward their data to. This selection process is done according to a cost function that determines the cost of sending to any neighboring rover. After constructing a table of all the costs, a sender rover will compare between these costs, taking into consideration the cost of sending directly to the mother ship, and will select the lowest cost. This selection of the lowest cost in the whole system will guarantee fast convergence, high fairness and longer lifetime. Some packets will be dropped if either the sender cannot find a neighboring rover to send to, or all potential receivers have their buffers filled with packets such that they cannot receive more packets. After τ is over, rovers will update their neighbors with their new parameters.

The metrics that were used in the cost function are the minimum hop count, the distance between the sender and the receiver, the residual energy and the available receiver's buffer capacity. These metrics will help optimizing the system taking into consideration the nature of the system where there is only one stationary sink and also the fact that all the rovers are battery powered.

III. PROPOSED WORK

In this section, the system layout, routing protocol used, and the simulation parameters will be discussed. Also, some design modifications will be proposed and studied in order to prolong system lifetime. Some new rovers with more capable batteries will be introduced in the system and will be placed in a specific orbit in order to maximize system lifetime. Furthermore, in Section IV, the best possible initial position for the rovers (that will result in the highest possible lifetime of the system) will be determined.

A. Problem Statement

In Mars missions, the solar energy is the main supplier of energy. Batteries are recharged during the day to take over at night. On such missions, energy is dissipated in different forms ranging from motion to sensing and most importantly communications. In [6], a new Space Mission Routing (SMR) routing protocol was proposed and studied; it was shown that this protocol resulted in a huge reduction in energy consumption and therefore an extended lifetime. Thus, the focus in this research will be on proposing new ways that can increase system lifetime even more. It was noticed that the rover that dies first almost always belongs to the third orbit thus new modifications were made to the system to elongate its lifetime. Also, it was found that the initial position of the rovers could largely affect the lifetime of the system. The focus will be on operations taking place at night where the energy is limited only to the lifetime of the battery.

B. System Layout

The system layout is composed of 11 rover nodes and a mother ship as in Fig.1. The mother ship is placed at the center while the rest of the rover nodes circulate around it in predefined concentric circles. There are 4 circular orbits around the mother ship with the first orbit having 2 rovers, the second having 2 as well, the third has 3 and finally the fourth has 4 rovers. The radii of these orbits are 1 km, 1.5 km, 2 km and 2.5 km respectively. Rovers in each orbit scan the orbit in the same direction for collision avoidance and opposite to the following orbit such that: the first orbit nodes move counter clockwise and so on. Rovers move with random velocities that follow a normal distribution and updated each 5 minutes. The mean velocities are 1.82 km/h, 1.43 km/h, 1.3 km/h and 0.74 km/h respectively and the variance is 0.25 km/h.

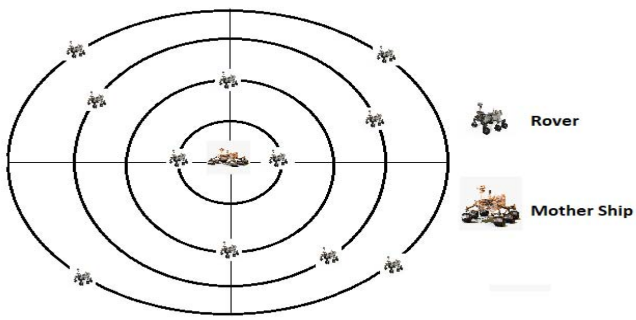

Fig. 1. System Layout

C. Protocol

The SMR routing protocol will be used in this research. It routes based on a cost function expressed by equations (1-5) and Table I explains the cost equation parameters.

Where:

$$C = T1 + T2 + T3 + T4 \tag{1}$$

$$T1 = \alpha_1 \times \frac{n}{N} \tag{2}$$

$$T2 = \alpha_2 \times \frac{D}{R} \tag{3}$$

$$T3 = \alpha_3 \times \left(1 - \frac{E_r}{E_i}\right) \tag{4}$$

$$T4 = \alpha_4 \times \frac{N_p}{B} \tag{5}$$

TABLE I. COST FUNCTION PARAMETERS

Symbol	Meaning
B	Maximum Buffer Size
C	Destination Node's Cost
D	Distance between Sending and Receiving Nodes
E_i	Initial Energy
E_r	Destination Node's Residual Energy
n	Destination Node's Orbit
N	Number of Orbits in the System
N_P	Destination Node's Packets
R	Maximum Communication Range
T1	Rank Term
T2	Distance Term
T3	Energy Term
T4	Traffic Term
α1	Rank Coefficient
α2	Distance Coefficient
α3	Energy Coefficient
α4	Traffic Coefficient

The proposed routing protocol in [6] was proven to be more efficient than distance and energy routing protocols like AODV.

Equations (6-11) illustrate the energy equations used to calculate the energy consumed by the nodes using this protocol and Table II explains the energy parameters [16].

$$E_{rx} = E_{elec} \times P \tag{6}$$

$$E_{prot} = E_{elec} \times P \tag{7}$$

$$E_{tot} = E_{rx} \times M + E_{agg} \times P \times M + E_{prot} \tag{8}$$

$$E_{prot} = E_{elec} \times P \tag{9}$$

$$E_{tx} = E_{amp} \times P \times D^{\gamma} \tag{10}$$

$$E_{tot} = E_{prot} + E_{tx} \tag{11}$$

TABLE II. ENERGY EQUATION PARAMETERS

Symbol	Meaning
E_{elec}	Transmitter/ Receiver Electronics
E_{amp}	Transmitter Amplifier
E_{agg}	Aggregation Energy
E_{prot}	Processing energy for transmitting a packet
E_{tx}	Transmit energy
E_{rx}	Receiving energy
E_{tot}	Node dissipated energy
γ	Path Loss factor
P	Packet Size
D	Distance

Table III has the simulation parameters that will be used in all the simulations conducted on MATLAB.

TABLE III. SIMULATION PARAMETERS

Variable	Value
Simulation Time	10 Hours
Radio Coverage	1.5 Km
Propagation Model	Free space
Path Loss Exponent	2
Area	19.63 Km^2
Number of Nodes	12
Mobility Speed	0.68-1.68 km/hr
Payload Size	50 Bytes
Control Packet Size	5 Bytes
Interval between packets	5 minutes
Buffer Size	20 Packet
Initial Battery	12J-18J
E_{elec}	50 nJ/bit [16]
E_{amp}	100 $pJ/bit/m^2$[16]
E_{agg}	5 nJ/bit/Signal [16]

D. Bottleneck Orbit Identification

In this subsection, the bottleneck orbit will be identified using simulations. The bottleneck orbit is defined as the orbit whose rovers almost always run out of energy first. Then, a new set of rovers with higher capacity batteries will be positioned at that bottleneck orbit to get the maximum lifetime possible.

Simulations were run many times with different random seeds to make sure that the randomness will not affect the results. It was found that, most of the time (92%), the nodes in the third orbit die first and cause the system to stop functioning. The reason for that is as follows: orbit 4 nodes only send their data without the need to relay any data from other nodes since they are positioned at the outer orbit and the protocol used will make it impossible for any node to pick an orbit 4 node to relay its data. Orbit 1 nodes are the closest to the sink, so they exert the least amount of energy while sending. Hence, rovers in orbit 3 consume the largest amount of energy and die first accordingly.

Based on the previous conclusion, a new set of rovers with a 50% increased battery capacity will be introduced to the basic rovers. The effect of positioning those powerful rovers at each orbit separately will be studied in order to determine the optimal orbit for these rovers that results in the highest lifetime possible.

Fig. 2 shows the relation between the lifetime of the mission and the initial energy of the rovers in different orbits. Each of these 5 curves illustrates the relation between the initial energy when using the powerful rovers at a specific orbit and the lifetime of the mission. There are five different curves in the graph, four of them illustrate how the lifetime will change when the new rovers are added in orbits 1, 2, 3, 4 and the final curve (none) depicts the normal case when the basic rovers are used in all orbits. In this graph, the initial energy of the rovers in each orbit is measured in Joules, whereas the lifetime of the mission is measured in a unit of 5 minutes.

Obviously, the more the initial energy is increased, the higher the lifetime will be. Also, the difference in the lifetime between the five cases increases with increasing the initial energy. Positioning the powerful rovers at some orbits has more effect on the lifetime than other orbits. In the case under study, positioning the powerful rovers at the third orbit has the highest effect on the lifetime of the mission. At 12j, when positioning the powerful rovers at the third orbit, the lifetime of the mission has increased by 30% compared to when using basic rovers in all of the orbits. This happened because orbit 3 rovers almost always die first so it is expected that adding more energy to them will result in the highest lifetime compared to any other orbit. One observation that might not be intuitive is that positioning the powerful rovers in some orbits actually causes the lifetime of the system to fall below the normal case. The reason for this is as follows. The nodes in the third orbit die first, so increasing the energy in other nodes will not help the system live longer. Moreover, increasing the initial energy in some orbits, like the first orbit, will actually change the cost of sending to this orbit. Nodes in the third orbit will always choose the first orbit, since it has higher residual energy, and since the nodes in the third orbit are the first to die, sending to the first orbit all the time, which is relatively far, will cause the nodes in the third orbit to die even earlier causing the overall lifetime of the system to go down.

In conclusion, the most effective way of increasing the lifetime if a limited number of these powerful rovers was available, is replacing the basic rovers in orbit 3, which are expected to die first, with these powerful rovers that last longer.

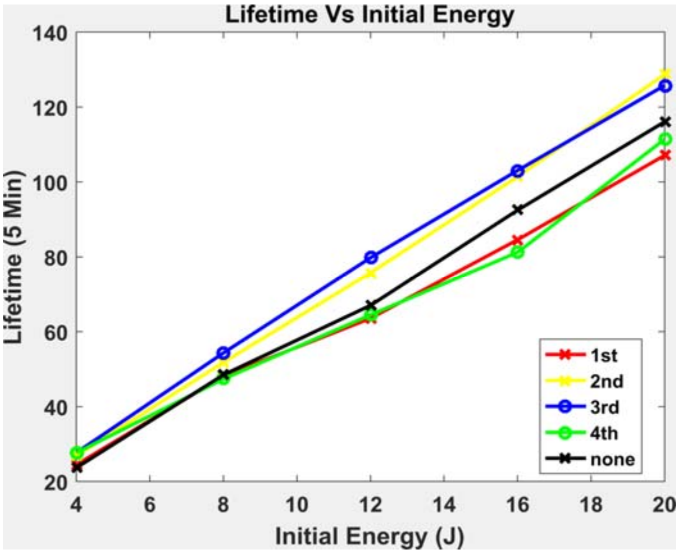

Fig. 2. Lifetime Vs Initial Energy

IV. Initial Position

The initial position is the position where the rovers are placed at the beginning of the mission. A good selection of this initial position would largely affect the lifetime of the whole system. The initial position will determine the relative distances between all nodes and since all nodes follow the same path for the rest of the lifetime, these relative distances change in a ratio relative to the initial position. With the distance between the pair of sending and receiving nodes being the dominant factor that determines how much energy is consumed while sending, a good choice of the starting position will result in a major reduction in the energy throughout the whole mission [17, 18].

In [6], some random initial position was used as a proof of concept on our proposed routing protocol. However, due to the effect it has on the lifetime, this issue will be examined in depth in this research. An exhaustive search was conducted to come up with the best set of starting positions for all nodes. These initial positions result in the longest lifetime possible given the same initial energies.

The scattered Fig. 3 shows the initial positions of the rovers with their resulting lifetimes. Initial positions are represented by indices from 1 up to 800 representing all tested initial positions. Fig. 3 proves that the proper selection of the initial position can have a huge impact on the lifetime since a 45% difference between the highest and lowest points can be seen.

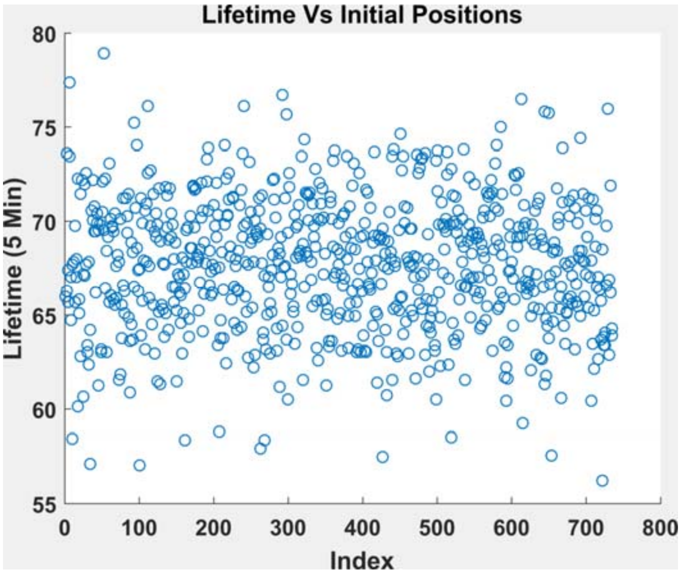

Fig. 3. Lifetime vs Initial Positions

Table IV depicts the effect of changing the starting position of the rovers on the lifetime of the mission. The angles ϴ1, ϴ2, ϴ3, and ϴ4 are respectively the starting position of the first rover in each orbit.

According to the number of rovers (nodes) in each orbit and the angle separation between them, the position of all the nodes can be obtained. This table shows a sample of the different angle combinations with their respective lifetime and total distance. The initial position that results in the highest lifetime and lowest cumulative sending distance is highlighted. The table shows that different starting points can result in a range of values for the lifetime. A 14% difference between the best and worst initial positions distances resulted in a 40% difference in the lifetime.

With the four rovers at orbit1 and 2 separated by π/2 each as in Fig.1, this facilitates their mission of relaying the incoming packets from the outer orbits and divides the weight equally between them since each one of them is directed towards one large quarter circle of the whole area covered by the rovers. The position of the rest of the rovers is not as important as these nodes only send their data unlike the fist 2 orbit nodes which relay others' data.

The reason why this specific position resulted in the highest possible lifetime is that it matches the least cumulative sending distances across the whole simulation time. A new metric was introduced where each time a node sends a packet, the sending distance is added to this metric until the whole simulation is terminated. The metrics generated from a set of initial positions are then compared and the results have shown that the chosen initial position maps to the least metric. With the least cumulative distance, the energy consumption is the least as well.

TABLE IV. INITIAL POSITIONS VS LIFETIME & DISTANCE

ϴ1	ϴ2	ϴ3	ϴ4	Lifetime (τ)	Distance (m)
0	0	0	0	66.00000	5.0194e+05
0	π/2	π/8	π/4	78.93333	4.7203e+05
π/2	0	π/4	π/8	70.06667	4.9840e+05
0	0	π/8	π/4	64.73333	5.1294e+05
π/2	π/2	π/8	π/8	69.93333	5.0100e+05
0	π	π/8	π/8	74.06667	4.9450e+05
π/3	0	π/4	π/2	71.33333	4.9819e+05
π	π	0	π/8	56.20000	5.3804e+05
π	5π/6	0	0	60.46667	5.1351e+05
π	0	π/4	3π/8	75.80000	4.8934e+05

V. CONCLUSION

The scarcity of energy on Mars makes it a necessity for the design of the system to be energy efficient. As such, in this paper, two new design modifications were determined that further prolong the lifetime of Mars exploration missions. The accurate selection of the optimum initial position of the rovers resulted in a sharp increase in the lifetime of the system. Also, introducing a new rover design, with a higher battery capacity, at a specific orbit helped increasing the lifetime as well.

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