An Energy-Efficient Architecture for Multi-Hop Communication Between Rovers and Satellites in Extra-Terrestrial Surfaces

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Abstract

Over the past three decades, several man-made vehicles have being sent into space to explore the extra-terrestrial bodies. As the search for water and other useful substances in the extra-terrestrial surfaces increases, this exploration activity is set to dramatically increase over the next decade (2020); with NASA planning to explore the surface of Mars, Moon and other planets and satellites. In this regard, it is imperative to build an extremely energy-efficient communication system that will cover a large area in the range of hundreds of kilometres which unfortunately is absolutely not possible today. A two-hop communication mechanism that has been well researched in the literature is insufficient to cover the extremely large distance of extra-terrestrial surface. In this paper, a novel three-hop cluster-based hierarchical communication architecture is proposed which could be easily extended to higher number of hops. In particular, it allows the individual rovers to move large distances for collecting data and at the same time provide an extremely energy-efficient mechanism for continuously exploring the surfaces. The simulation results show that in a Martian surface, the proposed three-hop design results in a higher capacity as compared to a single-hop or a cluster-based two-hop design even when the rovers move 100 km.

Categories and Subject Descriptors:
G.4 **[MATLAB]**
C.0 **[Systems Application Architecture]**

Keywords: Extra-terrestrial surface, Mars, Multihop, Rovers.

1. INTRODUCTION

Developing a communication mechanism for exploring surfaces of several hundreds of kilometres in extra-terrestrial surfaces is an extremely complicated operation. This is because; a lot of vehicle's energy was used solely to send data. This in-turn resulted in large battery requirement for the rovers which increases the overall load of the satellite sent to the extra-terrestrial surface.Hence, it is important that a communication system be built with low energy consumption in mind. A state-of-the-art mechanism for rover design is to have it solar powered, i.e., a rover that works by taking energy from the Sun. However, in these systems, the amount of energy consumed at any instant of time is nearly same as that of the energy produced during the same time period. Hence, these rovers work in the day time and 'sleep' in the night [1]. This is clearly not an efficient mechanism in terms of both capacity and signal monitoring. Also, the maximum possible travel distance of a rover is only 1 km [1] which is a great hindrance especially when the rovers are supposed to cover the entire surface of planet like Mars.

A multi-hop communication system has been proposed to carry out these exploratory works. However, as can be gathered from the extensive literature [2, 3, 4], most of the focus on multi-hop communication is geared towards two-hop communication. This is sufficient for cellular and wireless networks designed for establishing wireless communication in urban and densely populated areas in Earth. However, extra-terrestrial exploration has totally different requirements; ranging from distances, monitoring of signals, battery limitations, abundance of frequency resource, etc. Hence, it is imperative that an efficient architecture is developed that could form the basis for establishing communication mechanism in extra-terrestrial surfaces.

In this paper a three-hop cluster-based communication system is proposed that could be easily extended to higher number of hops. This design is developed, primarily for use in extra-terrestrial bodies like Moon, Mars, etc. Further, the communication mechanism would be investigated for two different surfaces; particularly for Earth and Mars. The difference in the propagation model of Mars is due to the weather, atmosphere composition and terrain. Mars's weather may be similar than the Earth's weather, but is still

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very complex [5]. Similarly, Moon has different set of variables to Mars and the Earth. For instance, Moon has no atmosphere. However the terrain, the cosmic radiation and the heat from the sun will all have an effect on how the communication system will work. It would be interesting to observe how the novel proposed architecture could be used for long-range communication and its efficiency across different surfaces and different extra-terrestrial bodies.

This paper is organized as follows. Section 2 describes the proposed mechanism for exploring Mars' surface using rovers and an efficient cluster-based architecture for realizing the same. Section 3 explains the simulation model, particularly the scheduling and communication mechanism; and importantly the propagation model in the surface of Mars and describes some initial results while Section 4 provides a brief conclusion of the work.

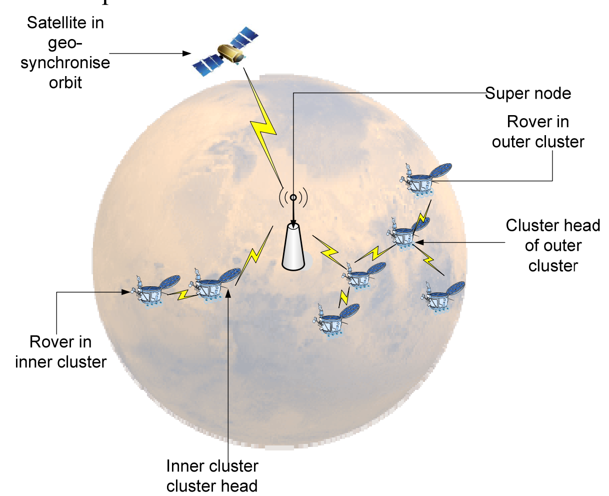

Fig. 1 Rovers used to explore extra-terrestrial surface (Mars)

2. COMMUNICATION SYSTEM

2.1 Architecture

At present, the Mars Odyssey is the current means of communication between the surface vehicles and Earth. It takes approximately 16 minutes to go from horizon to horizon and the surface vehicles send data to the satellite for 10 minutes [6]. Keeping this in mind, a cluster-based hierarchical multi-hop communication system is designed in this work; with the initial focus on three-hop model. This could be then further expanded to a four/higher hop system. The communication system consists of a central super node which would be the main source of communication between the rovers and the satellite. The satellite would be in geosynchronous orbit located directly above the super node. This way, the flow of data between the super node and geosynchronous orbit would remain constant.

In the proposed architecture, as shown in Fig. 1, the central super node is surrounded by several vehicles/ rovers. These vehicles are divided into groups/clusters. Hence, each cluster will contain several vehicles and one vehicle which will act as a cluster head as a means of communication between the cluster and the super node. The cluster head of each cluster will be placed at a minimum distance of 10 km (around 50 km) from the super node. All the vehicles/rovers in the cluster would communicate its information to the cluster-head which in turn would communicate the information of all the vehicles/rovers to the central super-node. As shown in Fig. 2, the proposed three-hop communication system has two sets of clusters – *inner-cluster* and *outer-cluster*. These inner clusters (marked by orange colour in Fig. 2) are surrounded by outer clusters. Each cluster in the inner set of clusters has the same structure; with all the vehicles in the cluster sending their information to a vehicle acting as a cluster head. However the vehicle that receives the information in the outer clusters does not communicate with the super node. These vehicles send their information to the cluster heads in the inner clusters. Through the inner cluster-heads, they communicate with the orbiting satellite.

Importantly, the communication mechanism would comprise of time division multiplexing (TDM) wherein, each vehicle in the cluster is provided a fraction of time period to communicate with the cluster-head. Further, since the cluster-head node communicates the information of all vehicles within the cluster to the super-node, the super-node to cluster-head communication is provided with M time slots, where M is the number of vehicles within the cluster. A detailed explanation of TDM for multi-hop communication is provided in [4].

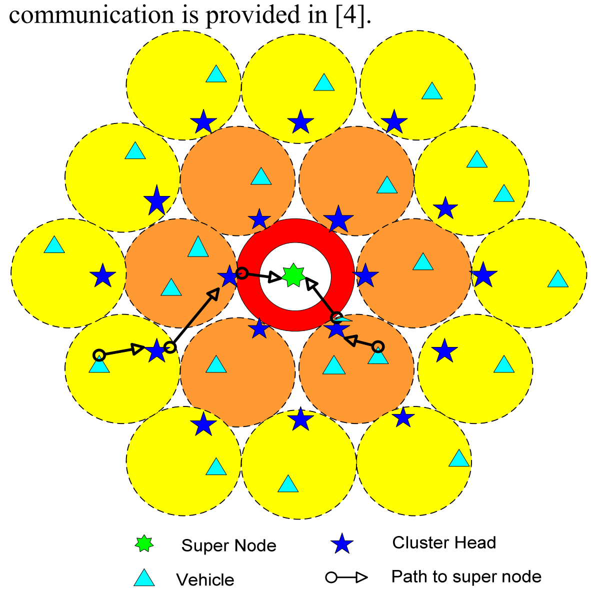

Fig. 2 Proposed architecture of three-hop communication system

2.2 Advantages of Cluster-based Model

The cluster-based architecture for three-hop model is considerably complex than a two-hop communication scenario. However, such three-hop architecture has two major benefits for exploration in extra-terrestrial surfaces.

<u>Energy Recharge:</u> The continuous exploration activity by the rovers would in general result in the battery of these rovers dying quite frequently. However, in case of the cluster-based design, if the battery of the vehicle where to reach a critical level, the communication of all the vehicles would not have to be stopped. The particular vehicle would stop its operation, handover its functionalities to some other vehicle/rover and then drive itself closer to the super node to charge. Vehicles will be only able to charge when it is close to the super node. The area where a vehicle is given permission to charge its self is shown as a white circle in the centre of the centre circles. If one of the vehicles that need to charge their battery is a cluster-head, other rovers/vehicles in the cluster would take over the responsibility of being the cluster-head and then communicate with the super-node.

Energy Consumption/ Large Coverage: The proposed cluster-based architecture for exploring large area surfaces is scalable beyond three; and even four hop communication system. With the increase in the number of hops, the communication complexity increases while at the same time, the overall coverage area also increases. With increasing number of hops, the energy levels needed for a surface vehicle to send a signal to a super node on the surface of the extra-terrestrial body is much smaller than the energy levels needed to send signals form surface vehicles to orbiting satellites

3. SIMULATION MODEL AND RESULTS

Most propagation models in the literature have been developed for use on Earth. When developing a propagation model for use on Mars, the differences in the environment of Mars compared to Earth need to be taken into account. This difference in environment is provided in [7]. In the simulations, an Irregular Terrain Model (ITM), also known as the Longley Rice Model is selected and used. ITM is described to fit the Mars surface very closely [7] and hence, is used in this paper. In the initial stage, the system was simulated for a free-space environment and for a rural environment of Earth based on Okumara-Hata model. Though it is a simple scenario, the overall surface of Mars would also be devoid of any building and other man made effects. Further, using the Longley Rice model, the capacity results in the surface of Mars is computed for a cluster-based three-hop design and compared against a single-hop and a cluster-based two-hop model. The system is simulated using Matlab with a transmit power of 1W and a path-loss exponent of *two*. Fig. 3 shows the improvement in the system capacity in the surface of Mars. It can be observed from Fig. 3 that the system capacity of a three-hop cluster-based system is 8% higher than a two-hop model and up to 23% higher than a traditional single-hop communication system. Notably, irrespective of the number of hops between the end-to-end link, the capacity results obtained for surface of Mars are higher than obtained traditionally in the surface of Earth. This is because; there is no man-made interference in the extra-terrestrial surface yet. Finally, the poster presentation during the conference would also compare the results obtained for surface of Mars with that obtained in Earth.

4. CONCLUSION

A hierarchical multi-hop cluster-based communication system is developed that could be used mainly for exploring extraterrestrial bodies such as Mars, Moon, etc. In particular, a three-hop the cluster-based model is proposed whereby the rovers could continuously sense the environment and send the signals to the geo-synchronize orbit through the central super-node. Such a design not only results in potential improvement in the energy efficiency but also provide a much larger increase in the coverage area – the two main factors in the design of communication system for any extra-terrestrial exploration.

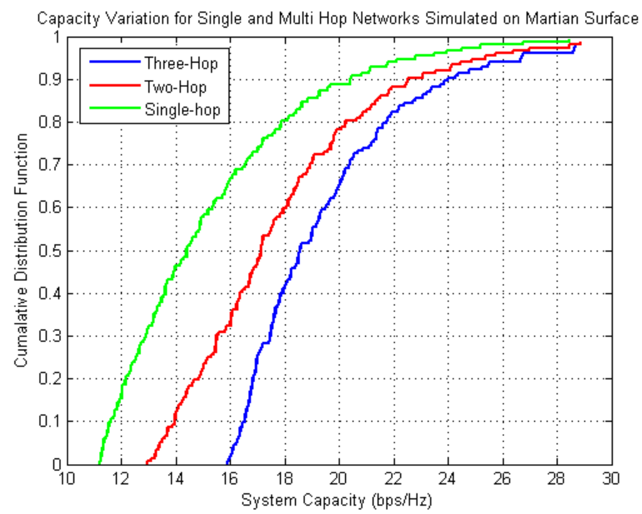

Fig. 3 System capacity variation of a single-hop and multi-hop network at Martian surface

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