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FRAMEWORK FOR THE COMMUNICATION OF SENSOR DATA IN MULTIPLE ROVER DEPLOYMENTS

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ABSTRACT

This work provides a method and framework for a low cost wireless sensor network (WSN) in support of autonomous exploration and intelligence gathering. In today's budget constrained environment, NASA is looking for innovative and cost effective methods to provide access to Space. Leveraging the success of the CubeSat Project, this work addresses the need of a low cost Mars Tumbleweed Rover WSN for the exploration and intelligence gathering of remote terrain. Mars Tumbleweed Rovers are designed to use wind to autonomously propel a network of sensors. While navigating the surface of Mars, or Earth based locations, the rovers' collect, aggregate, and communicate environmental and spatial sensor data. The Mars Tumbleweed Rover program envisions releasing numerous autonomous rovers packed with sensors into a remote, desolate, and harsh dynamic environment, requiring a self-configurable, adaptable WSN. This work provides a low cost framework for a WSN to be deployed on Mars Tumbleweed Rovers. This framework results in a platform to promote new research, exploration, and intelligence gathering of remote locations by Science, Technology, Engineering, and Math (STEM) students and educators. The result of this work provides a low cost framework for increased access to space exploration and sensing of remote locations.

MARS TUMBLEWEED ROVER

The Martian surface is vastly underexplored, even with the multi-billion dollar rover programs that currently explore the planet. NASA and other space agencies around the world are in search of new methods and ideas to scout out potential future landing sites and better understand the surface environment of Mars in an econmical and risk adverse way. The current fleet of wheeled rovers is severly limited in their ability to collect sensor data across the majority of the surface. Typical usage requires multiple teams of scientists and engineers to plan and execute every task performed by these wheeled rovers. Another constraint includes complete mission failure if critical systems fail to operate or breakdown, very much putting all your eggs in one basket. The result is a very expensive and risky endevor in the search for life and future landing sites of interest with regard to Mars.

One idea to cut cost, increase the volume of rovers scoutting out the surface, and reduce risk, include the NASA proposed Mars Tumbleweed Rover. These rovers are imagined to be deployed in large numbers with respect to the current wheeled rover fleet. Tumbleweed rovers are designed to use the natural Martian winds to propel and navigate over the harsh and rocky terrain, much like the well-known Russian Thistle that inhabits much of the central plain states within the United States. On average, the Martian surface wind speed is approximatly equivilent to a gentle breeze here on Earth, the force provided by this wind can be used to propel spherical sailed rovers packed with environmental sensors all over the surface. This paper provides a low cost framework for the communication of collected sensor data between multiple deployed Tumbleweed rovers. NASA conducted an in-depth feasibility study of motion and design requirements on various Tumbleweed designs in a simulated Martian environment. The conclusion presented details that a wind-driven Tumbleweed sensor network appeared feasible for exploring the surface of Mars; if the Tumbleweed is sufficiently lightweight (5 to 10 kg) and relatively large (radius of 3 to 6 m)[1].

These mobile sensors are envisioned to use an inertial measurement unit (IMU) to have a rough notion of location from some starting position. Regardless of this known location the vehicle does not have a method for effectively controlling when or in what direction movement occurs, this is largely dictated by the topographical features of the surface of the planet, wind velocity, and wind direction. Therefore, the rovers tend to randomly distribute themselves across the surface. Due to this random dispersal of sensors, a wireless sensor network (WSN) is needed to aggregate and disseminate data back to Earth via relay nodes. The Tumbleweed mission is to cost effectively scout out broad areas of Mars, including areas inaccessible to traditional rovers, and provide feedback/data to Earth about potential locations for subsequent investigation via guided rovers, or future manned missions[2] [3].

THE NEED FOR MARS TUMBLEWEED ROVERS

A review of the literature shows that much of the Tumbleweed research fizzled out around 2006. We are now seeing a renewed interest in the past few years with new journal publications on this topic. NASAs Exploration Systems Mission Directorate (ESMD) and supporting partner, Space Operations Mission Directorate (SOMD), are charged with deploying robotic rover missions to scout out potential future landing sites on Mars and its moons, our Moon, and nearby asteroids in an effort to train space pioneers on these new celestial bodies[4]. It has been said that future Martian exploration missions are likely required to cost less than $800 million in total program cost, which is a drastic reduction from program costs of past rover programs, such as curiosity that came in at 2.5 billion dollars[5] [6]. Any new rover program will need to be better, faster, and cheaper than programs such as the Mars Curiosity Rover design and deployment[4] [5]. Due to the simplistic design and ease of deployment, a Mars Tumbleweed Rover mission is anticipated to be a significant reduction in cost when compared to past rover systems, and presents itself as an interesting alternative for future investment.

WIRELESS COMMUNICATION NETWORK

The scope of this work is to create a framework for communication of sensor data in multiple rover deployments. This entails focusing on the wireless communication system. Requirements from other rover subsystems such as power budget, and data rate will be needed to select appropriate hardware and communication protocols. The methodology employed to create this framework is to define customer/mission needs, develop system requirements based on these needs, create a robust model of the network (both physical and upper layers), perform simulations using this model, develop hardware that can be used to implement the model/communication network, and finally refine/improve the model via multiple iterations using real world testing on actual hardware prototypes. The resulting model and framework for selecting the appropriate communication system based on the desired mission can then be used to further develop solutions for communication of multiple rover deployments.

NASAs long-term goal for the exploration of Mars includes the use of rovers and sensors which intercommunicate through proximity wireless networks[7]. Elements of the network have a short transmission range, require little power, low cost, and have a relatively short-life span[7]. The performance of any such wireless network depends fundamentally on the radio frequency (RF) environment[7]. In order to evaluate and optimize the performance of a wireless network, an understanding or model of the environment and the radios operating inside of it, is essential. With such a model, better engineering trades can be explored and choices for the protocols to be used, physical (PHY) layer modulation and coding schemes, equalizer design, and antennas can be more logically developed.

MISSION NEEDS

Skelton and Qing prepared a paper on “Multi-Rover Collaboration”[8]. They presented the idea of local collaborative wireless communication networks that aggregate sensor data to higher power relay nodes via a mesh network. Among the rover group, one is identified as the coordinator, accountable for organizing the network nodes when the nodes are out of range of the command station. In the case of a coordinator node failure the cluster members are able to elect a new coordinator to substitute, which can make the network more robust to mobile nodes coming in and out of the network.

The current focus of NASAs Exploration Systems Mission Directorate (ESMD) with support from the Space Operations Mission Directorate (SOMD) is to send early robotic missions to potential landing site locations such as the Moon, Mars and its moons, and nearby asteroids in preparation for future human exploration[4]. As is the case in our current political and economic environment, any future mission development will be expected to be "Faster, Better, Cheaper"[4]. NASA has made it very clear that any new planetary lander/rover systems will need to focus on minimizing cost while giving added capabilities[5]. Fortunately, a Tumbleweed rover system is expected to be much cheaper than traditional multi-ton, multi billion dollar rover systems, and would therefore be an excellent candidate for future investment.

CUBESAT AS A MODEL TO DEPLOY MULTIPLE LOW COST ROVERS

When compared to traditional multiple million-dollar satellite missions, CubeSat projects have the potential to do useful science while giving hands on learning experiences to students and professionals at a much lower cost. The paradigm of hitching a ride on a larger space mission to fill excess space and weight within a rocket payload helps reduce the cost of these devices/missions when compared to traditional satellites. This idea can be extended to Mars missions which can help fill a gap that otherwise may go unfilled. CubeSat payloads and experiments are often innovative, new, unique, and project timelines are typically 9-24 months from inception to launch. This quick turn ability due to standard space tested hardware allows for great flexibility when integrating on future space platforms and within a variety of missions.

CubeSat missions still require considerable planning and many hours of labor to maximize the chances for success. By employing as much standardization as possible you can concentrate on the projects mission-specific goals. This wouldn't be any different on a Mars Tumbleweed platform; the mechanical rover, power generation system, processing hardware, and communication systems would all be standardized. This would provide a consistent platform where the user can select or create their own sensor systems using standard interfaces. Such sensors could be radiation, chemical, microware, x-ray, or optical sensors to name a few possibilities. Individuals, universities, and private companies could essentially own their own Mars rover system, providing endless opportunities for new discoveries. By making use of a standardized portfolio of commercial-off-the-shelf (COTS) parts, commercial as well as open source software tools and components in the construction of the Mars Tumbleweed Rover, users will save time and money, while still deploying a capable Mars rover.

WIRELESS COMMUNICATIONS NETWORK REQUIREMENTS

Type of service requirement

Does the network need to simply move data from one location to another? Is it expected to provide situational awareness and provide more than just data? The framework shall take into account both situations/missions, either data mover or provide answers to queries, and provide applicable solutions of each service type.

Quality of Service

The data being transmitted over the network is tolerant to latency as it is envisioned to be mostly time stamped environmental sensor readings, along with telemetry of the rover. The bandwidth of the transmitted data is expected to be relatively small compared to typical high-end data networks here on Earth. Due to these characteristics of the network, requirements such as bounded delay and minimum bandwidth are not essential elements and do not apply. The amount and quality of the data that can be extracted at a given sink node about measured environmental characteristics is critical and should have a requirement wrapped around it. Quality metrics like reliable detection of events or the correctness of a temperature map can be more useful than typical networking requirements. Therefore, the wireless communication system shall provide >90% of the transmitted data to the sink node for nodes that are not disconnected from the primary network. This allows for <10% of the data transmitted to be lost during communication activities.

Fault Tolerance

The rover wireless communication network shall tolerate node failure, node mobility in and out of the network, and temporary power loss.

Lifetime

The lifetime of the mote shall exceed its planned deployment cycle. In other words the mote shall have a longer lifetime than 80% of the expected time within the network, based on the planned travel distance of the deployment. Physical distance causing the mote to be disconnected from the network shall be the typical "failure mode". Tumbleweed Rovers are power constrained and they shall generate their own power, likely through solar or kinetic generators. This power generated and stored is intrinsically intermittent and losing power is not considered a failure of the lifetime, but rather, a temporary state of inactivity. Lifetime and Quality of Service have direct tradeoffs with one another where, using more energy can increase quality but reduce node lifetime. These types of tradeoffs need to be dealt with in a thoughtful way. The definition of lifetime in this paper is the time it takes for the node to become disconnected from the network without any chance of reconnecting. The lifetime of the network is the time it takes for 50% of the nodes to become disconnected from the sink node without a chance or reconnecting.

Scalability

The network shall be as small as 2 nodes with a relatively short lifetime, or exceed 100 nodes with a longer lifetime. The network shall not exceed 512 active, in range, nodes at any given time.

Density

More nodes result in increased spatial resolution initially, and then gradually disperse and become increasingly distributed with reduced resolution/density as time progresses, as the rovers travel further and further away from one another. The wireless communication network shall be capable of supporting communication of 512 nodes within a single hop. The wireless communication network shall be capable of communicating data as many as 512 hops to get back to a sink node.

Programmability

The motes shall be capable of over the air programming of new firmware and software through communications with the base station or sink node in either a multi hop or direct communication topology while the motes are in operation. This requirement allows for flexibility of the network and evolving mission needs. A fixed method of information processing is insufficient based on the prescribed mission needs.

Maintainability

The wireless communication network shall maintain itself and adapt to changing power needs and degradation over time. It shall also monitor its own health and status to change operational parameters such as power transmitted, while in operation.

Cost

Each Tumbleweed Rover shall cost less than $100k per rover with a long-term target on par with CubeSat at $15k per rover, with an initial quantity of at least 20 units, and scale downwards with increased rovers due to economies of scale. The non-recurring engineering (NRE) effort should not exceed $10 million for the initial requirements, system architecture, integration, verification, and validation. This effort includes the systems analysis, modeling, and simulation.

Timeline

The non-recurring engineering (NRE) effort, period of performance shall be less than 36 months from contract award.

Low Power

The communication system shall consume less than 1A when transmitting/receiving data, and less than 1mA when in a sleep state or low power mode. The duty cycle of the transmission/reception of data shall not exceed the available power stored or generated by the power sub-system.

Data Rate

The data rate being sent to the wireless radio from an upper layer software application shall be less than 10k bits per second at any given time.

WIRELESS COMMUNICATION NETWORK MODEL RESULTS

Probability of Data Loss

Similar to other tools used to measure wireless communication network effectiveness, the power (range) model can be used to evaluate a nodes capability to send data, subject to various constraints. Once a nodes characteristics and network requirements are established, the model can be used to develop advanced algorithms to optimize network performance and reduce power over the expected Martian coverage area. An analysis of the probability of data loss between Tumbleweed Rovers was executed. The Friis Transmission Equation, Equation 1, formed the basis of the analysis to better understand the Martian environment given a number of probabilistic scenarios.

With each communication packet transmitted and received there exists a minimum amount of power that must be incident on the receive antenna, P_r. Equation 1, describes the power received, P_r, as the product of the power transmitted, P_t; the transmissivity of the medium through which the electromagnetic wave propagates, Υ_{Mars}; the fixed gain of the transmit and receive antennas, G_t and G_r respectively; and the square of the wavelength of the carrier frequency, λ, divided by the surface area of a sphere of radius R [9]. The variable for the radius of the transmitting sphere of energy, R, is defined in this paper as the Range between rovers.

$$P_r = P_t \Upsilon_{Mars} G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

Equation 1: Friis Transmission Equation

Using a probabilistic analysis software package, NESSUS, a First Order Reliability Method (FORM) was used to perform the baseline probabilistic analysis. FORM assumes that the variables are either normal or lognormal distributions. A method to reduce the probability of system data loss is to increase the transmitted power from the antenna. Table 1 illustrates the effect of increased transmit power on the probability of system data loss over a range. It is clear that by increasing the transmit power; the system requirement of less than 10% data loss can easily be met with plenty of margin to spare. This result serves as a model in which variable power modes can be used to ensure that data loss is reduced, at the same time optimizing the power required to successfully transfer data from one point to another. In essence, if the system detects excessive lost data packets then it can increase the power transmitted to acquire additional range until the data loss is reduced below a predetermined threshold, in this case 10%.

Transmit Power	Range Sensitivity	Trans. Sensitivity	Prob.Of Failure	Prob. Of Data Loss
100mW	77%	22%	41.4%	17.1%
1W	79%	20%	2.2%	<0.05%
10W	80%	19%	0.006%	<0.0000004%

Table 1: Transmit Power Analysis

Comparing MAC Protocols

The hypothesis that different MAC algorithms exhibit different levels of power consumption based on their respective structure/location/topology within a wireless network is explored in this section. This analysis seeks to demonstrate a correlation between a network's geographic dispersion and power usage and compares multiple MAC algorithms in order to choose an optimal solution when dealing with power consumption in a Tumbleweed Rover constellation. This analysis demonstrates that different MAC algorithms have different power consumption signatures. The result of the investigation evaluates the representative algorithms impact on a nodes power usage.

The Mars Tumbleweed Wireless Sensor Network MAC Simulator models multiple data being sent from multiple mobile nodes over a number of Martian days. The simulator generates a square map (i.e. X by X square map, user configurable) of a given dimension, of a given user configurable number of nodes. These nodes are randomly distributed throughout the map. Given a user configurable node range, R, the simulator takes the generated node map and overlays a sink node at the center, creates a communication map with in-range node links. Once the node map and communication links are created, different user implemented MAC protocols can be used to qualitatively compare the power used from each protocol.

For this research IEEE 802.11 (basis of Wifi), IEEE 802.15.4 (basis of ZigBee), and SMAC were compared. In an effort to make the data/comparisons statistically significant the simulator can iterate a user configurable number of iterations. The result of a single day simulation is a qualitative, statistically valid average of a 200 iteration power comparison of multiple MAC protocols, as well as a data point of the average percentage of nodes not able to communicate with the sink due to being out of range of the sink or a sink connected neighbor. Only the effects of MAC layer protocol changes were studied, the Network layer routing protocol and physical layer were kept constant.

Knowing that Mars Tumbleweeds will be randomly blown over the Martian surface over many days, the simulator allows for multi day simulations. To implement this feature the simulator allows for a user configurable variable to control not only the number of days but also the rate at which the map will grow each day. The assumption is that the tumbleweeds will start off relatively close to one another and as time progresses, move randomly away from each other. This feature simulates the tumbleweeds being randomly blown further and further away from one another on the Martian surface.

Results of MAC Model and Simulator Study

As expected, the IEEE 802.11 MAC showed to be the largest consumer of power compared to IEEE 802.15.4 and SMAC implementations. This is largely due to the fact that 802.11 nodes do not have a sleep mode and are always either transmitting or listening/receiving. Both transmitting and receiving consume power and without a sleep mode the relative amount of power used was expected to be high. An interesting observation from Figure 1, shows that as the nodes move further and further apart in distance they lose signal strength and ultimately become disconnected from each other and the sink, this results in a drastic reduction in the power used by the 802.11 MAC. The explanation for this effect is that as fewer nodes have a communication path to the sink the result is less slot frames. This significantly lowers both the number of transmit cycles, but also greatly reduces the time that all the nodes are listening, thus the large reduction in power shown in the power plot.

SMAC used slightly more power than 802.15.4 in the simulations, but tends to track well and will likely converge to 802.15.4 as fewer nodes have a path to the sink. One reason for the difference in power usage between SMAC and 802.15.4 is that SMAC implements a schedule as part of its MAC layer whereas 802.15.4 assumes that a slot frame schedule already exists at a higher stack level. The result is SMAC has the extra power consumption overhead of transmitting and receiving to create a schedule whereas 802.15.4 assumes this task to be outside the scope of the MAC, and therefore does not result in power consumption. Again, as the number of nodes disconnected from the sink node increases, the extra overhead of generating a SMAC schedule is minimized.

This phenomena leads to a convergence of the SMAC and 802.15.4 protocol as the nodes move apart. 802.15.4 was, relatively speaking, the lowest power consumer given all other parameters are equal.

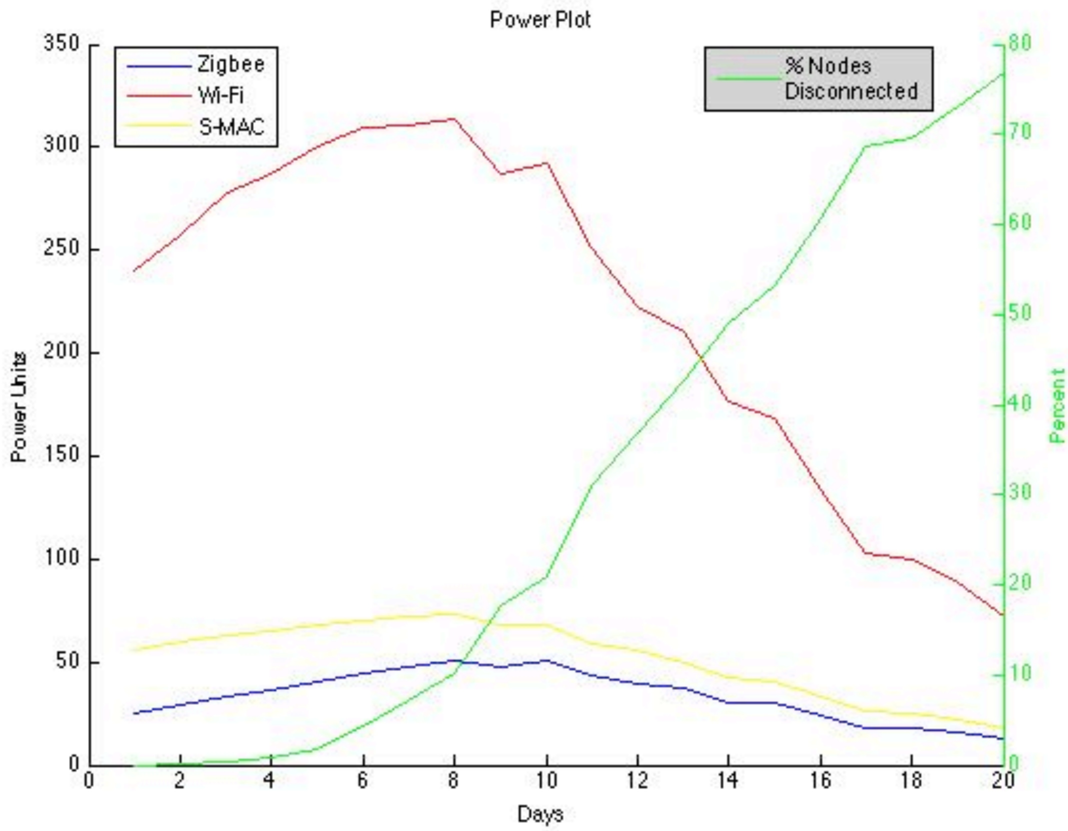

Figure 1: Comparative Power Plot of Three MAC Protocols

802.15.4 and 802.11 are similar MAC protocols as they share the same base standard, IEEE 802. One difference between the two implementations is the fact that 802.11 nodes are either transmitting or receiving which consumes large amounts of power on average, whereas 802.15.4 has a low power sleep mode that can be triggered whenever it is not needed for communications. From the power plot, it's clear that these differences between listening all the time, 802.11, and sleeping when not needed, 802.15.4, can make a profound difference in the amount of power consumed.

WIRELESS COMMUNICATION NETWORK SIMULATION AND OPERATING SYSTEM RESULTS

Contiki, a great open source operating system for sensor networks and other embedded communication devices, is used as a basic building block on which to develop and simulate a wireless network. Working in conjunction with Contiki is Cooja. Cooja is a wireless network simulator that is able to emulate a number of commercially available embedded communication devices, such as the Tmote Sky, MicaZ, Z1, and many others. The code simulated is the exact same code that can be downloaded into physical motes and tested in the real world. This tool chain provides a powerful method to create new algorithms, simulate, and deploy for real world testing. Cooja also has a number a fantastic plugins, for instance the mobility plugin allows the developer to script the movements of mobile nodes and analyze how these changes affect the network.

For this work multiple simulations have been created. Figure 2 shows a communication map of ten nodes with the center being the sink node. Using the mobility plugin within Cooja, these ten nodes were programmed to move at random throughout the map, thus simulating wind blown tumbleweeds. Sensor data is collected from all nodes and forwarded to the sink node. As the nodes move in and out of range of other nodes, the Cooja power tracker plugin keeps track of each nodes percentage of radio on time and the average over the entire network. This data can be coupled with the operating voltage and current when the radios transmit and receive to get a clear picture of power used during a deployment/mission. For this simulation, communicating a relatively small amount of sensor data (temperature, acceleration, velocity, orientation, position) over a period of four minutes. Simulation showed that the peak radio on percentage (node ID 4) was 1.45% with 0.55% transmitting, 0.02% receiving, and the remainder, 0.88%, idle radio on time (listening/receiving). With a radio supply voltage of 3.0V, a transmit current of 191mA, a receive current of 30mA, the power consumed is calculated to be 573mW for 1.32 seconds, and 90mW for 2.16 seconds over a 240 second simulation. While the average for the entire network was 1.39% with 0.53% transmitting, 0.01% receiving, and the remainder, 0.85%, idle radio on time (receive current draw). This data shows that this network is relatively well balanced and can support more data with the penalty of increased power usage as data throughput goes up.

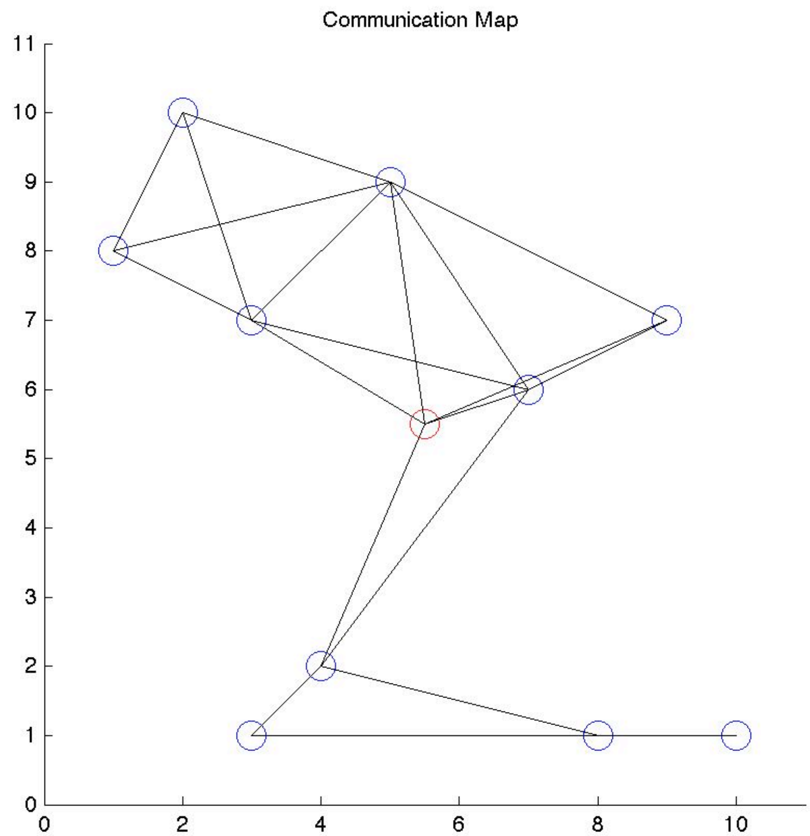

Figure 2: Communication Map of Ten Mobile Nodes and the Sink at the Center

FUTURE WORK

As discussed earlier in this paper, the next step is to take the knowledge gleaned from building the model and simulation, deploy the algorithms onto actual hardware to be field-tested. These test results can then be fed back into the model to better understand areas that are well defined and match simulation and other areas that do not match simulation results. An iterative approach will need to take place where the model is modified based on real world testing and then new simulations are run to see the outcome, which will then result in new field tests, until the solution meets the system requirements.

CONTRIBUTION

This work contributes a significant step forward in developing a new framework for wireless communications between multiple rovers. The impetus for this new framework is based on a need presented by NASA and JPL for multiple rovers to survey and collect sensor data in wide swaths or rugged terrain on distant planets such as Mars[10] [11]. This need, presents an opportunity to create a new framework for wireless communication between multiple sensor nodes that are low-cost and components are readily available off the shelf. This research demonstrates how node power usage varies in relation to network distance, and as a function of algorithm choice. Utilizing different algorithm methods impact the network functionality in a dynamic environment. Based on a desired output, the designer of the network selects the number and type of nodes, process, and communication algorithms to best fit the desired mission or topology. Algorithms can be evaluated and ranked based upon their level of power consumption as a function of distance. This choice of multiple implementations creates a framework that can be used to design future rover wireless networks. This new framework provides a method for sensor data to be aggregated from multiple sensor nodes and relayed back to a more powerful sink node that can relay the resultant data extreme distances (e.g. from Mars to Earth). This local network aims to enable removal of redundant or obsolete data from the data stream so as to not overload the network with useless information. The contribution of this work to the state of the art is the creation of a new framework, model, simulation, physical prototype, and testing data that serves proof of the significance of this new framework.

[1] J. Antol, S. Woodard, G. Hajos, J. Heldmann, and B. Taylor, “Using Wind Driven Tumbleweed Rovers to Explore Martian Gulley Features,” presented at the 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reston, Virigina, 2012.

[2] J. Antol, “A New Vehicle for Planetary Surface Exploration - The Mars Tumbleweed Rover,” presented at the 1st Space Exploration Conference: Continuing the Voyage of Discovery, Reston, Virigina, 2012.

[3] J. Antol, P. Calhoun, J. Flick, G. A. Hajos, and R. Kolacinski, “Low cost mars surface exploration: The mars tumbleweed,” 2003.

[4] J. Marsh, “Conceptual Design and Analysis of a ‘Simple’ Tumbleweed Rover,” pp. 1–85.

[5] B. G. Drake, S. J. Hoffman, and D. W. Beaty, “Human exploration of Mars, Design Reference Architecture 5.0,” 2010 IEEE Aerospace Conference, pp. 1–24, 2010.

[6] G. Yoder, “Exploration Systems Mission Directorate,” 2007.

[7] V. Chukkala and P. De Leon, “Simulation and analysis of the multipath environment of Mars,” presented at the Aerospace Conference, 2005 IEEE, 2005, pp. 1678–1683.

[8] G. W. Skelton and P. Qing, “Multi-rover collaboration,” presented at the Southeastcon, 2009. SOUTHEASTCON '09. IEEE, 2009, pp. 284–288.

[9] F. T. Ulaby, E. Michielssen, and U. Ravaioli, “Fundamentals of Applied Electromagnetics,” pp. 430–431, 2001.

[10] S. Mahboubi, M. M. S. Fakhrabadi, and A. Ghanbari, “Design and Implementation of a Novel Spherical Mobile Robot,” J Intell Robot Syst, vol. 71, no. 1, pp. 43–64, 2013.

[11] A. Olea, A. Montesano, C. Montesano, and S. Arenas, “X- band High Gain Antenna qualified for Mars atmosphere,” presented at the Antennas and Propagation (EuCAP), 2010 Proceedings of the Fourth European Conference on, 2010, pp. 1–5.