Wireless Sensor Networks for Space and Solar- System Missions

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Abstract— **Wireless sensor networks (WSNs) are multi-hop self organizing networks which include a huge number of nodes integrating environmental measuring, data processing and wireless communications in order to apprehend, collect and process information to achieve defined tasks. The use of WSNs is adapted to Space and Solar-system missions. It outlines the usage of a space-based wireless sensor networks (SB-WSNs), which applies the concept of terrestrial wireless sensor networks to the space. Some of the distributed spacecraft missions are used for this purpose. It is also focused on communication architecture for space based sensor networks. Because of the large inter-spacecraft distances, directional antennas are used, with a single half duplex transceiver. A technique is presented that derives the link activation schedule and routes used for efficient traffic relay through the network.**

Keywords—Multi-hop self organizing networks; distributed spacecraft missions; space based sensors; single half duplex transceiver; link activation schedule

I. INTRODUCTION

The wireless sensor networks (WSNs) are networks of compact micro-sensors for data acquisition or monitoring some environment characteristics, such as temperature, sound, vibration, pressure and motion. These sensors are embedded devices capable of data communication. Each sensor node has processing capability (one or more microcontrollers, CPUs or DSP chips), may contain multiple kinds of memory (program, data and flash memories), have a RF transceiver (usually with a single Omni-directional antenna), have a power source (e.g., batteries and solar cells), and accommodate various sensors and actuators. The nodes communicate wirelessly and often self-organize after being deployed in an ad hoc fashion. Systems of 1000s or even 10,000 nodes are anticipated. Therefore, a sensor node can adapt easily to its environment because of topological changes.

Recent advances in miniaturization and wireless communication have enabled a new class of tiny powerful computers: Wireless Sensor Networks (WSNs). WSNs consist of large scale, highly distributed and self-organized networks, mainly developed for surveillance and monitoring. They are composed of a large number of tiny and cheap nodes, having computing, sensing and communication capabilities.

The applications are many and varied. They are used in commercial and industrial applications in warehouses and factories to monitor data. They could form a perimeter about any environment characteristics and monitor the alterations from one node to another. There are many uses for WSNs. Typical applications of WSNs include monitoring, tracking, and controlling processes. Some of the specific applications are industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications, home automation, and traffic control, object tracking, nuclear reactor controlling, fire detection, etc. In a typical application, a WSN is scattered in a region where it is meant to collect data through its sensor nodes. A WSN consists of hundreds or thousands of sensor nodes deployed in a geo-graphical region. These nodes are able cooperate together to make the required measurements of the environment.

Numerous planned and proposed future space exploration missions will employ multiple spacecraft that perform multipoint sensing. Distributed space-based sensing missions can significantly benefit from incorporation of cross-link communications capabilities, thereby forming space-based networks, by enabling continuous access to any/all Spacecraft via single ground contact, real-time coordinated observations, and autonomous processing among in situ spacecraft. An explosion of sensor network research and development has occurred in recent years, owing to the recognition of the power they can achieve. Technological advancements in micro sensors, low-power electronics, cooperative processing among distributed nodes and wireless communications protocols have contributed to the rapid progress made. Sensor networks have been applied across a variety of applications, including battlefield surveillance, condition based maintenance in factory automation, and habitat and environmental monitoring. Here focusing is done on sensor networks in the space exploration domain, and provide a communication architecture that is well suited for this application. One key characteristic of distributed spacecraft missions is the large distances between spacecraft, which drives the use of directional transmit and receive antennas.

II. SPACE BASED WIRELESS SENSOR NETWORKS

Wireless Sensor Network (WSN) is a wireless network consisting of spatially distributed autonomous devices that use sensors to monitor physical or environmental conditions. In space, WSNs could be used for many different purposes such as; space weather missions in low Earth Orbit (LEO), implementation of WSN within a spacecraft in order to replace electrical wires, single probe missions or as very small satellite nodes flying in close formations and physical and chemical sensing of the atmospheres, surfaces and soils of other planets. The main idea is the use of the benefits coming from the nature of WSNs for space activities. Its flexibility and low cost of implementation alternates many implementations of space missions.

A. Architecture of Space based Wireless Sensor Networks

This architecture presents a wireless UWB-based space-time network communications. The sensor networks communications contain N wireless UWB-based space-time sensor nodes, M sensor node forward stations and a sensor base station. Each of wireless UWB-based space-time sensor nodes is to support data collection with a multimode sensing, signal processing and analysis, and transmission fashion by using an UWB pulse modulation with a multiple antenna. The sensor node forward stations have a dual-mode transmitting function based MIMO space-time and UWB approaches along with a spread spectrum technology. The sensor base station also uses a space-time approach with MIMO sensor-antenna architecture as shown on Fig.1. Thus, the wireless UWB-based sensor networks communications simultaneously exploit temporal and spatial diversity for sensor networks communications, thereby converting spatially distributed UWB-based sensor nodes into efficient, robust, reliable, and secure wireless sensor communications.

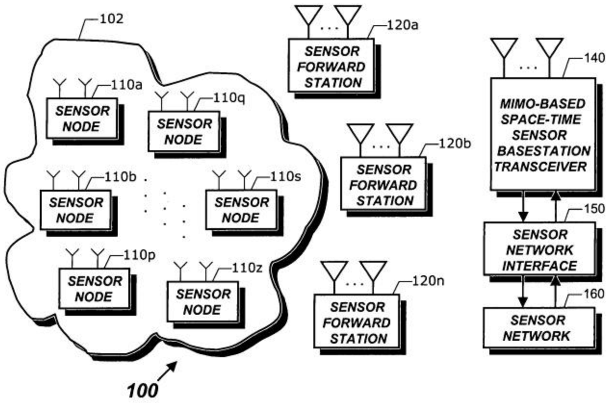

Figure1. Architecture of Space based WSN

B. Exploration of Solar-system

The usability for exploration of the Solar system by SBWSNs is topically discussed in the past few years. Distributed smart monitoring with WSN for the exploration of the Solar system has started to gain interest in the view of project ESA. Given this way, SB-WSN exploration missions can be atmospheric or ground based measurements. But, traditional WSNs cannot be used directly in space without any modifications. SB-WSNs will have to be optimized to meet the specific requirements of space exploration: need for self localization and reliable long distance communication such as a few kilometers. The SB-WSN nodes released to the atmosphere will collect the desired calculations as shown on Fig.2.

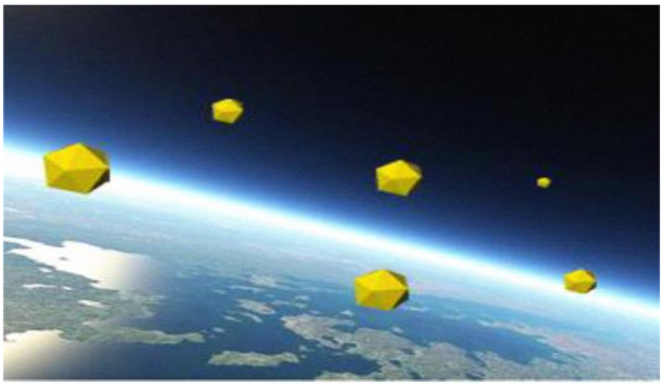

Figure2. Scenario of atmospheric measurements on a planet

This kind of missions requires low sampling rate and data acquisitions forms per hour or per 30 minutes. As an alternate to this mission, sensing nodes can be deployed to the surface or ground of the planet. Deployment can be executed via a spacecraft with parachutes or using an accessory vehicle such as Mars Lander as shown in Fig.3. As measurements and sensing processes can be applied on planets, also low mass Solar-system objects such as asteroids can be observed with SB-WSNs.

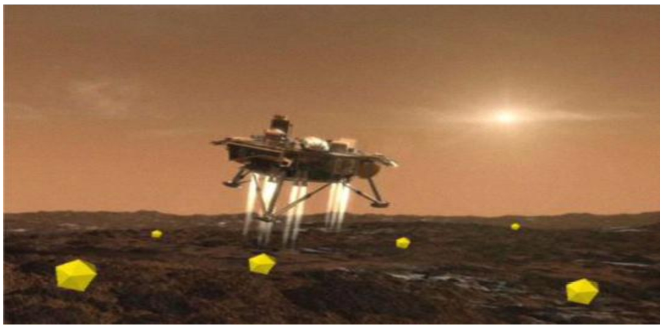

Figure3. Scenario of ground measurements of a planet

Sensing nodes would be deployed to the asteroids ground by a space craft. This scenario is also similar to ground measurements mission of a planet. A more complex scenario could concern a cloud of SB-WSNs that will swathe on the surface of a low mass object. The measurements performed as a group or a cloud will be more accurate.

Sensors are also used in many situations on the inside of the spacecraft as shown on Fig.4. Cabin pressure and oxygen levels must be kept under constant control. In the case of using multiple wireless sensors, the reduced installation effort is even more apparent. Other benefits may follow; maximize the transmission range, provide security of data transmission, improved networking capability, reduced installation and maintenance cost.

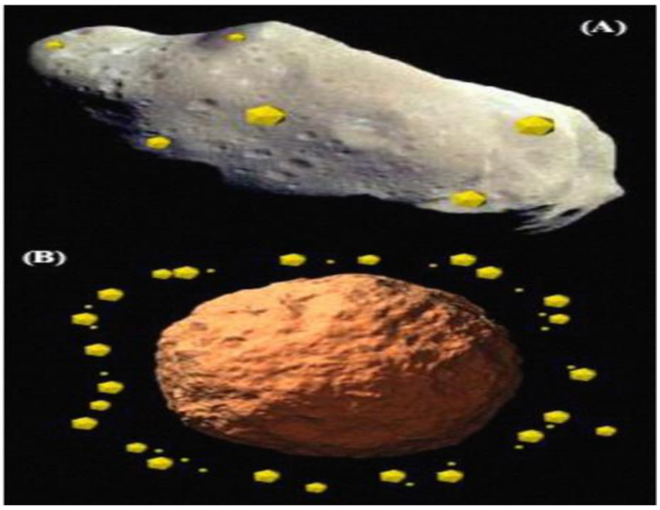

Figure4. Scenario of measurement process of an asteroid

The most basic use of sensor nodes is to check robustness of the spacecraft's body. This will allow to view and report hull integrity autonomously. Trajaola mentions the importance of sensors in the Ariane 5 rocket .Sensors are commonly used in collecting data about the behavior of the rocket when flying, identifying the anomalies in operation and giving a coherence and standardization of the equipment such as power supplies. There are 260 different measurements applied in the vehicle as the following classification.

- 32% Pressure,
- 45% Temperature,
- 13% Collusion Detection,
- 10% Displacement

C. Network Design Characteristics

SB-WSNs communications are affected by some orbital dynamics such as satellite ranges, orbital storms and mostly radiation. To overcome this negative effects selection of the antenna is the important factor. One of the key features in space communications is to use of directional antennas. There are plenty of options for the use of SB-WSNs in the space. In Fig 5A illustrates the couple of micro sensors transmitting their collected data to the pivot traveler satellite. If the distance increases between the sensors and the space vehicle, it is recommended that to use a micro satellite which has a bigger antenna to transmit collected data (Fig 5B). In another scenario, a space vehicle is listening to its sensors which are dropped to a surface of a planet (Fig 5C).

Another critical issue is the selection of routing strategy of sensor nodes to the access point. A sensor charging its batteries in the daylight eliminates the energy requirements. So that, much more measurements can be applied to the environment and higher resolutions in results can be obtained. Multipath routing scheme is an ideal candidate for space based missions of sensor nodes. It is the most important factor s for less usage of bandwidth, reliability, load-balancing, energy-conservation, and Quality-of-Service (QoS). Multipath routing allows the establishment of multiple paths between a single sensor node and single destination sensor node. It is typically proposed in order to increase the reliability of data transmission and QoS.

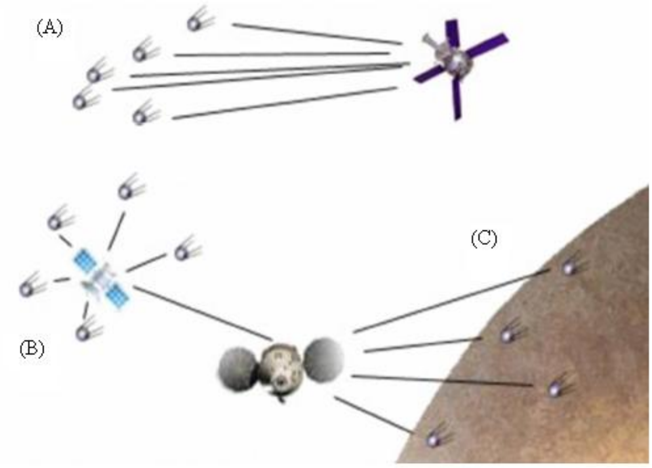

Figure5. Multiple Access scenarios

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III. DISTRIBUTED SPACECRAFT MISSIONS

The need for multi-spacecraft sensing has long been recognized. The Space Science Board of the National Academy of Sciences recommended multi spacecraft missions for “space weather” investigations. Towards this aim, the Interplanetary Monitoring Platform (IMP-7 and IMP-8) spacecraft were launched. These missions yielded “simultaneous coordinated measurements to permit separation of spatial from temporal irregularities in the near-Earth solar wind, the bow shock, and inside the magnetosphere” and were “able to break the space-time ambiguity inevitably associated with measurements by a single spacecraft on thin boundaries which may be in motion, such as the bow shock and the magnetopause.” The Dynamics Explorer (DE) mission, consisting of two spacecraft, and many subsequent missions followed (e.g., GEOTAIL, WIND, INTERBALL, SOHO, POLAR).

A broad classification of multipoint sensing types has been presented. The three basic classes are:

(1) Pixellation/voxellation**-** in which each sensor perceives its local area “pixel” so that collectively the overall “picture” of the phenomenon of interest is derived.

(2) Beamformation- where an emission by an object of interest is received by multiple sensors and the signals are combined to achieve higher **SNR** or target localization.

(3)Tomography/rendering-where a target object is viewed from different perspectives corresponding to projections, and these are combined to form a higher dimensional representation.

A. Motivation for Networking

In a sensor network is designed to collect information at a single base station. In space-based networks, spacecraft data will be relayed to one or more ground terminals and routed via terrestrial network to a Ground Data System**.** Thus conceptually the Earth is the base station.

There are three basic capabilities enabled by space-based networking. First, mission operations users are provided continuous access to any and all spacecraft via a single ground contact with any single member of the constellation. This greatly increases ground operations efficiency and permits operation of the whole fleet as a single mission. The ability for the overall constellation to "act as a single mission spacecraft for coordinated observations" is a critical goal.

Second, space-based networking enables real-time coordinated observations by virtue of rapid dissemination of sensor observations. For example, ground-based sensors may be alerted while the phenomena of interest are still active. Instances of **this** have already been demonstrated, such **as** the gamma burst detected by the High-Energy Transient Explorer (HETE) that cued the European Southern Observatory's Very Large Telescope, which confirmed a correlated supernova explosion**.** Real-time coordinated sensing may also occur within the sensor constellation itself, in which interaction among the space assets is generated by sensed events (e.g., alert neighboring satellite to raise its sensing sensitivity/resolution, or corroborate/fuse data prior to transport to Earth). For example, early detection of a magnetic storm (arising from a Coronal Mass Ejection event) may be relayed to spacecraft further distant from the **Sun,** so that appropriate procedures may be taken.

A third important capability enabled by space-based networking is autonomous local processing among the distributed spacecraft to achieve system functions beyond the sensor information exchange already mentioned. For example, many distributed spacecraft missions require precise, virtually rigid positioning in a formation flying configuration. It is also noted that use of space-based networking allows the spacecraft to quickly move the data out of onboard buffers, clearing the contents to make room for new sensor information. Therefore significantly smaller sized buffers are required.

IV. SCHEDULING ROUTING METHOD

The network's ability to transport the offered traffic will be realized by defining the combined link activation schedule and routing procedure. The link activation schedule determines for each node for each time slot whether the node should be idle or whether it should communicate with a neighboring node. The approach is used that the schedule routing is calculated and used throughout the duration when the potential topology (or "visibility matrix") G, is constant.

Our objective is to derive an efficient schedule that provisions bandwidth to each node equal to its prescribed traffic load Li, i = 1,. . .,M. Unicast traffic is used from each spacecraft to Earth, broadcast traffic from Earth to all spacecraft, and their duals (reverse direction traffic). Initially, consider the unicast case, which is expected to be characteristic of the primary flows in a sensor network. The basic problem is to find a schedule that maps the required ''traffic topology" onto the network's physical topology. The traffic topology, in all cases considered here, has a star topology nature, with all traffic either terminating or originating at the Earth node. Therefore, when this is optimally overlaid onto the physical topology subgraph is generated within the physical topology will be dominated by tree-like structure. Therefore, our approach is to begin by pruning the potential topology to derive a tree subgraph, using heuristics to obtain a good tree. We can then determine the best schedule for the given offered load and tree based on existing algorithms that are known to be optimal for tree structures.

A. Unicast Scheduling

Derive the schedule for sensor traffic that originates at each spacecraft and is destined for Earth. Assume that the amount of bandwidth allocated to spacecraft i is denoted **Li** = **I**..., **M.**

Step0. Assume that the potential topology has been derived; for a dynamic topology case this will be valid over a specific time interval during which the potential topology is constant.

Step1. Using the **connectivity matrix G**, we determine all nodes that are directly connected to Earth. Suppose there are B such nodes, indexed in some fashion over **b** =**1,**...,B. Partition the potential topology, excluding Earth, into min-hop tree subgraphs, one for each of the B nodes that connects directly to Earth, B subgraphs is referred as branches. Work outward from Earth, adding a node at a time, after which the node is marked as processed for this step. Every node has an associated attribute vector indicating to branch it has been assigned and its hop distance from Earth, initially the attributes are set to **0** to indicate that the node hasn't yet been assigned to a branch. Let **h** be the min-hop distance for a node to Earth. Then B is the number of nodes at distance **h** = 1; attribute the branch ID and hop distance accordingly for these nodes. The procedure begins with h = 1. For each branch **b** = **1**,...,**B**, For each node in branch ***b*** at distance **h,** Using the connectivity matrix G, find all unassigned nodes that are directly connected to it and assign them to that branch together with hop distance **h+ 1.** Increment **h** and loop. The process terminates when all nodes are assigned. The maximum hop distance for each branch **hmax(b)** and the overall graph **hmax**(graph diameter) are also determined in this process. It is noted that this step does not depend on the offered load, but only on the potential topology. Subsequent steps require the load distribution **{Li, i** = **1**,..**M}.**

Step2. Work inward toward Earth to determine an additional attribute **Lsubtree** for each node that represents the total load associated with the subtree formed by the node and all its children. The procedure begins with **h =hmax.** For each branch **b = 1,..., B.** For each node at distance h, initially set its **Lsubtree** value to its own load **Li.** Then, add the value for each of its immediate children, which are determined by being directly connected (from **0,** at distance **h+ 1,** and assigned to the same branch **b.** The procedure terminates when all nodes (except Earth) are processed. In particular, it will result in determining the load associated with each branch, namely the **Lsubtree** value for each of the B nodes with **h** = **1.** Denote these values by **Lbranch(b),b** = **1**,..., ***B.***

Step3. The total load offered to the network is denoted **Ltotal.** If **B = 1** (only one branch) or if **Lbranch(b)** <= **Ltotal/2** for all **b** = 1 ,..., B, then skip to Step 4**.** Otherwise, this step will attempt to improve the balancing of the loads across the branches by moving nodes (subtrees) between them.a.) We begin by finding the branch **bmax** having the **maximum** load **Lbranch(bmax).** If **this** branch's hop-distance **hmax(bmax*)*** = **1** then this step terminates (go to Step 4)**.** Otherwise for **h** = **2,..., hmax(b).** For all nodes in branch **bmax,** that are **h** hops from Earth**,** process them in the order of decreasing **Lsubtree** value. Denote the node **n***and denote its subtree value as **Lsubtree(n*).** If we loop through all nodes in branch **bmax** without finding a subtree to move, this Step terminates and go to step 4.

Step4. We now have found a subgraph of the original potential topology that is a tree rooted at Earth. We may now find the schedule that will enable the given load to be relayed to Earth using the algorithm of Florens et. a1. This algorithm is known to be optimal in providing the minimum-length schedule for any load distribution over any tree. The schedule is derived from the root (Earth) outward as though the traffic flow occurs as a one-to-each dissemination from the root; since we desire the "dual" case where flows are actually inbound, the final schedule desired is simply found by reversing its temporal order of execution.

B. 16-Satellite Example of Unicast Scheduling

Assume there are **A4** = **16** satellites that are evenly distributed geometrically along a single orbit as shown on Fig.6. There is a single Earth terminal, so that the total number of nodes in the network is **M+l** = **17.**

Our goal is provision bandwidth for the sensor telemetry across all satellites. Assume that even distribution of bandwidth is desired, so that **Li** = constant over all **i.** Because we assume even bandwidth provisioning over all satellites, the algorithmic step that prunes the graph to a tree results in this case is shown in Fig.7.The schedule lengths for all eight topologies are provided in Table 1**,** together with the time averaged schedule length (weight each summation term by its proportion of the orbit period), which is found to be 18.95 time slots. The time-averaged throughput capacity of the system is therefore one packet originating at each of the 16 satellites and all destined to Earth every 18.08 time slots, or 16/18.08 = .885 packets per slot.

Application of the algorithm of Florens and McEliece results in the schedule having length **17** time. An entry in the table indicates the satellite (or Earth if the entry is "E") that would receive a transmission from the satellite associated with the entry's column. In comparison, we applied the algorithm and found the schedule to have length 19. Thus both our algorithm are efficient.

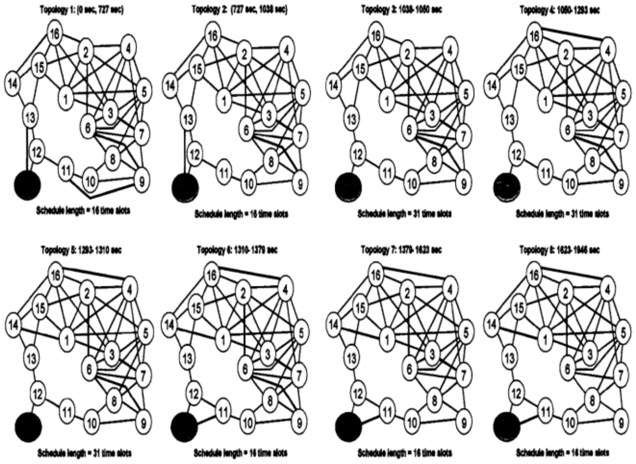


Figure6. Potential Topologies during a Single Orbit

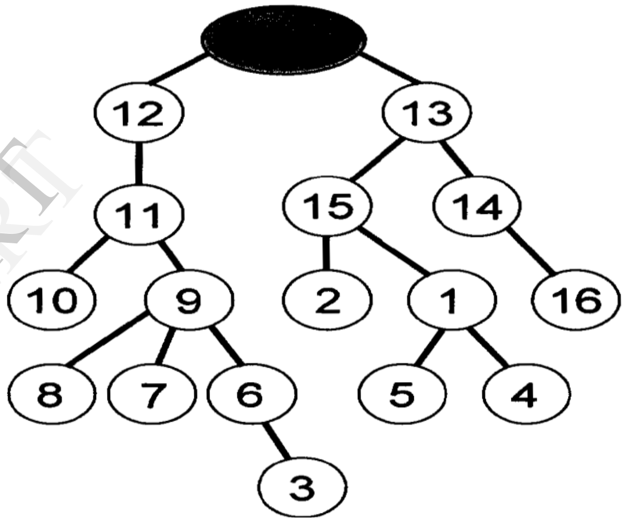
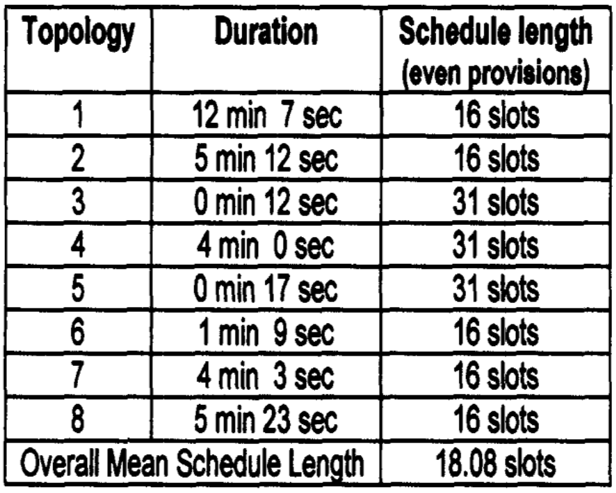


Figure7. Tree Subgraph Derived from Algorithm



Topology	Duration	Schedule length (even provisions)
1	12 min 7 sec	16 slots
2	5 min 12 sec	16 slots
3	0 min 12 sec	31 slots
4	4 min 0 sec	31 slots
5	0 min 17 sec	31 slots
6	1 min 9 sec	16 slots
7	4 min 3 sec	16 slots
8	5 min 23 sec	16 slots
Overall Mean Schedule Length		18.08 slots

Table1. Schedule Lengths over Entire Orbit Period

C. Traffic Adaptive Extension

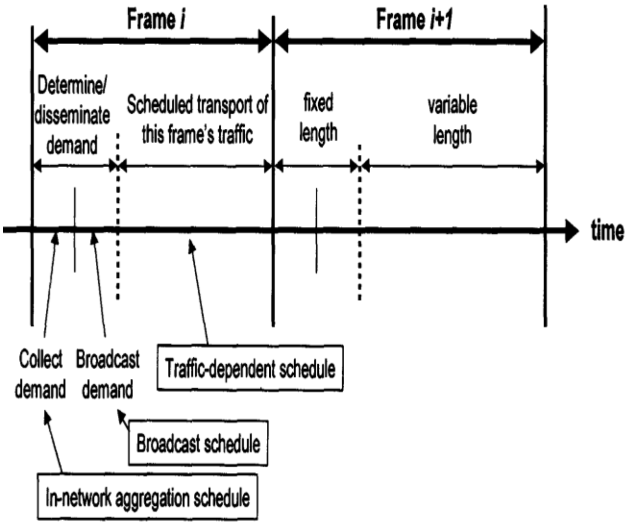


Figure8. Demand-Driven Network Operation

The fixed-provisioning type of scheduling is expected to provide excellent performance traffic sources that generate packets at relatively even rates. However, when traffic is spatio-temporally bursty, one may pursue greater system performance by attempting to allocate resources dynamically to satisfy short-term demand conditions. Our approach is to generalize the operation from periodic repetition of a fixed schedule corresponding to a **TDMA** frame to operating with dynamic frame lengths. This will be accomplished by extending the frame structure into two Subframes: one for "signaling" (our "reservations") and one for actual data transfer. The general form of system operation is depicted by Fig.8. The "signaling" subframe consists of two parts. The first part essentially polls all the satellites to determine their current load. The process proceeds by first collecting the total load vector at the Earth terminal. This could be accomplished by each satellite sending a single packet with its current traffic load state. However, one expects that the entire load vector can be represented in a small number of bits relative to the overhead associated with a single packet. Therefore we propose that such a representation be used, with each node updating the packet with its own state information. The appropriate schedule is then for aggregated traffic, which is more compact.

The second part of the signaling subframe is used to broadcast the global load vector to all nodes. Each node would then determine the global schedule based on the given global load vector. This schedule would be customized to carry exactly the given load vector, with minimum schedule length. The second subframe of the frame would be used to transport all traffic that was pending at the onset of the current frame. The next frame will begin with a load vector created from all new packet arrivals that occurred during the frame preceding that time instant. The performance benefits of the traffic adaptive scheme will depend on the burstiness of the offered traffic both in space and time.

V. CONCLUSION

As there are some important astro-dynamics and engineering research challenges to adapt WSNs to space conditions, design issues are also been focused. Selection of antenna, power supply and software must be done by inspecting the mission characteristics. Routing is the key factor in nodes communication. Selecting the best suitable method will increase life time and QoS. Network architecture for space-based sensor networks is presented. Components of the system model include node motions and topology dynamics, use of inexpensive half-duplex radios with directional antennas for cross links, network timekeeping, and a protocol that coordinates each node's operation for each time slot. An algorithm was presented for efficiently scheduling the communications resources to satisfy the sensor network traffic with minimum latency. The approach derives a tree with load balanced over its main branches, and leverages the Florens and McEliece algorithm for scheduling tree networks. The network operation was generalized to be traffic adaptive, by incorporating a signaling capability.

There are a great number of opportunities for extensions of this work. In relaxing assumptions, other applications may be considered, such as sensor networks deployed on the ground (surface). Ongoing work is investigating refinements to better accommodate specific traffic needs of precision formation flying mission, including real-time control traffic and multi-way exchange of navigation data types. WSN is a new technology for space missions and it will play an important role in future's space-based adaptive systems.

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