

# STDAS: Sensing Task and Data Aggregation Scheduling for Astronaut Health Monitoring using Wireless Mesh Networks

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**Abstract** — Astronaut health monitoring (AHM) during long durations of space missions will play a significant role in mission success. Designing networked healthcare systems for aerospace exploration that will enable continual surveillance and timely notification of astronaut health information to terrestrial healthcare providers at minimal deployment and operation cost is an extremely challenging problem. However, such capabilities will enhance the opportunities for remote medical assistance during space missions. In this paper, we extend our task and data aggregation scheduling from single-hop and multi-hop network to mesh network. The algorithm aims to optimize the network performance with respect to response time and network delay. The upper and lower bounds are derived to provide certain guarantee on data delivery time. The performance of a wireless mesh network with 25 sensor nodes is examined by varying network bandwidth and sensing power of sensor nodes. Basic recursive equations for sensing and data reporting are developed for the case of homogeneous and heterogeneous mesh networks and the performance results of two representative data sensing and reporting strategies are presented.

## I. INTRODUCTION

The capability of continuous monitoring of physiological condition of crew members has been of paramount importance as NASA is taking concrete steps to return to the moon and beyond. This is especially true as the onboard and extravehicular activities (EVA) performed by NASA astronauts are getting more mentally and physically demanding, and may last for several hours.

Astronaut health monitoring (AHM) during long durations of space missions will play a significant role in mission success. Designing networked healthcare systems for aerospace exploration that will enable continual surveillance and timely notification of astronaut health information to terrestrial healthcare providers at minimal deployment and operation cost is an extremely challenging problem. However, such capabilities will enhance the opportunities for remote medical assistance during space missions. Even though there have been environmental control/life support systems (ECLSS) and active thermal control systems (ATCS) [1] developed for both communication and physical capability monitoring, as shown in Fig. 1 [2], they require wired connection for both communication and power supply. Wired connections are cumbersome and bulky and therefore, supporting wireless capabilities will enhance mobility in such environments.

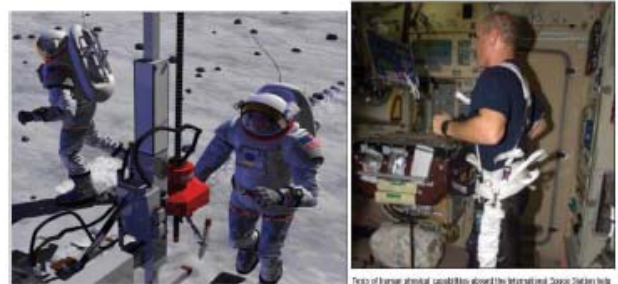


Figure 1 Spacesuit with wired communication and human physical capability testing onboard of International Space Station [2]

We are developing an integrated networked Astronaut Health Monitoring (AHM) system that takes advantage of the recent advancements in wireless communication, MEMS [3] and computation technologies. In this paper, we present the application layer sensing task and data aggregation schedule method we developed for astronaut health monitoring system. The mesh networks are getting more attention because of its redundant links remove the single point failure which is present in the classical star or tree networks. Most researches has been focusing on the development of various routing and medium access control protocols [4-6] while we sought to introduce the application layer task and data aggregation scheduling algorithm for minimum response time from task distribution to data sensing and reporting back to the sink node. This is critical for online astronaut health monitoring based on wireless sensor networks. One of the fundamental services of such systems is to achieve automatic task priority that can assist data acquisition and feedback at the right time by integrating sensing, computation, and communication.

The majority of literature on wireless sensor networks scheduling involves minimizing communication since it is the dominant operation in time [7] and energy [8-11]. To improve the computation efficiency of sensor networks, research focuses on sorting [12] and distributed sensor networks [13]. In our previous work [14-15], we have developed scheduling algorithm that integrates the communication with sensing speed for single level tree networks and linear daisy chain networks respectively. The complexity of the sensing task and data aggregation scheduling problem is shown in Table 1.

Table 1 Design Consideration for STDAS Algorithm

Design	Parameters			
Network topologies	Multi-hop	Single-hop	2D mesh	Hypercube
Sensor node behavior	Homogeneous		Heterogeneous	
Request dissemination strategy	Concurrent		Sequential	
Data aggregation strategy	Concurrent		Sequential	

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The organization of this paper is as follows. Section II discusses the problem formulation and the system model and some notations used in this paper. In section III the modeling of the sensing and data reporting strategies in mesh networks is presented. In section IV, performance evaluation results for heterogeneous mesh network from extensive simulation and analysis, comparison of different scheduling strategies and recommendation of selecting

optimal strategy from them are presented. Finally we conclude and point to future work in section V.

## II. SYSTEM MODEL AND NOTATIONS USED

In this section, the problem formulation as well as the various network parameters used in this paper are presented along with some notation and definitions.

The network topology discussed in this study is the mesh network consisting of one sink node and 24 wireless sensor nodes as shown in Figure 2. To describe the STDA method, we extend the notation and definitions detailed in [15]. In summary, the  $y_i$  and  $z_i$  represent the sensing and communication speed of sensor node  $SSN^i$  in the network, and  $\alpha_i$  is the fraction of sensing task assigned to it. It is assumed that every node will be assigned non-zero task, i.e.,  $0 < \alpha_i < 1$ , and the task for all nodes sums to 1 ( $\sum_{i=1}^n \alpha_i = 1$ ).  $T_i$  is

the total response time,  $T_f = \max(T_1, T_2, \dots, T_n)$ , in which  $T_i$  is the time that elapses between the beginning of the scheduling process at  $t = 0$  and the time when  $SSN^i$  completes its reporting.

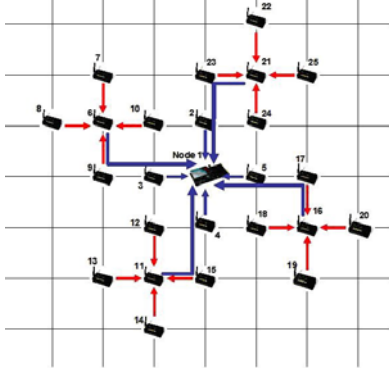


Figure 2. Example of a Mesh Network with 25 nodes

### A. Simultaneous Sensing Start, Sequential Data Aggregation ( $S^4DA$ ) Strategy

There are two ways of communication between the sensor nodes and the sink node: SEQUENTIAL or CONCURRENT. In the SEQUENTIAL communication, each sensor node is able to communicate with only one child at a time. In the CONCURRENT communication, each sink node can talk simultaneously with all its children. The concurrent strategy does not reflect the real wireless sensor network stack and protocols, thus the study focuses on sequential communication strategy.

### B. Data Aggregation Scenarios

Communication happens at two stages: when distributing scheduled sensing task and when sensor nodes conduct data aggregation. Among the four combinations of communication strategies, we consider the case where the sensor nodes start sensing immediately upon receiving its sensing task portion  $\alpha_k$ . After sensing jobs are completed, sensor nodes report their data sequentially.

We adapted the 2D torus network [16-17] terminologies to schedule the data aggregation sequences from each sensor node to the sink node. The sensor nodes locate within the reach of the sink through a Knight Move as in a chess game (shown in Fig. 2 as blue arrows), denoted as the Knight nodes, are grouped together and sequentially report to the sink node. The nodes connected to the sink through these Knight nodes form a single-level tree network

and the Knight nodes are responsible to report their children's data to the sink node as well.

Unlike two-level tree network, the sink node schedule sensing task for all nodes involved in the 2D mesh network. Considering a 9 node neighborhood, the fully expanded 2D mesh network will have 25 nodes and 5 submeshes. The expansion process as described above is optimum for response time since all 5 submeshes can work in parallel for the assigned sensor task and aggregate the data. Based on whether the sub-mesh that directly connects to the sink node will report before Knight nodes or not, we define BEFORE Case and AFTER Case, the time-diagrams are shown in Fig. 3(a) and (b) respectively.

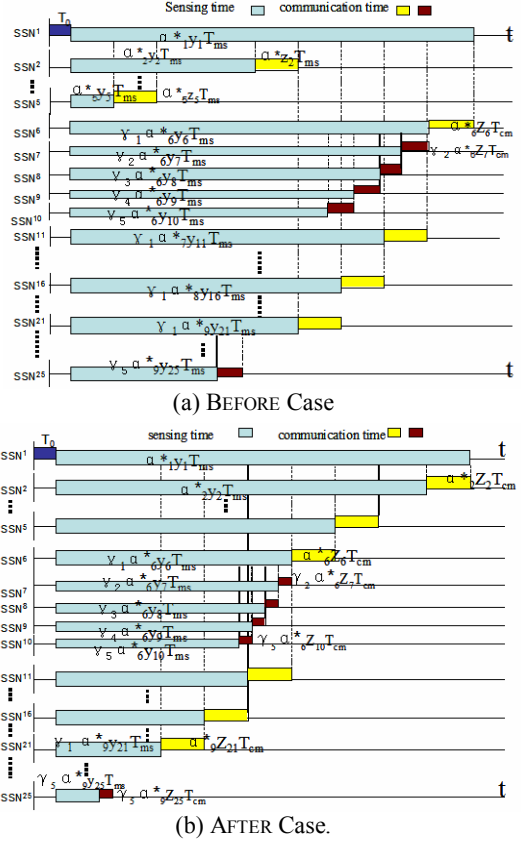


Figure 3 Time Diagrams for 2D mesh network with 25 nodes

## IV. STDAS MODELING AND SOLUTIONS

Based on the given notation, the  $S^4DA$  communication strategy, and the timing diagram shown in Fig. 3, we derive the following set of linear equations:

For Knight nodes  $SSN^1 \sim SSN^4$ :

$$\alpha_1^* y_1 T_{ms} = \alpha_2^* y_2 T_{ms} + \alpha_2^* z_2 T_{cm} \quad (1)$$

$$\alpha_2^* y_2 T_{ms} = \alpha_3^* y_3 T_{ms} + \alpha_3^* z_3 T_{cm} \quad (2)$$

$$\alpha_4^* y_4 T_{ms} = \alpha_5^* y_5 T_{ms} + \alpha_5^* z_5 T_{cm} \quad (3)$$

For sensor node 5 the expression is slightly different and is given as

$$\alpha_5^* y_5 T_{ms} = \gamma \alpha_6^* y_6 T_{ms} + \alpha_6^* z_6 T_{cm} \quad (4)$$

in which  $\gamma$  denotes the portion of sensing task assigned to the

$$\text{submesh: } \gamma_i = \prod_{j=i+5n+1}^{i+5n+4} (f_j) / (1 + \sum_{i=1}^5 \prod_{j=i+5n+1}^{i+5n+4} f_j) \quad (5)$$

where  $i=1,2,3,4$  represents the submesh groups  
 $f_i = (y_i + z_i \delta) / y_i$  (6)

$$\sum_{i=1}^5 \gamma_i = 1 \quad (7)$$

The parameter  $\delta$  is defined as the ratio between the communication intensity constant  $T_{cm}$  and the sensing intensity constant  $T_{ms}$ .

Similarly, for all Knight nodes  $SSN^{6,11,16,21}$ , the following set of recursive equations can be used to describe the submesh:

$$\gamma_1 \alpha_6^* y_6 T_{ms} = \gamma_1 \alpha_7^* y_{11} T_{ms} + \alpha_7^* z_{11} T_{cm} \quad (8)$$

$$\gamma_1 \alpha_7^* y_{11} T_{ms} = \gamma_1 \alpha_8^* y_{16} T_{ms} + \alpha_8^* z_{16} T_{cm} \quad (9)$$

$$\gamma_1 \alpha_{N+5}^* y_{5(N+1)} T_{ms} = \gamma_1 \alpha_{N+5+1}^* y_{5(N+1)+1} T_{ms} + \alpha_{N+5+1}^* z_{5(N+1)+1} T_{cm} \quad (10)$$

The task assignment and response time for each of the child node in submeshes can be represented using the recursive equation:

$$\gamma_i \alpha_{n+5}^* y_{i+5n} T_{ms} = \gamma_{i+1} \alpha_{n+5+1}^* y_{i+5n+1} T_{ms} + \gamma_{i+1} \alpha_{n+5}^* z_{i+5n+1} T_{cm} \quad (11)$$

in which the  $n$  denotes the submesh group 1, 2, 3 and 4.

## V. SIMULATION RESULTS AND PERFORMANCE ANALYSIS FOR HETEROGENEOUS MESH NETWORK

When all the sensor nodes have the same communication and sensing capability, i.e.,  $y_i = y$ ,  $z_i = z$ , we consider it a Homogeneous network. When any of the nodes has different sensing and communication capability, it is defined as a Heterogeneous network. Note that some sensor nodes still can have the same communication and sensing capability. Three sets of experiments are designed to study the impact of various parameters has on the final response time, we designed simulation experiments for a 25-node mesh network with heterogeneous sensor nodes, assuming  $T_{cm} = T_{ms} = 1$ .

The first two sets of experiments study the effect of them on the task assignment and total finish time when varying the sensing or communication capability of the Knight nodes. In both the BEFORE and AFTER case, three scenarios are simulated based on the aggregation sequence of sensor nodes at the same layer to get the performance boundary of the sensor network.

Case 1: Data aggregation starts from the sensor node with slowest sensing/communication speed, then sequentially reporting until the node with the best sensing/communication speed reports to the sink node.

Case 2: Sensor nodes with the fastest sensing/ communication speed reports first, while the one with the worst sensing/communication speed reports last.

Case 3: Data aggregation sequence is random with respect to sensing/communication speed of the Knight nodes.

Fig. 4 shows the experiment results when fixing the sensing speed  $y_i = 1$  and varying communication speed  $z$ . Fig. 4(a) shows the task distribution among all sensor nodes for three cases described above. Fig.4(b) shows the total response time for the three cases for AFTER case. It can be observed that the

performance for random reporting sequences falls between the boundaries defined by the other two extreme cases. The first case, Case 1, has the best accumulated total response time (i.e.,  $T_r$  for  $SSN^1$ ) because the sensing task was assigned in a more balanced way (Fig. 4(a)).

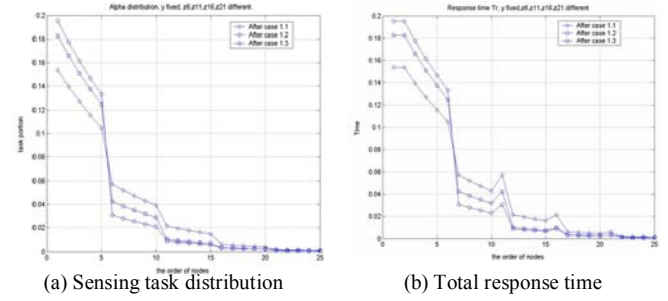


Figure 4. Results for a 25 nodes mesh network when fixing sensing speed for three data aggregation sequence cases based on communication speed.

Fig. 5 shows the experiment results for varying sensing speed  $y$  while fixing the communication speed  $z_i = 1$ . The simulation shows the task distribution and the total response time for all three cases overlapping with each other. When fixing  $z_i$  at other values ranging from 0 to 2.0, the results show the same trend, though the task assignment will be more balanced when  $z_i$  approaches 0. In addition, when comparing Fig. 4 and 5, we can observe that the total response time depends more on communication time ( $T_r = 0.09$ ) than on the sensing speed ( $T_r$  ranges from 0.15 to 0.19).

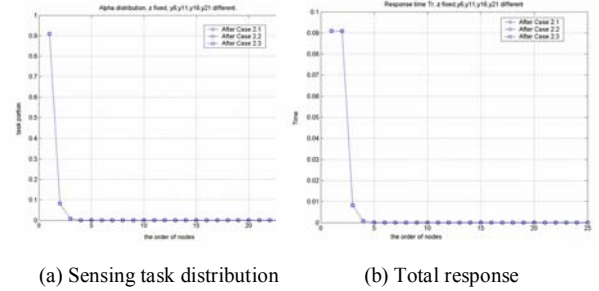


Figure 5. Results for a 25 nodes mesh network when fixing communication speed for three data aggregation sequence cases based on sensing speed.

The same set of simulation were conducted for the BEFORE case and similar trend were achieved. In both cases, the data aggregation sequence defined as in Case 1, i.e., nodes with worst capability reports first and the one with the best capability reports last, is the best sequence.

The 3<sup>rd</sup> set of experiments compare the performance of the BEFORE and AFTER cases, correspond to whether or not child nodes in submesh directly connected to the sink report before or after all other submeshes reporting action. Fig. 6 shows the task assignment (Fig. 6(a)) and accumulative response time (Fig. 6(b)) for BEFORE and AFTER case using the best reporting sequence as defined in Case 1. From the experiment results, we observe that in AFTER case, all nodes were assigned more balanced sensing task, and as the result, the accumulative total response time is better than that of the BEFORE case. Since balanced sensing task corresponds to balanced communication load, which corresponds directly to energy consumption of each node and the life cycle of it, the

AFTER case not only provides the best total time response but also the minimum energy consumption of the whole sensor network.

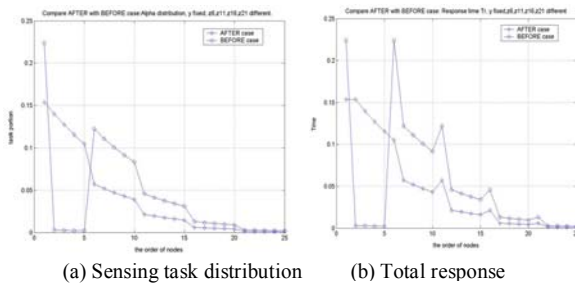


Figure 6. Comparing BEFORE and AFTER Cases

## VI. DISCUSSIONS AND CONCLUSION

In this paper, we extended our sensing task and data aggregation scheduling (STDAS) algorithm from single-hop and multi-hop network to mesh network. The model achieves the best scheduling strategy that assign optimum sensing task to each node in the network so that the whole network achieve the best total response time and maximum life cycle. This is achieved by taking advantage of parallel sensing and processing at different sub-meshes while avoiding unnecessary collision by scheduling the sequential data aggregation. The model successfully achieves two equally important performance indices, i.e., the minimum response time and maximum life cycle of the whole network for astronaut health monitoring (AHM) systems during long durations of space exploration missions.

When the best data aggregation strategy identified cannot be achieved, our model provides the upper and lower boundaries for performance indices such as balanced sensing task assignment and total response time.

With the vulnerability to node and communication link failure, the mobility and the plug&play capability of sensor nodes, it is desired to study the resource control strategy when the sensor nodes getting into the network and moving out of it. We plan to extend the model to answer following questions: (1) How to select the best sink/access point for the incoming sensor node? (2) How to rebalance the network when certain node left, while keeping the network performance indices such as the total response time and the sensor network life cycle into consideration.

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