Wireless sensor web for rover planetary exploration

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Abstract

Together with the "traditional" approach, during the last years a new concept of planetary surface exploration has been introduced and investigated by the space community, including the European Space Agency (ESA). The concept consists in deploying a number of sensors communicating among themselves in a wireless networked architecture (WSN). These sensors, altogether, constitute a distributed instrument with the potential of broadening the capabilities of making science on and around a planetary body.

When compared to big and monolithic planetary probes, with payloads able to obtain high-quality local measurements (e.g. by imaging or sampling), wireless sensor networks allow mapping larger planetary surfaces and/or volumes over a large time span. This concept is particularly suitable to retrieve localised simple measurements such as pressure, temperature, humidity or gas type, which could support the major interests of space exploration: 1) determine if life ever arose on a certain celestial body, 2) characterise the geology and topology of the body surface, 3) characterise its climate, and 4) prepare for human exploration.

In line with this trend ESA initiated the RF-WIPE project (RF Wireless for Planetary Exploration), with GMV leading a consortium completed by SUPSI (University of Applied Sciences and Arts of Southern Switzerland) and UPM (Technical University of Madrid).

1 Introduction

The RF-WIPE study [1] focuses on a single but important element of the wireless scenarios: the sensor networks for planetary exploration. Wireless sensor network technologies offer low power and low mass characteristics, as well as self-healing capability. They can be used in many types of exploratory missions and their utilization may increase the scientific capability of planetary surface missions. For example, in order to prepare for future human exploration missions, more precise, broaden and extensive planetary surface data shall be acquired in the upcoming decades, and this is an area where wireless sensor networks (WSN) have a promising potential.

The background "motor" of this activity is the set of recommendations and priorities identified within the "Wireless for space exploration" workshop organised by ESA in July 2006 [2]. These can be summarised as:

- **Promote the use of low power sensor networking for space exploration.**
- **Promote the introduction of wireless techniques in support to the AIT process.**

The RF-WIPE study focuses on to the use of wireless sensor network for planetary exploration. Within this scope two major applications were easily identified:

- **In situ instrumentation and experiment design**. In this case multiple web nodes are spread in or over a large area to form a virtual payload able to retrieve planetary data to map the target planetary area.
- **Support to robotic mean to facilitate surface exploration**. In this case the wireless sensors are used both for navigation and localization, and for communication.

The present RF-WIPE activity is considered a first step towards the full characterisation of suitable scenarios for wireless sensor networks. The main objective of the activity was the theoretical modelling, simulation and bread-boarding of two different WSN topologies.

2 Planetary surface exploration

In the context of the planetary surface exploration we have identified the following categories:

- **In situ instrumentation and experiment design.** In this case multiple web nodes are spread in or over a large area to form a virtual payload able to retrieve planetary data to map the target planetary area. Depending on the environment where the network is deployed, the data can be retrieved from the surface of the planetary body or from its atmosphere:

- **Surface data retrieval (SDR)**, covering not only the in situ sensing of not easily accessible sites, but also the deployment of a distributed payload for extended coverage and time evolution analysis of the parameters under study. Table 1 lists some mission scenarios while Figure 1 shows a representation of a distributed payload mission scenario.

Mission scenario	Remarks
Distributed payload	A certain number of fixed/mobile nodes are located on the planetary surface. The WSN is used to retrieve scientific data for surface characterisation and mapping. The sensor network acts as a distributed payload.
Jumping nodes	Rolling and jumping nodes.
Anchored nodes	The sensors could be cover with stickers allowing them to be anchored to the ground in case of wind.
Aerodynamic nodes	The wireless sensors could be cover with aerodynamic cups allowing them to move on the surface due to the planetary wind.

Table 1. Surface data retrieval scenarios.

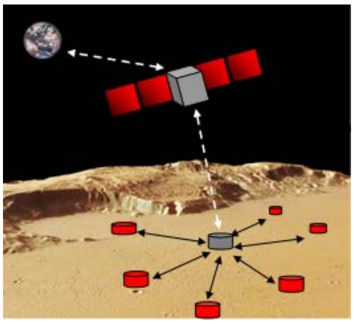

Figure 1. Distributed payload WSN.

- **Aerial/atmospheric data retrieval**, for the exploration of the atmosphere by deploying the network from an orbiter or other atmospheric element. Table 2 lists some mission scenarios while Table 3 depicts a WSN falling sensor scenario.

Mission scenario	Remarks
Falling sensor network	The sensor network is falling through the atmosphere of a planet. The nodes are released by an orbiter or atmospheric element.
Atmospheric microprobes	Mobiles atmospheric microprobes.
Bouncing nodes	Clouds of nodes that would rebound on the surface of a low mass object [3].

Table 2. Aerial/atmospheric data retrieval scenarios.

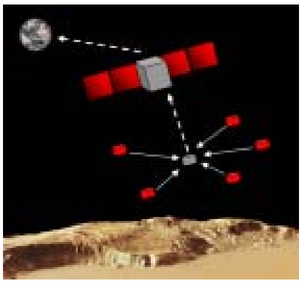

Figure 2. Falling sensor WSN.

- **Support to robotic mean to facilitate surface exploration.** In this case the wireless sensors are used both for navigation and localization, and for communication. Table 3 presents two mission scenarios while Figure 3 shows a navigation and data retrieval scenario.

Mission scenario	Remarks
Navigation and communication support	A certain number of fixed/mobile nodes are located on the planetary surface. The WSN is used for localisation and/or communication of planetary rovers and/or astronauts.
Navigation and communication support + surface data retrieval	A certain number of fixed/mobile nodes are located on the planetary surface. The WSN is used for localisation and/or communication of planetary rovers and/or astronauts. In addition, the wireless sensors collect local data that could either complement or complete the scientific data retrieved by the rover along its exploration route.

Table 3. Surface navigation and communication scenarios.

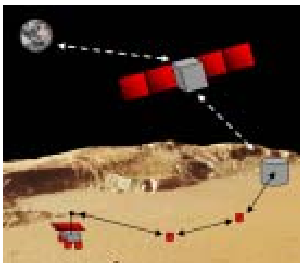

Figure 3. WSN for navigation and surface data retrieval.

3 Rationale for the selection of the reference scenarios

In order to propose and select two reference scenarios to be used both for simulation and breadboarding, the major operational requirements and constraints affecting both the setting-up and the performances of an eventual wireless sensor network for space exploration have been outlined.

The previous section has already mentioned that the environment in which the sensor network will operate affects both the design of the sensor itself and the achievable performances. The following sections highlight the major wireless sensor network operational constrains. Those aspects will also be taken into account while selecting opportune validation tests.

3.1 Sensor deployment

This is a key element of the WSN. Multiple strategies might be used to deploy the wireless sensors in case of exploration scenarios. Example of those might be:

1. Dropped by an orbiter and with individual propulsion.
2. Dropped by the Lander.
3. Dropped while using small parachutes, balloons or rotors. This would also depend on the target body.
4. Dropped by a rover.
5. Fired by the Lander. As already mentioned in this case the sensors could be used both as data collection point and navigation and/or communication beacons.

While deployment strategies from 1 to 3 result particularly applicable to atmospheric and ground measurements, solutions 4 and 5 are directly applicable to ground measurements missions. Additionally, the listed strategies are also characterized by a different level of accuracy and range of the node distribution. For instance solution 1 might guarantee a large and accurate nodes distribution at the prize of a bigger complexity of both deployment strategy and sensors technology, while strategies 2 to 3 presents lower accuracy than solution 1 despite a higher simplicity. In case of deployment with a rover, an elevated positioning accuracy might be guaranteed at the expense of a very time consuming strategy.

3.2 Sensors localization

The sensor localization is a technology that will need to be developed further to allow WSN exploration.

- Different localization techniques might be preliminarily identified:
- Pseudolite (GPS-Like) sensors.
- Optical
- Electromagnetic wave propagation
- Radio-frequency signal strength.

3.3 Sensor/network life-time

One key and obvious element to be considered while thinking of WSN is the power consumption. In order to guarantee a large mission operational lifetime, different strategies shall be applied in order to minimise the sensors power consumption. As a preliminary iteration it is possible to recall at least:

- Adopting a “sleep mode” strategy. This will consist in putting to sleep wireless sensor and awake them only periodically (when data are acquired or transmitted) or on demand (when queried for data)
- Low-power electronic allowing a minor operational consumption for the settled sensors network.
- Antenna design. The power consumption could be reduced while selecting a high gain antenna.
- Optimizing the communication protocol. Reducing the overhead due to control packets, aggregating data, optimizing the data delivery frequency.

3.4 Physical channel

The WSN power will be strongly influenced by the used frequency, the emission power, the communication protocols, etc.

4 Reference scenarios

Taking into account previous considerations within this study we have analyzed the following two scenarios:

- **Distributed Sensors Web Instrument**. Traditionally, in the frame of space mission’s exploration scenarios, the retrieval of scientific data is handled by monolithic instruments performing a certain set of required measurements. The introduction of distributed WSN could introduce a new perspective into the procedure of direct scientific measurements. In this case multiple web nodes are spread in or over a large area to form a virtual payload able to retrieve planetary used to map the target planetary area. Depending on the environment where the network is deployed, the data can be retrieved from either the surface of the planetary body or from its atmosphere. This concept would allow a higher spatial and temporal sampling of the data, allowing building important scientific mapping of the planet/s investigated.
- **Networked planetary surface exploration**. This scenario is proposed for a space mission having a probe landing over a surface planet. The proposal is to carry the wireless sensors and the deployment mechanism inside the back-shield probe. Whenever the main mission is achieved and the probe is safely landed over the surface, the deployment engine will spread wireless sensors on concentric circles around the Lander.

4.1 Distributed Sensors Web Instrument

The objectives of the distributed sensors web instrument scenario would be to:

- Shape a distributed sensor web network able to generate a spatial-temporal map of the area.
- Prove the transmission of retrieved data from the secondary nodes to the primary one.

- Test the latency of information during no transmission/no measurement events.

This scenario as depicted in Figure 4 will include the following elements:

One main node: This main node or sink node shall be installed over a laptop and its goal is to collect data acquired by the measurement nodes.

Two transmission nodes: These nodes will relay the meshed information generated by the sensors up to the Main Node. The distance between transmission nodes will be around 20m.

Seven measurements nodes: Every measurement node will collect several magnitudes values and will broadcast it, trying to reach the transmission nodes. These nodes shall be placed in a mesh distribution at a distance of 30m. approximately.

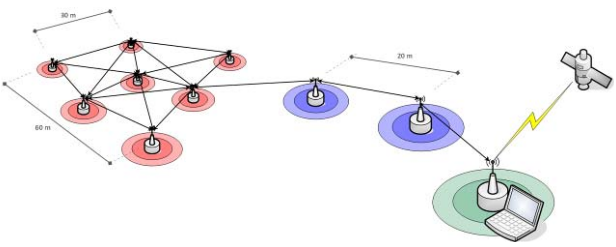

Figure 4. Distributed sensors web instrument topology.

The sensor nodes will measure the following weather variables: **temperature** and **relative humidity**. Once the nodes are deployed, supposedly in a non regular structure, they shape a meshed tree model topology for communications. In this configuration, end nodes send the values acquired trough the secondary node(s) which, including its own measure, retransmits the information up to the main node.

4.2 Networked planetary surface exploration

The goal of the networked planetary surface exploration scenario is to prove the following capabilities:

- Characterize a predefined area from the point of view of a magnitude like ambient light/solar radiation.
- Change of the measurement sampling rate depending on special events.
- Guarantee communication coverage for additional exploration agents as a mobile rover.

This scenario will measure ambient light and it will include the following elements:

One static sink node: This main node shall collect data acquired by the measurement nodes.

One mobile sink node: This sink node shall be installed over a rover and its goal is to collect data acquired by the measurement nodes.

Six measurements nodes: These nodes shall be placed in a circle radius 30m approximately.

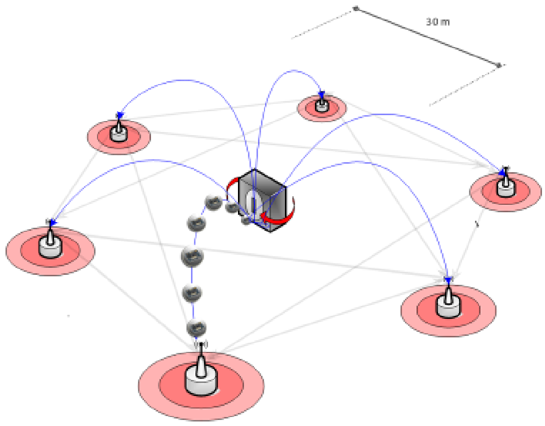

Figure 5. WSN star topology with rover as sink node.

In this star topology the coverage area is equal to a circle of radius 30m. This area could be expanded by connecting several WSN islands trough a chain of several transmission nodes.

5 Simulation and laboratory tests

The laboratory tests have been done mainly to validate the following features:

- the power model implemented in the simulator,
- the ability of the applications implemented in the outdoor tests to follow the environmental changes in order to optimize as much as possible the power consumption of the nodes,
- the performance of the nodes platform selected for the real network implementation.

For validating the power model implemented in the simulator we ran a series of acquisitions with a real wireless node instrumented with a precise multimeter measuring the current consumption. The application running on the node performed periodically the same sequence of operations: seven consequent acquisitions from the light sensor, computation and transmission of the average light value and transition to sleep mode during 500ms. The same operations were replicated in the simulation and the results were then compared with the acquisition done by the multimeter, as reported in Figure 6.

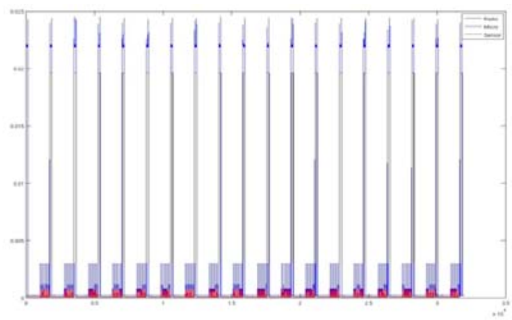

Figure 6. Power consumption in simulator vs. reality

The blue lines are the real current acquisition during the sampling and transmission, while the other graph superimposed are the result from the simulation. As it can be seen from the graphs the simulation results are very close to the real acquisition. Even the simulated value of the average energy consumed is much closer to the measured one:

- Energy_Experimental=0.0674A*sec
- Energy_Simulator=0.0652A*sec

In order to verify the correct behaviour of the application that implements a dynamic sampling we implemented a very small network with two nodes and a sink. The first node has been illuminated for intermittent periods of 5 min with duty cycle of 50% with a varying light intensity values. A Luximeter was used in parallel of the wireless node. The second node has been ventilated with hot air for intermittent periods of 5 min with duty cycle at 50%. A Thermometer was used in parallel of the wireless node. The first period of 5 min was in normal conditions.

Finally, the node platform has been tested in different condition form the transmission point of view and the sensor nodes acquisition capability. It performed very well in all tests. The only limitation that we have detected, but it was anyway expected, it is the unreliability of the sensor measures when the node is positioned upside down.

The simulation tests have been done mainly for comparing, and then validating, the results obtained from the simulation with the ones obtained with the outdoor tests. We simulated the two different scenarios presented in section 4, in different working conditions:

- With a simple application, that ran for one hour that had to sample and transmit the acquired value every minute and put then the node in sleep mode. This test has been implemented for checking the correct behaviour of the network depending on the network topology applied for the two scenarios.
- With a simple application, like the previous one, we changed the condition of the networks adding and or subtracting nodes in order to check the capability of the network to react accordingly.
- With the same application we simulated changes in the environmental conditions by adding and then removing some obstacles able to change considerably the path loss among the nodes.

At the end the simulation results had confirmed that both the model and the simulator are able to reproduce correctly the behaviour of a real network performing the same tests in outdoor conditions.

6 Outdoor-field tests

A series of outdoor-field tests were executed to evaluate how the network reacts when it is exposed to adverse conditions, as it could happen in an actual planetary exploration mission. In this sense, the presence of obstacles, the possible loss of the communication link or malfunctioning of one or several nodes should be taken into account and the operation of the system under these conditions should be probed and verified.

In order to guarantee it, each test designed tries to check one side of the net performance, including some tests combining several aspects. The aspects we have evaluated are the following:

- Reception at the sink in different circumstances: the correct mesh communication has been tested in different places and weather conditions.
- Correct performance during long periods. Several tests have been executed during long periods in order to verify the stability.
- System adaptability to environment conditions. The net is able to adapt its behaviour depending on the external conditions (e.g. the sample time). Data acquisition has been performed during changing conditions in order to verify the correct performance of the dynamic fitting.
- Capacity to build and rebuild the net dynamically. When initializing the net is able to build itself. If during the normal execution one or more nodes are turned on, the net reconfigures itself for including it/them in the mesh or in the communication chain.
- Performance at obstacles presence. The net continues working normally even when some obstacles, either positives or negatives (holes).
- Robustness when failures. The net should be able to manage some node errors, malfunction or connectivity lost. It is closely related with re-routing capacity, so when one node is out, the rest of the network reorganizes itself as a new mesh.
- Performance when mobile sink. When the base station is moved around the area covered by the WSN, the connectivity should be guaranteed.
- Robustness when relocation of nodes. The nodes composing the net could be displaced o rellocated, and it must not affect the normal performance of the system.

The results derived from the partial tests allowed solving some problems, achieving in the final tests a right performance in every field.

The tests were done under different conditions and situations (including, for example, electromagnetic and human interferences) (Figure 7) and the outcomes were satisfactory in every aspect.

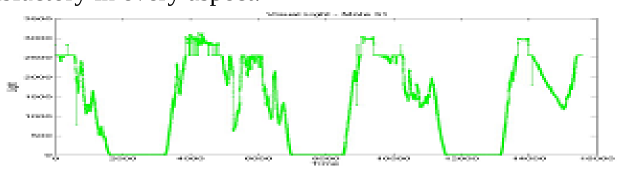

Figure 7. Light measurements during 3 days.

Special attention was paid to the Arbutus routing protocol [4] verifying the optimum route election and the reconfiguration capacity.

Finally, the careful analysis and processing of the data showed the expected correlation between the environmental data acquired (temperature, humidity and visible light), and how they fit the behaviours expected along the time (e.g. sunset in Figure 8: temperature and light values decreases, while humidity increases). The constant attention to the evolution of the magnitudes measured and its rate of change provided a good sign for evaluate the correct operation of the test.

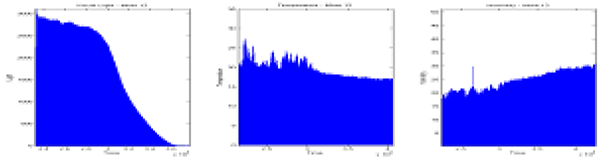

Figure 8. Light, temperature and humidity measurements during sunset.

7 Mobile deployment engine

Nowadays, most of the Wireless Sensor Network applications do not take into account how to place the nodes on the chosen locations. Human placement could be enough in Earth's deployments, but is clearly not functional on planetary exploration missions. In this sense, a robotic way for deploying the nodes has been studied, evaluating several different options.

Depending on the approach, we have considered both aerial or ground deployers, accurate or random systems, online or offline planners, and main or secondary task (if the deployment task is the main one on the mission or not). Considering each point, a ground vehicle has been selected due to its stability and its easiness of control, but including a component to increment its range and effective distance. Furthermore, an intermediate option between random and high precision deployment has been chosen: local area accuracy. This means that we are able to place each node in the area of interest without the need to place it in a particular location.

The navigation trajectory planning would be done offline, in order to guarantee the optimization of the route and the layout, avoiding local minimum points, while the deployment task will be performed by the main rover mission.

Beginning with these requirements, a robotic launcher carried by a rover has been designed, implemented, tested and validated. As Figure 9 shows, the system is composed of four different components, apart from the nodes and their capsules.

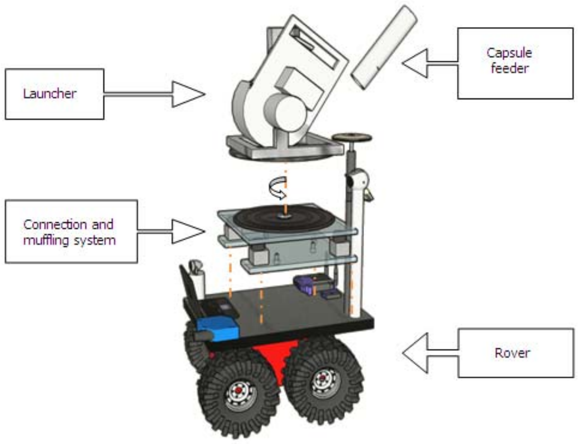

Figure 9. Mobile deployment engine design.

The first component is the partial autonomous rover that will carry the rest of the system and will move over any planetary surface scenario. A muffling and connection base is placed on top of the rover, specially designed to uncouple the rover from the launcher. Furthermore, this base provides the orientation capability for the launcher.

The launcher is placed over the base, and gives the capsules containing the nodes the required velocity to be launched at the desired position. The range is defined by the disk tangential speed, transmitted by means of friction to the node. This velocity is controlled electronically by the supplied voltage.

Finally, the last part is the capsule feeder. This component places the node on the launcher when required, synchronizing this process with the launcher speed and the orientation system.

Figure 10 shows the real implementation of the deployer engine over a Pioneer rover platform.

Figure 10. WSN deployer rover.

In order to allow the adaptation of the nodes to the launching system, as well as to protect the sensor from the impacts caused during the deploying, the motes are encapsulated in plastic spheres capable of absorbing and muffling the impacts, equipped with many holes on its surface so it do not interfere with the measurement of environmental variables.

The evaluation of the system has been done through a series of exhaustive tests, focusing each one on one characteristic of the system. In this sense, accuracy, repeatability and precision, both statically and dynamically, have been assessed. Furthermore, the variations depending on the distance, the node resistance to impacts and the maximum absolute ranges have been evaluated. Also the performance when following some patterns or spatial distributions has been considered.

Furthermore, results were considered satisfactory, obtaining a mean precision higher than 0.5m and repeatability around 0.3m (see Figure 11). The maximum range achieved was 30m, enough for the proposed application, and the general response and performance of the system in terms of processing time and ergonomy were quiet sufficient for the intended application.

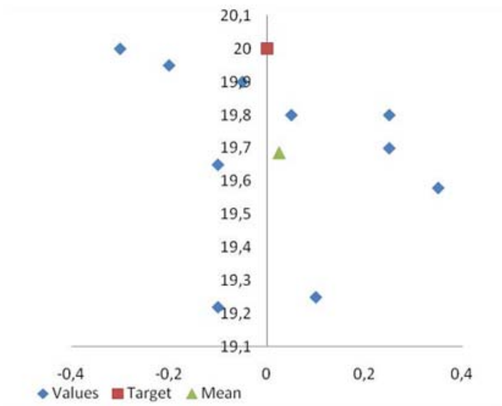

Figure 11. Deployment chart at 20m distance.

8 WSN advantages vs. single measurement instruments

By its nature WSNs are an ideal solution to collect data required for biosphere modelling, such as temperature, pressure, gas concentrations, gas types, water vapour, humidity, light intensity, etc.

Major scientific and economic benefits expected while using WSNs when compared with traditional instruments are:

- Better spatial and temporal sampling capabilities.
- Higher reliability.
- Reduced payload weight.
- Lower overall costs.
- Shorter mission programmatic.

9 Conclusions

The major benefit of WSNs applied to planetary space exploration is the possibility to provide measurements of different types of data both on larger volumes and longer periods of time. Those characteristics make WSNs an almost unique opportunity to gather spatio-temporal data in a manner that would be difficult, or even impossible, with methods and techniques based on the “traditional approach”, being those big and monolithic instruments.

In addition, the onsite presence of sensors web would supply an added means for navigation and communication purposes. In this sense we have identified several planetary exploration scenarios and demonstrated the benefits of WSNs.

Finally we have demonstrated the feasibility of the deployment of WSN’s using robotic means as a rover platform.

References

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