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AD-HOC WIRELESS SENSOR NETWORKS FOR EXPLORATION OF SOLAR-SYSTEM BODIES

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ABSTRACT

In this work, we evaluate the exploration of the solar system by ad-hoc wireless sensor networks (WSN), i.e. networks where all nodes (either moving or stationary) can both provide and relay data. The two aspects of self-organization and localization are the major challenges to overcome to achieve a reliable network for a variety of missions. We point out the diversity of environmental and operational constrains that would have to face WSN used for space exploration.

The first group of scenarios we evaluated concerns nodes moving relative to each other either above or on the surface of a solar system object. These scenarios enable collecting data simultaneously over a large surface. The second group of scenarios we considered concerns the use of nodes fixed in or on the ground of an asteroid or planet.

We considered both physical and chemical sensing of the atmosphere, surface ground and soil as candidates for such networks. Emerging highly integrated technologies are investigated in order to make a distinction between the elements that can be common for a variety of missions and the others that are specific to an exploration scenario. Finally, we compare the specific requirements of WSN for space exploration with those of WSN designed for terrestrial applications.

INTRODUCTION

We can distinguish two groups of application of WSN in space: 1. implementation of WSN within spacecraft in order to replace harnessing and enhance the robustness and functionalities of the mission or 2. direct scientific measurements with distributed WSN on, in or around solar system bodies [1].

More and more wireless networks (WN) will be used within satellites, spacecraft and launchers in order to reduce the number and mass of cables for the data bus. In some cases, measuring certain physical quantities and transmitting them to a central processing unit could be useful. Simple WSN in launchers or spacecraft could be used to detect impending failure of the structure or components, for instance by detecting changes in the resonance frequencies. However, the approach generally followed in satellites is oriented toward a wireless data bus that transmits all the data from the various subsystems to a central processor. This data could come from complex sensing elements (e.g. high resolution imagers) or from microprocessors, and the data flow can therefore be much higher than the one produced by simple sensors of a WSN.

Distributed smart monitoring with WSN for the exploration of the solar system has started to gain interest in the view of ESA [1]. Compared to single instruments, WSN for exploration are very promising in terms of cost reduction, set-up time of a mission, scientific interest of the data acquired, etc. However, to our best knowledge, until now no mission based on WSN for exploration has been flown. WSN based exploration mission can address either atmospheric or ground based measurements. Such missions would require robust nodes capable of acquiring valid data in harsh environments while communicating with other nodes over large distances, i.e., a few kilometers. Depending on the mission, the requirements can be very different, but in general self-organization and localization of the WSN are needed. In contrast to single probe based mission, the success of a WSN based relies on the robustness of the WSN which cannot be fully tested on earth. However, some earth based test can approach the situation that would be encountered in space by the WSN.

EXPECTED BENEFITS FROM THE INTRODUCTION OF WSN IN SPACE

Scientific benefits

The scientific and technological differences, advantages and drawbacks of WSN for space exploration are best shown when comparing those missions to single probe/instrument based missions. Fig. 1 shows that exploration of space with WSN would not necessarily tend to replace single probe missions, but can provide different type of data that would enable to map accurately an area or volume of interest with simple sensors over a long period of time if necessary. WSN are likely to provide new data that would be difficult to collect with other methods based on single probe (Table 1).

Single large size probes can contain essentially three types of instruments: complex local sensor (spectrometer for measuring soil, AFM, etc), sensor capable of remotely mapping the atmosphere or the ground surface (LIDAR, telescope, atmospheric spectrometer, etc), and/or simple local sensor (temperature, pressure sensor, etc).

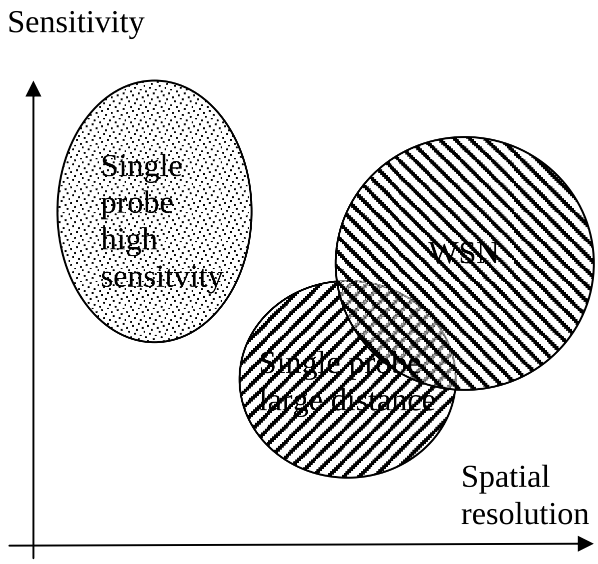

Fig. 1: Schematic showing the domain of application of WSN vs. Single probe large distance measurements and single probe high sensitivity localized measurement.

Some large size single probes are capable of realizing high quality local measurements with complex expensive instruments that have not yet been scaled down. Such type of measurements cannot for the moment be conducted by WSN.

On the other hand, WSN can use essentially only simple low cost sensors that can be distributed in a large number. In such scenario, if the position of each node is well known, the spatial resolution is excellent.

For WSN exploration missions, the robustness relies essentially on the whole network, i.e. nodes can fail without inducing a shut down of the whole network. Therefore the testing procedure would be verified differently than the one of single probe based mission. Nodes would have to be tested in simulated harsh environment. In WSN, due to the redundancy of the measurements, a higher node level of failure than for single node based mission could be tolerated. The whole WSN would have to be tested on earth in scenario as similar as possible to the one encountered after deployment during the space mission.

Scientific & technical considerations	One instrument	AD-HOC WSN
Complex sensing involving long distance measurements (spectrometry, Lidar, optical, imaging)	Largely reported on past missions. Can obtain a large amount of data with one single probe. The spatial resolution of those instruments is a major limiting factor.	Difficult due to: • miniaturization problems, • amount of data provided larger than WSN bandwidth No significant advantage to distributed measurements
Localized simple measurements (temperature, pressure, gas type and concentration, humidity, light intensity)	Reported on past missions. The data provided was for only one single location on a planet or asteroid.	Should enable mapping of the parameters in a large area or volume over a long period of time if necessary. Robust due to the AD-HOC network structure.

Table 1: Comparison of the scientific and technical aspects for one instrument based missions and AD-HOC WSN based missions

Economic benefits

The costs of a mission based on WSN for space exploration are best shown when comparing those missions to single probe/instrument based missions. Table 2 shows that the cost of sending into space a WSN could be lower than the one of a single probe mission carrying very costly equipment. The factors that can induce low costs for WSN based missions are: simple testing procedure, small size and mass of the nodes and the eventual possibility in the long term to use similar WSN equipment with different sensors.

Economic aspects	One instrument	AD-HOC WSN
Complex sensing involving long distance measurements (spectrometry, Lidar, optical, imaging)	High reliability of each element required. Each element fully space qualified. No off the shelf elements. Very costly.	High global reliability of WSN required. Off the shelf WSN do not meet space requirements. Off the shelf sensors do not exist yet. Costly.
Localized simple measurements (temperature, pressure, gas sensing, humidity, light intensity)	High reliability of each element required. Each element fully space qualified. No off the shelf elements. Very costly.	High global reliability of WSN required. Off the shelf WSN do not meet space requirements. Some off the shelf sensors exist. Could become the less costly exploration method.

Table 2: Comparison of the characteristics highly influencing the cost of the mission for one instrument based missions and AD-HOC WSN based missions

Benefits summary

Compared to single probe missions, we can see many advantages in the long term of introducing WSN in space exploration:

- Shorter time between the elaboration of a mission and its launch,
- Simpler testing procedure,
- Higher reliability,
- Lighter payload,
- Lower costs.

However in our view, the introduction of WSN in the space exploration domain will be gradual, starting with the development of a technologically simple mission.

ALTERNATIVE AND POTENTIALLY COMPETING SOLUTIONS TO WSN

There are 3 main ways to explore space:

- Using earth based instruments
- Single probe missions
- WSN based missions

Earth based instruments cannot map the solar system to get the level of detailed information that can be obtained with exploration mission that are closer to the scientific data to be measured. Measuring with an instrument close to the object of interest provides much more accurate data than measuring from far away for two main reasons: the electromagnetic wave carrying the information can be modified by the physical channel it propagates through, and the signal to noise ratio deteriorates when going away from an information source. Even instruments capable of long distance measurements are more sensitive close to their location. Placing the measuring instrument close to the information enables the use of simpler measurement techniques (Fig. 2). When we consider a network of instruments located close to the information sources, there is no need to map the environment around the instruments and the measurements are local.

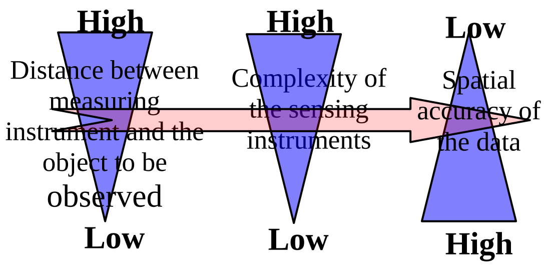

Fig. 2: Schematic showing the link between the instrument-object distance and the accuracy of the data measured.

Long or middle range distance measurements cannot provide as accurate data as numerous short distance measurements. When such a high spatial accuracy is not required, there can be some overlap between the different techniques (Fig. 1).

The observation and exploration of the solar system is not anymore at its infancy, so it is likely that scientist will in the future want to obtain more and more accurate data in order to map the atmosphere and ground of all the objects of the solar system.

THE ENVIRONMENTAL CONSTRAINTS

The environmental constraints will vary largely from a mission to another:
Typical values:

- Temperature range: -133°C to +22°C on surface of Mars
- Pressure range: up to 90 bar on the surface of Venus
- Irradiation: kRad to MRad depending on orbit, solar activity, and mission duration
- Vibrations: up to 20G from 5 Hz to 2000 Hz at launch
- Shocks: up to 10'000G at separation of stages and heat shield.

Non aerospace industry is developing WSN nodes capable to withstand harsh environment (e-CUBES project). These devices can be the starting point for optimizing nodes for specific missions.

THE OPERATIONAL CONSTRAINTS

Localization of the sensors in the environment

In most space missions, the localization of each node is essential in order to know where each measurement has been made. Most distribution methods that can be used in space do not allow the node position to be accurately determined by a mean external to the network (Table 3) [2]. Therefore in space exploration, there is a large need for self-localization of nodes, i.e. intrinsic localization by the network. Furthermore, in some missions, nodes are moving relative to each other and therefore their position would have to me updated frequently, i.e. continuous self-localization.

	Advantages	Drawbacks	Typical mission
Initial momentum	Simplicity Small node size Could allow large distance distribution	Could involve high accelerations Not accurate distribution	Atmospheric & ground measurements
Dropped from a spacecraft	Simplicity Small node size Could allow large distance distribution	Could involve high accelerations Not accurate distribution	Atmospheric & ground measurements

Distributed with a rover	Accurate distribution No need for node self localization Small node size	Large distance and node number distribution is time consuming	Ground measurements
Individual propulsion	Low accelerations Could enable an accurate distribution	Very complex Large node size	Atmospheric & ground measurements

Table 3 : Typical node distribution methods.

Different localization techniques exist, but they rarely have been implemented on small size sensing nodes used in WSN. Table 4 gives an overview of the localization techniques that could be used in space [3],[4]. The most promising localization technique is based on wave propagation delay. However, new developments are required to implement an accurate and reliable localization technique in sensing nodes.

	Advantages	Drawbacks
Electromagnetic wave propagation delay	Could be very accurate Continuous self-localization	Possible ambiguity due to multiple reflections Could require UWB which might not be ideal for large distance communication
Signal strength	Simplicity Continuous self-localization	Probably not accurate
GPS/ Gallileo type	Accurate Well tested and developed Continuous self-localization	Large infrastructure required, numerous satellites orbiting
Optical (smart dust project, NASA)	Could be accurate	Would rely on the central data processing (at the base station) New development Continuous self-localization difficult

Table 4 : Overview of localization techniques that could be used in WSN for space exploration.

Low Power consumption

One essential parameter for the success of WSN in space is power consumption [1]. All options to achieve low power consumption of WSN have to be considered:

- Sleeping
- High gain antenna
- Low power electronics

Many scenarios for data acquisition by WSN in space exploration have a low sampling rate. Putting the nodes into “sleep” when not acquiring data is an excellent option to drastically reduce the consumption. Different level of sleeping mode could be considered depending on the scenario and the sampling rate.

The antenna can have a major influence on the overall performance of the nodes and their consumption. It is likely that depending on the physical channel electromagnetic wave propagates and the frequencies, different types of antennas have to be considered.

Using low consumption electronics can have some impact on the overall consumption of the WSN.

Physical channel

In some space exploration scenarios, the maximum distance between nodes (overall footprint of the network) can be up to 100 km. If the nodes are only capable of communicating at a distance of a few 100 m, this would largely limit the scenarios where WSN can be applicable.
For some missions, the physical channel is poorly characterized. Having nodes capable of communicating with a good reliability in an unknown physical channel could largely facilitate the introduction of WSN.
The frequency band, type of modulation, emission power, and protocol of communication will strongly impact the performances of the WSN. We think that frequencies ranging from 100 MHz to 2 GHz would allow a good tradeoff between the antenna size and the distance of communication that could be achieved. Using UWB could be an option to consider in order to combine mid-range (100 m) communication with efficient localization techniques [4].

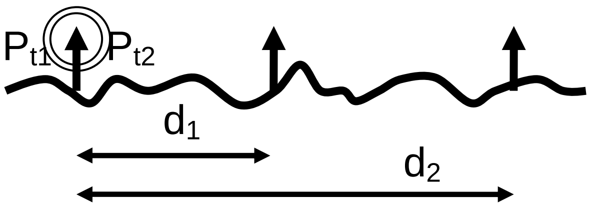

Fig. 3: Figure illustrating the power required to transmit at two different distances in the same physical channel.

$$P_{t2} = P_{t1}\left(\frac{d_2}{d_1}\right)^n \quad (1)$$

The power required to transmit in a defined channel is highly dependent on the distance between the transmitter and receptor. When a transmission works fine in a defined physical channel with a transmission power P_{t1} at a distance d_1, it would require a much larger transmission power P_{t2} when the distance is increased at d_2 (see eq.1, [5]). Depending on the physical channel characteristics, the power dependency factor varies from n=2 (in free space) up to n=6 (in the worst transmission condition on the ground).

All those aspect are tightly coupled and require a thorough study to optimize the WSN for any given scenario. A special challenge for space applications in WSNs is the wide range of possible scenarios, each of which has a very different RF solution.

EMC issues with other systems in the environment

In space exploration, normally there are no EMC perturbations coming from other systems in the environment, other than the space craft. Furthermore, there are few limitations in the frequency band or emission power that can be used.

There have been some discussions regarding frequency allocation for space communication between NASA, ESA, and JAXA, but this imposes very few limits on WSN with communication ranges of only 100s of km.

The energy issues

Depending on the mission and objectives, energy could be either harvested from the environment or/and stored in batteries. Energy harvesting being more complex than using batteries, the first WSN sent into space will be more reliable if using batteries.

The mission that will have to last over really long period of time will benefit most from harvesting technology. In space, the most common source of energy that can be harvested is sun light. Vibration energy or thermal gradients are much more difficult to harness.

Technology availability issues

For space exploration with WSN, one key technology is essential to further develop: the localization of the nodes [3]. Different approaches are possible, but using the transmission signal for this purpose seems to be more appealing [3],[4]. The bandwidth is an important parameter as larger bands favor better localization (UWB). Different RF techniques of localization such as: direction of arrival, location based fingerprint, amplitude, phase and time of flight have to be evaluated. On the surface of a planet, time of flight is likely to give good results, while the amplitude of the signal could give good results in free space.

TYPICAL WSN FOR SPACE EXPLORATION

The typical architecture of a WSN for space exploration is based on an AD-HOC multi hop network that collects scientific data and transmits it via a relay either directly to earth or to an orbiter or spacecraft (Fig. 4). The topology of the network will largely depend on the type of mission, i.e., number of nodes, distance between nodes, etc.

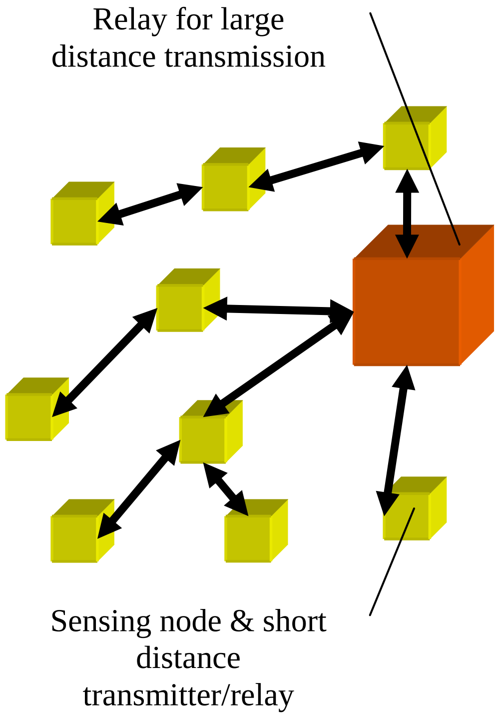

Fig. 4: Typical architecture of a WSN used for space exploration.

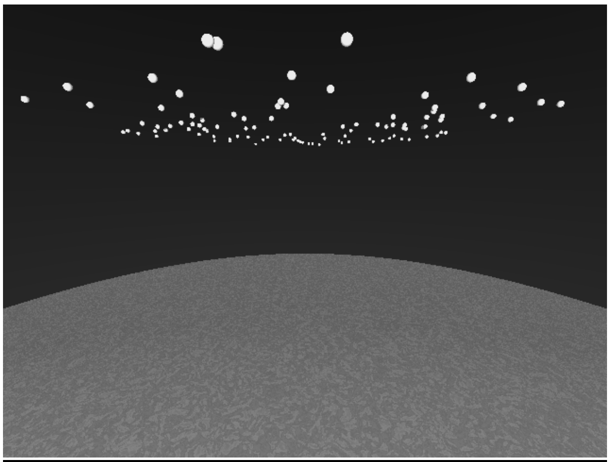

Fig. 5 Typical scenario of atmospheric measurements where the sensing nodes are falling through the atmosphere of a planet.

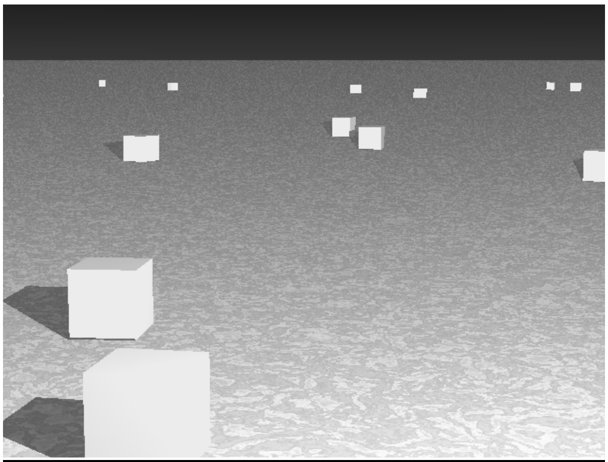

Fig. 6 Typical scenario where the sensing nodes are located on the ground of a planet or moon.

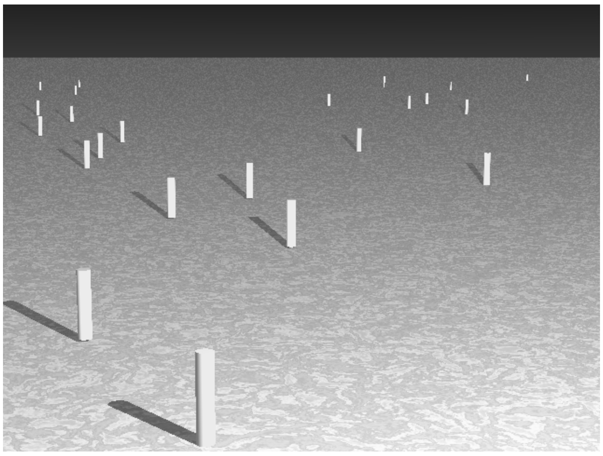

Fig. 7 Typical scenario where the nodes are anchored into the ground of an asteroid (low mass object).

Typical scenarios

In a mission where nodes are falling through the atmosphere of a planet while taking measurements (Fig. 5), the relay for large distance transmission would fall among the nodes at the same speed. The duration of such a mission could be relatively short (up to a few hours) and the sampling rate quite high (for instance a data acquisition per second). In a scenario where the sensing nodes land on the ground of a planet or moon (Fig. 6), a relay would transmit the data collected by the nodes to an orbiter or directly to earth. The mission could last up to a few years, while the sampling rate would be very low (for instance one data acquisition per hour). An alternative to this scenario for low mass solar system objects, i.e. asteroid, is to anchor the nodes into the ground for instance to conduct seismic measurements (Fig. 7).

More advance scenarios would concern moving nodes over long period of time. For instance actively moving nodes, i.e. micro robot, on the ground of planets or moon could collect data while they would receive directions from earth regarding the surface area to be explored. Dubowski et al.

proposed a concept where the nodes are rolling and bouncing on the ground [6]. In this perspective, different node design can be considered. For instance, the nodes could be constituted of a central heavy part that contains the electronics package into an inner sphere that is displaced by electroactive polymer actuators into an external hull. Slow motion of the actuators would induce a rolling behavior by continuously translating the center of gravity, while quick motion of the actuators would make the node jump over obstacles (Fig. 8).

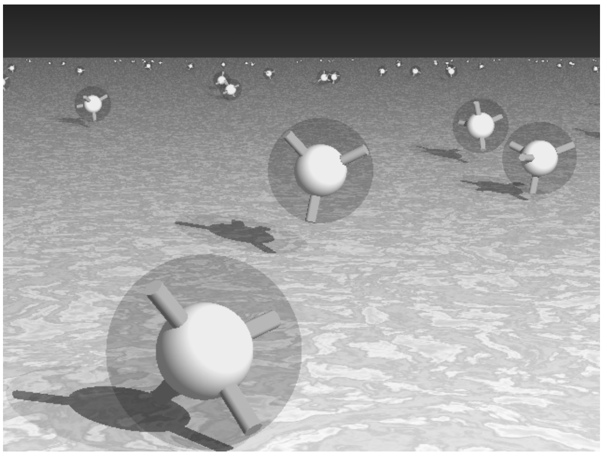

Fig. 8 Rolling and jumping nodes on the ground of a planet or moon.

Another advance scenario could concern a cloud of nodes that would rebound on the surface [11] of a low mass object, i.e. asteroid (Fig. 9). The low attraction and the absence of gas would enable the nodes to rebound at high altitude (few kilometers) with relatively low impact speed. Acceleration sensors could provide data on the surface nature, for instance to locate a good landing place for large probes.

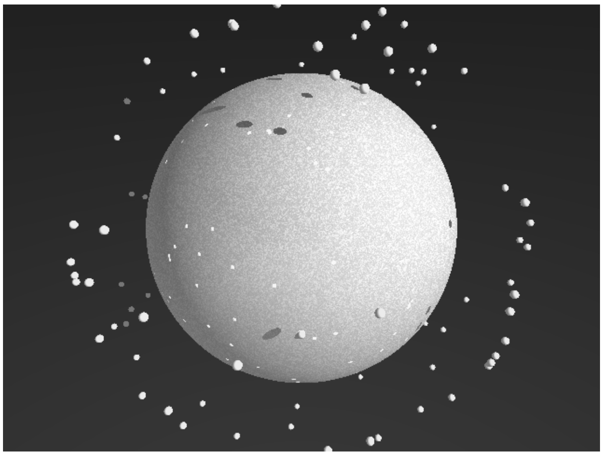

Fig. 9 Rebounding nodes around an asteroid (low mass object).

Typical architecture

The nodes would have the following main components (Fig. 10):

- MEMS sensor (analog or digital)
- A to D converter
- Microcontroller (signal conditioning, communication protocol and power management)
- DSP layer
- Memory
- RF Transceiver
- Antenna
- Power supply

In our view only the microprocessor can be common to all mission types. The other units would largely depend on the mission scenario, especially the RF components, and some parts may not be required in all cases, especially the DSP.

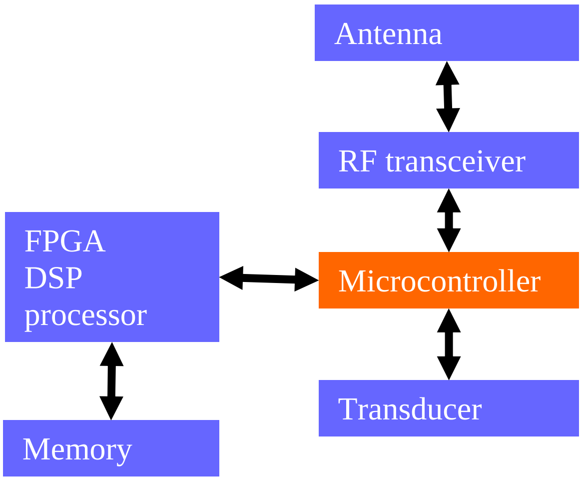

Fig. 10 Data flow between the different functional units. In our view only the microprocessor can be common to all mission types. The other units would largely depend on the mission scenario.

The transducers

The transducer section will typically consist of the following units (Fig. 10):

- MEMS sensor die for measuring for instance:
    - gas pressure
    - temperature
    - accelerations
    - gas concentration and type
    - light intensity
    - light direction
- Signal conditioning IC with sensor functions and power supply voltage measurements.

The characteristics of the MEMS sensor will depend on the mission scenario and scientific objective. Ideally, the microcontroller would be capable of conditioning different type of AC or DC signals from a variety of sensors.

The microcontroller

The different level of software (OS, communication protocol, limited data treatment, localization calculations) will run on the microcontroller. Two options can be followed: either having the same high performance microcontroller for a variety of missions or using for each mission the minimal microcontroller in order to reduce power consumption.

The RF transceiver

The RF transceiver has to meet the requirements of a specific mission:

- emission power
- frequency domain
- drift of the oscillator over the required temperature range
- modulation scheme
- localization
- sleep mode
- fit the requirements of the communication protocol
- signal to noise ratio
- power consumption& efficiency
- heat generation
- temperature range
- full or half duplex
- etc.

Many of these parameters are tightly linked. The overall performance of the RF transmission would largely depend on the interface to the antenna and itself.
The interface between the transceiver and the antenna shall be as primitive as possible, using a minimum of external components for the Rx/Tx switch and matching network.

The antenna

The mission type will influence the antenna choice:

- in free space the antenna has to have omni directional capabilities
- on the ground, the antenna would have to transmit the RF signal in two directions essentially

Balanced antenna should be preferred to limit the influence of the ground while having a high gain.
The antenna can be integrated into the nodes or unfolded/unrolled when the nodes are deployed.
Probably a large effort would have to be placed in the development of high gain compact antennas.

The power supply system

Depending on the mission and objectives, two types of energy source can be used:

- battery
- energy harvesting (solar energy)

Energy harvesting being more complex than using a battery, the first WSN sent into space would be more reliable if using battery source that does not require DC/DC converters and charging circuits.

The packaging issues

The packaging of the node must be robust and hermetic to allow for reliable operation on the asteroid, planet, or moon, as well as safe transit from earth. The package serves as a mechanical support, and can provide electrical routing of signals and power.
For cm^3 packages, ceramic chip carriers are an appealing solution, due to their robustness and also for instance to ability to build a patch antenna directly into the lid. The EADS micropack [10] project is an excellent illustration of this concept, using a stack all functional layers, each in a ceramic package.
For mm^3 packages, chip-scale and wafer-scale packaging becomes an important aspect, and integration of thin-film batteries and compact antenna will require novel packaging approaches.
The European integrated project e-CUBES aims to integrate all the node elements into 1 mm^3 (Fig. 11) using direct chip to chip stacking and bonding.

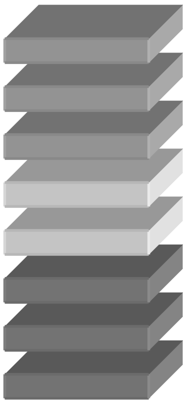

Fig. 11 In the e-CUBES packaging concept, nodes are constituted of a stack of all the functional layers in a volume of 1 mm^3.

Radiation shielding (most likely in the form of a few mm of Al) may be required and may play a large role in node size and mass.

Software functionalities

Having minimal software for each scenario is an option to consider since it would allow reducing as well the hardware and the power consumption.
The software functionalities would largely depend on the mission scenario. There can be three levels of software:

- Upper level programs for data processing
- Layer that handles the data flow and the power management
- The communication protocol (Medium Access Control MAC level)

An OS can be used to support the upper level programs and facilitate the data flow management.
Main functionalities of the software that are particular to the WSN used for space exploration:

- Sleep mode: different sleeping mode can be considered in order to reduce consumption during operation and minimize EMC perturbations during node distribution
- RF localization calculations: can be based on time of flight or amplitude in order to map the topology of the network

Typical specifications of visionary demonstrators

In the following table typical specifications for space exploration with WSN are summarized (Table 5):

Parameter	Value
Range (distance between sensors)	10 m to 10 km
Total network size	500 m to 100 km
Sensor movement (in the network)	Fixed or mobile
Medium for wireless communications	Different gases, free space, surface of a planet
Volume occupied by all nodes while in transit	~ max 1 dm^3, the smaller the better
Lifetime	Under operation: hours to few years
Frequency range for communications	100 MHz to ~2 GHz
Type of data transfer	Continuous, duty-cycled or occasional
Data rate provided by a sensor	Few byte per acquisition
Temperature range	For instance: -140°C to +30°C on the surface of Mars
Main available energy from the environment	Solar
Need for network self-organization	Yes, and continuous in case some node fails or are mobile
Need for a self-localization of the nodes	Yes, continuous if the network is mobile
Typical power consumption (can be largely dependant on the mission and technology)	1 mW when transmitting
Typical total energy for a mission per node	Typically 400 mWh for one year operation @ a rate of one hour operation per day during one year

Table 5: Typical specifications of WSN that could be used in the space exploration domain.

USE OF COMMERCIAL WSN FOR SPACE EXPLORATION

To our best knowledge, to date, commercially available WSN are capable of:

- Ad/hoc functionalities
- self organization and reconfiguration
- less than 1 km range communication

Therefore there are two essential needs of WSN for space exploration that are not yet met by commercial WSN:

- communication at distances up to 10 km
- localization functionalities (preferably without relying on GPS/Galileo-type technologies)

Commercial WSN products can be used now to demonstrate on earth most aspects of an exploration mission. They are not yet mature enough to be used in space to collect reliable scientific data. To develop WSN for space exploration an effort would have to be made towards: increasing the communication range and implementing localization functionalities, and understanding radiation and environmental constraints and associated packaging and shielding issues.

CONCLUSION

WSN is a new technology for space exploration that has yet to prove the numerous advantages one can expect: low cost, accurate measurements over a large surface or volume, short set-up time of a mission, high reliability through redundancy.
WSN will have to be optimized to meet the specific requirements of space exploration: need for self-localization and reliable long distance communication (few km). Each mission will require highly optimized nodes, with sensors, communication, and packaging suited to the environment the WSN will be operating in, and to the characteristics that must be measured. For each mission, the data acquisition and transmission of the WSN will have to be tested on earth in an environment as similar as possible to the one that would encounter the nodes when deployed in space.

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