The e-CUBES Space demonstrator:
A flying 5 node WSN demonstrating self-localization and dynamic multi-hop networking

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Zorro Paragliding School Sàrl and pilots for flying the nodes
Outline

1. Why Wireless Sensor Networks for space and planetary exploration? (p. 3)

2. Some proposed scenarios using WSNs for space exploration (p. 7)

3. The e-CUBES “space” demonstrator (p. 12)
WSN in space?

In the short term, WSN are only planned in space on spacecraft (max radio range of order 5 m) as a way of reducing cabling mass and complexity.

WSN enable a different way of collecting data on planets (surface and atmosphere), asteroids:

- In this presentation, possible uses of WSNs for exploring space are presented, where WSN replace or complement larger (more expensive) spacecraft.

In all scenarios addressed here, it is assumed that the same orbiter that delivered the hundreds or thousands of nodes to the planet also acts as a relay to forward the acquired data back to Earth.
An example of a single probe mission (no WSN)

Galileo mission, *atmospheric probe* on Jupiter:

First probe to sample the atmosphere of a gas planet

**Data collected:**
- Local weather:
  - wind speed
  - temperature
  - pressure
  - chemical composition
  - sunlight energy
  - lightning

**Radio:**
- 1.4 GHz
- Crossed dipole pair antenna

**Total energy stored:**
- 700Wh
### Single probe mission vs. WSN based missions

#### Scientific & technical considerations

<table>
<thead>
<tr>
<th>Complex sensing involving long-range measurements (spectrometry, Lidar, optical, imaging)</th>
<th>Single instrument</th>
<th>AD-HOC WSN</th>
</tr>
</thead>
</table>
| • Largely reported on past missions.  
• Can provide a large amount of data with a single probe. |  | • Difficult due to:  
• miniaturization (physical limit on sensor size)  
• fabrication cost  
• amount of data provided |

<table>
<thead>
<tr>
<th>Localized simple measurements (temperature, pressure, gas sensing, humidity, light intensity)</th>
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| • Reported on past missions.  
• The data is only provided for a single location on a planet or asteroid. |  | • Never tested with large amount of probes (N>2)  
• Could enable mapping over a large area or volume and for a long period of time.  
• Robust due to the AD-HOC network structure |
## Single probe mission vs. WSN based missions

### Economic considerations

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<td>• High reliability of each element required.</td>
<td>• High global reliability of WSN required.</td>
<td></td>
</tr>
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<td>• Each element fully space qualified.</td>
<td>• Off the shelf WSN do not match space requirements.</td>
<td></td>
</tr>
<tr>
<td>• Never off the shelf elements.</td>
<td>• Few off the shelf sensors are suitable.</td>
<td></td>
</tr>
<tr>
<td>• Very costly</td>
<td>• Costly.</td>
<td></td>
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<td>• Some off the shelf sensors exist.</td>
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<td>• Very costly</td>
<td>• Could become a less costly exploration method.</td>
<td></td>
</tr>
</tbody>
</table>
Example WSN scenarios based on moving nodes

Scenario 1.1:

Cloud of sensing nodes (5-100) falling in the atmosphere of a planet (Venus). The relay falls along with the nodes.

Typical data collected:
- p, T, light intensity, (spectrum)

Technical “+”: Low stored energy required, short lifetime required
Technical “-”: Evolving data routes
Scientific interest: moderate

Scenario 1.2:

Data collection with network of sensor nodes rebounding on the ground of a low gravity solar system objects.

Typical data collected:
- Acceleration at rebound
- ground surface nature

Technical “+”: communication without obstacle
Technical “-”: Quickly evolving data routes
Interest: TBD

Scenario 1.3:

Network of sensor nodes using energy scavenging and individual node propulsion.

Typical data collected:
- T,p, wind, atmosphere spectrum --> gas composition, (seismic)

Technical “+”: simplified distribution, slow motion and network update
Technical “-”: obstacles to wave propagation, long lifetime
Scientific interest: long term exploration, great interest

Typical data collected:
- p, T, light intensity, (spectrum)
Scenario 2.1:
Data collection with network of sensor nodes attached to the surface of a low gravity solar system objects.

**Typical data collected:**
- Acceleration (seismic data) during a specific event
- \(\rightarrow\) mass repartition, etc

**Technical “+”**: No communication needed during measurement

**Technical “-”**: Large acceleration at impact

**Scientific interest**: could be of great interest

Scenario 2.2:
Data collection with network of sensor nodes laying on the ground of planets or moons.

**Typical data collected:**
- \(T, p, \) wind, atmosphere spectrum, (seismic)

**Technical “+”**: Slow data rate

**Technical “-”**: Wave propagation depends on the roughness of the planet surface

**Scientific interest**: significant interest to measure in a distributed fashion with simple sensors.
## Node distribution methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Drawbacks</th>
<th>Typical missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial momentum</td>
<td>Simplicity</td>
<td>Could involve high accelerations</td>
<td>Atmospheric &amp; ground measurements</td>
</tr>
<tr>
<td></td>
<td>Small node size</td>
<td>Not accurate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Could allow large distance distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dropped from a spacecraft</td>
<td>Simplicity</td>
<td>Could involve high accelerations</td>
<td>Atmospheric &amp; ground measurements</td>
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<td>Could allow large distance distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed with a rover</td>
<td>Accurate distribution</td>
<td>Time consuming</td>
<td>Ground measurements</td>
</tr>
<tr>
<td></td>
<td>No need for node self-localization</td>
<td>Limited range</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Small node size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individual propulsion</td>
<td>Low accelerations</td>
<td>Very complex</td>
<td>Atmospheric &amp; ground measurements</td>
</tr>
<tr>
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<td>Could enable an accurate distribution</td>
<td>Large node size</td>
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</tbody>
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## Node localization techniques

<table>
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<tr>
<th><strong>Technique</strong></th>
<th><strong>Advantages</strong></th>
<th><strong>Drawbacks</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic wave propagation delay</td>
<td>Can be very accurate&lt;br&gt;Continuous self-localization</td>
<td>Ambiguity due to multiple reflections&lt;br&gt;Could require UWB which might not be ideal for long distance communication</td>
</tr>
<tr>
<td>Signal strength</td>
<td>Simplicity&lt;br&gt;Continuous self-localization</td>
<td>Not accurate</td>
</tr>
<tr>
<td>GPS type</td>
<td>Accurate&lt;br&gt;Well established&lt;br&gt;Continuous self-localization</td>
<td>Large infrastructure required, numerous satellites orbiting</td>
</tr>
<tr>
<td>Optical</td>
<td>Can be accurate</td>
<td>Need to rely on central data processing (at the base station)&lt;br&gt;New development&lt;br&gt;Continuous self-localization difficult</td>
</tr>
</tbody>
</table>
Example specifications of a node network fixed on the ground, scenarios

Estimated typical node network on the ground of a solar system object. Specifications will be different for different missions.

<table>
<thead>
<tr>
<th>Node # &amp; distance</th>
<th>Localization</th>
<th>Typical sensors</th>
<th>Data rate of each node</th>
<th>Sensor power</th>
<th>Power @ 1 node for the transceiver</th>
<th>Total power/node</th>
<th>Total energy active 1 hour/day 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 nodes 1 km</td>
<td>Required</td>
<td>T, p</td>
<td>4 byte/h</td>
<td>20 $\mu$W</td>
<td>1mW</td>
<td>1mW</td>
<td>365mWh</td>
</tr>
</tbody>
</table>

Power/transmission distance relation:

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

Depending on the transmission media:

- $3<n<5$ antenna on the ground with reflections
- $n=2$ in free space
As seen above there are many possible scenarios for using WSN for distributed exploration of planets, their atmospheres, asteroids...

The e-CUBES space demonstrator (on earth) will perform distributed measurements in the atmosphere, demonstrating key general features:

- ad-hoc mesh network with rapid dynamic networking
- self-localization with coordinates transmission through the network
- long-range communication (5 km)
Are Commercial WSN platforms suitable for space exploration?

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• AD-HOC functionality</td>
<td>• not space qualified</td>
</tr>
<tr>
<td>• relatively low power</td>
<td>• do not provide localization</td>
</tr>
<tr>
<td>consumption</td>
<td>• have usually a short transmission range &lt; 200 m in outdoor</td>
</tr>
<tr>
<td>• robust transmissions</td>
<td></td>
</tr>
<tr>
<td>• can be interfaced with</td>
<td></td>
</tr>
<tr>
<td>analog or digital sensors</td>
<td></td>
</tr>
</tbody>
</table>

Can be suitable for concept evaluation on earth

WSN for space exploration need additional development in order to meet mission requirements
e-CUBES “Space” Demonstrator

5 nodes, each on one paraglider. One additional fixed node on the ground serves as gateway, while the others fly around for several hours, covering up to 10x30 km². Demonstrate:

- **Dynamic self-organized** Mesh network, with links up to 5 km, data point transmitted every 1-20s.
- **Localization** (via GPS) & coordinates transmission through the WSN
General considerations on algorithm & software
(differences between space and terrestrial WSNs)

Specific requirements of WSN for space exploration:

- Mobility of the nodes
- Localization of the nodes required (need to know accurately the location of the measurements)
- High sampling rate for dynamic scenarios
- Heterogeneous network is acceptable (sensing and relay nodes)
- Size, weight, calculation and power limitations for the sensing nodes, but not for the master node located in the space craft
- Highly fault tolerant

Centralized vs. decentralized approach:

- Centralized approach takes advantage of the larger resources (RF transmit power, antenna size, computation power…) available to the master node.
- Decentralized is most useful when the access point to the network is changing and direct communication from the master node toward sensing node is not feasible or not guaranteed. Also best for networks having very large numbers of nodes (>1000)
We choose, due to the high sampling rate, a WSN organization where nodes spontaneously sample and transmit data toward the master node.
### Example of specs (highly mission dependent)

<table>
<thead>
<tr>
<th></th>
<th>Demo in Earth atmosphere</th>
<th>Mission in Venus Atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td># of nodes</td>
<td>5-10</td>
<td>50-200</td>
</tr>
<tr>
<td>Relay/Gateway</td>
<td>On ground</td>
<td>Falling with nodes (numerous relays possible)</td>
</tr>
<tr>
<td>Localization</td>
<td>GPS</td>
<td>LIDAR or RF TOF</td>
</tr>
<tr>
<td>Size</td>
<td>200 cm³ (without GPS)</td>
<td>3 cm³</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>868 MHz</td>
<td>868 MHz or other</td>
</tr>
<tr>
<td>Power supply</td>
<td>Lithium battery (~2Ah, 3.6V)</td>
<td>Battery</td>
</tr>
<tr>
<td>RF power</td>
<td>Max allowed by regulation</td>
<td>Unregulated</td>
</tr>
<tr>
<td>Node speed</td>
<td>&lt; 10 m/s</td>
<td>&lt; 100 m/s</td>
</tr>
<tr>
<td>RF range between cubes</td>
<td>5 km</td>
<td>25 km (from Relay to Orbiter&gt; 1000 km)</td>
</tr>
<tr>
<td>Minimum data rate per node</td>
<td>64 bit/s</td>
<td>640 bit/s</td>
</tr>
<tr>
<td>Operating time</td>
<td>1 hour</td>
<td>4 hours</td>
</tr>
<tr>
<td>Radiation tolerant</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Environment</td>
<td>Benign</td>
<td>Corrosive</td>
</tr>
</tbody>
</table>
“Space demo” hardware

• For demonstration, cannot wait for integrated e-CUBES radio, nor can we expect an e-CUBES radio to meet the range (>5km). So we modified node hardware from partners in a Swiss project.

• Hardware and mesh networking software is based on product and research from IP01 (Neuchatel, Switzerland) and IMT, University of Neuchâtel.

• Main modification to existing hardware is integration of GPS for each node and modification of antenna

• Software modified to allow true multi-hop networking

Characteristics:
- Output amplifier power = 13.5 dBm, dipole antenna gain = 2dBi
- Consumption: sleep = 2µA, active = 300 µA
- Sensitivity = -112 dBm
eCUBES “Space demo” hardware

- Master node
- Sensing node
- GPS
- Wireless communication
- I2C communication
Initial Test results: Real time localisation

The database on the master node is automatically filled during the test, as the paragliders fly with the nodes.

A PHP program extracts coordinates from a database and exports them into a Google Earth file (.kml) after a sorting process. The visualization can be done during the deployment enabling the tracking of the nodes. Post visualization allows to analyze communication losses while providing a 3D view.

Localization data obtained by GPS was sent every 5 seconds to the ground. Self-Localization was thus demonstrated.

The maximum distance of communication is over 6 km in direct line of sight.

The goal is not to simply to get GPS data from paragliders, as this could be done by GPS logging, or GPS + mobile phone. The Goal is to show long-range multi-hop data transmission, with GPS as an example of self-localization.
See related movie of paragliders carrying the nodes for details on node placement in backpack and testing environment.
Test results: Mesh functionality of a dynamic WSN (1)

We tested a reconfigurable mesh network with up to 5 nodes transmitting in real time sensed data (location) through the network using the multi-hop functionality.

The sampling time was increased from 5 to 12 s to guarantee no data loss due to network congestion even when the nodes are organized in a chain having 5 communication hops.

The nodes were flying at a ground speed of about 10 m/s.
Test results: Mesh functionality of a dynamic WSN (2)

During the flight we observed situations where the data followed up to three hops to reach the base station. This occurred for different source nodes.

This demonstrated the multi-hop mesh network behavior.
Achievements & Observations

• A WSN with communication distance in the 5 km range, self-reconfiguration and multi-hop capability, and ability to determine node location was successfully tested during 3D displacement of up to 5 nodes at ground speed of 10 m/s

• The data (location of the nodes), was sent through the network by multiple hops to the base station allowing live tracking of their position

• We observed that the communication algorithm, amount of data transmitted and sampling rate largely influence the capacity of network to withstand large node number

• Commercial WSN products are rapidly improving and are coming close to meeting the requirements for a simple exploration mission

• An important open challenge is the node self-localization (that would obviously have to be done without GPS/Galileo in a real mission)
Optimization and Perspective

• The communication algorithm can be optimized to achieve higher sampling rate with more nodes while maintaining high robustness

• Earth testing for situations similar to a Space exploration scenario can be the basis for providing the input parameters to simulations of real exploration scenarios

• Two approaches can be followed:
  • mission oriented developments
  • generic developments that can provide adaptable WSN for a group of missions

• Mission oriented developments will allow to achieve better performances, but will be much more costly and time consuming

• Generic WSN can be an approach much less costly on the long term, taking advantage of the versatility of WSN:
  • for instance WSN with hardware and software modularity can be foreseen

• The size and weight of the nodes shall not be an issue in the future since new developments will provide tiny nodes of about 1-5 cm³ capable of withstanding harsh environments