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Wireless Sensor Networks for Planetary Exploration: Experimental Assessment of Communication and Deployment

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Abstract

Planetary surface exploration is an appealing application of wireless sensor networks that has been investigated in recent years by the space community, including the European Space Agency. The idea is to deploy a number of self-organizing sensor nodes forming a wireless networked architecture to provide a distributed instrument for the study and exploration of a planetary body. To explore this concept, ESA has funded the reseach project *RF Wireless for Planetary Exploration* (RF-WIPE), carried out by GMV, SUPSI and UPM. The purpose of RF-WIPE was to simulate and prototype a wireless sensor network in order to assess the potential and limitations of the technology for the purposes of planetary exploration.

In this paper, we illustrate the results of the work carried out within the context of RF-WIPE. Two test case scenarios have been investigated: a distributed sensor network-based instrument and networked planetary surface exploration. Each scenario is related to a particular network configuration. For such configurations, energy models and communication protocols have been developed, simulated, and validated both on laboratory tests and with

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outdoor field tests. Additionally, node deployment was investigated, and a deployment system based on a mobile robotics platform has been designed and tested.

Keywords: Wireless Sensor Networks; Planetary Exploration; Automatic Nodes Deployment

1. Introduction

Wireless sensor network (WNS) technologies are a great fit for space exploration (in particular, in planetary exploration) since their nodes offer a small form factor, low power consumption, and self-healing capability. They can be used in many types of exploratory missions and their use may boost the scientific capability of planetary surface missions. For example, in order to prepare for future human exploration missions, WSNs can be employed to collect more accurate and extensive planetary surface data.

Compared to large monolithic planetary probes, WSNs can collect heterogeneous measurements over larger areas and longer periods of time. For instance, WSN are 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 WSN when compared with traditional instruments are: better spatial and temporal sampling capabilities, higher reliability, reduced payload weight, lower overall costs, and faster deployment.

Such characteristic make WSN a unique opportunity to gather spatio-temporal data in a manner that would be difficult, or even impossible, to collect with methods and techniques based on the traditional approach, using large monolithic instruments.

A set of recommendations and priorities were identified within the "Wireless for space exploration" workshop organised by ESA in July 2006 (Magness, 2010):

- to promote the use of low power sensor networking for space exploration.
- to promote the introduction of wireless techniques in support to the AIT (Assembly, Integration and Test) process.

The RF-WIPE study focuses on the former topic, and its activities were meant as a first step towards the full characterisation of suitable scenarios for

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WSNs. The main objectives were the modelling, simulation, and evaluation of two different WSN topologies.

The paper is structured as follows. The remainder of this section describes the framework of the RF-WIPE project, the test cases chosen and the rationale of such choice. Section 2 describes the communication issues. Section 3 describes the preliminary laboratory simulations aimed at modelling the power model and testing the routing protocol, and reports on the field tests of the sensor network. Section 4 illustrates the robotic deployment means developed and the deployment tests. Finally, Section 5 discusses the results of the project.

1.1. Reference scenarios

Based on a survey of missions and possible scenarios identification (see (Medina et al., 2010) for more details, summarised in Tables 1 and 2), we established two representative study cases. These are the ones that have been taken forward for breadboarding and proof-of-concept:

- **Distributed Sensors Web Instrument**. 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 data used to map the target planetary area.

- **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.

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 following sections highlight the major wireless sensor network operational constrains. In Section 4, the requirement for automated deployment will be outlined.

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Table 1: Surface data retrieval scenarios

Mission scenario	Description	Target body
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.	Moon, Mars, NEO
Jumping nodes	Rolling and jumping nodes.	Moon, Mars, Venus, Titan
Anchored nodes	The sensors are equipped with anchoring means to remain fixed to the ground in case of wind.	Mars
Aerodynamic nodes	The wireless are covered with aerodynamic cups allowing them to move on the surface due to the planetary wind.	Mars

Table 2: Aerial data retrieval scenarios

Mission scenario	Description	Target body
Falling sensor network	The sensor network is falling through the atmosphere of a planet. The nodes are released by an orbiter or atmospheric element.	Mars, Venus, Titan
Atmospheric microprobes	Mobiles atmospheric microprobes.	Mars, Venus, Titan
Bouncing nodes	Clouds of nodes that would rebound on the surface of a low mass object.	NEO

1.1.1. Sensor deployment

In a WSN the node deployment is not straightforward since it affects both the network lifetime and the choice of the node localisation system to be used. A random node placement is simpler to manage but fails to take into consideration the structure of the investigated area (e.g. obstacles positions, craters etc.). In this case the network typically experiences connectivity issue;

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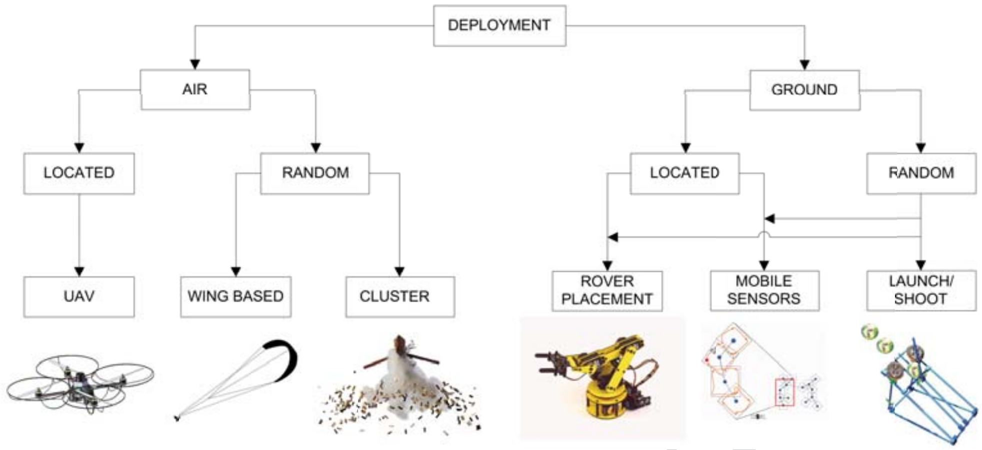

Figure 1: Deployment alternatives. At the top level, either aerial (both flying and atmospheric) and ground deployment can be defined. At the next level, random (uncontrolled) or located (controlled) deployment can be chosen for both aerial and ground deployment. At the last level, examples of means are depicted (autonomous aerial vehicles, parachuted, dispersed, deployed by a rover, by a launcher or mobile nodes.

for instance, there may be islands of high density of nodes connected with a few number of nodes that form bottlenecks. This situation is very costly in terms of network lifetime, since the nodes in the bottlenecks are overused and deplete their energy reserve in a short time resulting in network partitioning.

Multiple strategies may be used to deploy WSNs in case of exploration scenarios. Example of those might be (see also Fig. 1):

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 are particularly applicable to atmospheric and ground measurements, solutions 4 and 5 are directly applicable to ground measurements missions. Additionally, the listed strategies are

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also characterised 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 present 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.

1.1.2. Node localisation

Node localisation technology needs further development before it can be used for WSN exploration. As a general concept for WSNs the device costs will need to be low, sensors will need to last for years or even decades without battery replacement, and the network will need to self-organise with as little outside intervention as possible.

Clearly, localisation techniques like global positioning system (GPS) do not apply due to the lack of the satellites system needed as references for the GPS system. A possible solution has been proposed by the Aerospace Robotics Lab of the Stanford University[1]. The idea is to use GPS in a local area using small ground-based GPS transmitters called pseudolites (pseudo-satellites). A disadvantage of this approach is that all previous work with pseudolites required that the pseudolite locations be known at centimetre-level accuracy, which would be difficult to achieve placing such devices on another planet.

Hence, the localisation problem in wireless sensors networks can be solved in a distributed way, with nodes discovering each other other and estimating ranges between them, which serve as *relative* position references. Several location estimation models and algorithms have been proposed such as: time of arrival (ToA), time difference of arrival (TDoA), angle of arrival (AoA), received signal strength (RSS), Trilateration and Multilateration (Ji and Zha, 2003). An important requirement, in this case, is a distributed approach that minimises computational, and especially communication, overhead, and is robust enough to survive disconnection.

1.1.3. Sensor/network lifetime

Lifetime is extremely critical for most applications, and its primary limiting factor is the energy consumption of the nodes. It is often desirable for

[1]http://sun-valley.stanford.edu/users/rover/

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nodes to be capable of local power generation, for instance by means of energy harvesting (these aspects, however, have not been investigated within the scope of RF-WIPE). Although it is often assumed that the transmit power associated with packet transmission accounts for the lion's share of power consumption, sensing, signal processing and even hardware operation in standby mode consume a consistent amount of power as well (Puccinelli and Haenggi, 2005).

In some applications, extra power is needed for macro-scale actuation. Many researchers suggest that energy consumption could be reduced by considering the existing interdependencies between individual layers in the network protocol stack. Routing and channel access protocols, for instance, can greatly benefit from an information exchange with the physical layer (Puccinelli and Haenggi, 2010).

Using low-power mode for the processor is generally advantageous, and duty cycling the radio at the link layer and/or the application layer is imperative.

Medium Access Control (MAC) solutions have a direct impact on energy consumption, as some of the primary causes of energy waste are found at the MAC layer: collisions, control packet overhead and idle listening. Energy-saving forward error control techniques are not easy to implement due to the high amount of computing power that they require and due to the fact that long packets are normally not practical. Energy-efficient routing should avoid the loss of a node due to battery depletion. Many proposed protocols tend to minimise energy consumption on forwarding paths, but if some nodes happen to be located on most forwarding paths (e.g., close to the base station), their lifetime will be reduced. In order to guarantee a large mission operational lifetime, different strategies shall be applied in order to minimise the sensors power consumption.

1.1.4. Physical channel

There are different physical phenomena and parameters that affect the physical channel. They can be classified in three different categories:

- Controllable at the design stage: antenna gain, antenna characteristics, EIRP;
- Environmental-dependent: the ground topology (e.g. obstacles, craters), the ground composition and its conductivity, other environmental factors (e.g. humidity, wind, ...);

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- Physical constraints: large-scale path loss, multipath fading, and shadowing.

The first category is controllable during the node design phase. Moreover, its influence on the physical channel is well known and can be considered as time invariant. On the second category, it is not possible any human intervention. However, its influence on the channel can be known. Furthermore, apart from the wind, that is unpredictable, the other environmental factors are completely understandable. Finally, the last category is the most relevant in terms of influence on the RF propagation. The large-scale path loss depends on the distance between the wireless terminals, fading is due to the particular reflection patterns of the deployments area, and shadowing is due to obstacles that interrupt the line-of-sight between terminals. Multipath fading has a distinct impact on the fragility of wireless links. It is considered a small-scale phenomenon in the sense that the level of attenuation of the signal changes substantially if the position of the receiver or the transmitter is varied by about half a wavelength.

One of the most common features of wireless sensor networks is that the nodes are usually static; static multipath fading is therefore of particular interest. Another physical phenomenon of interest is shadowing. It is considered a large scale effect, as it corresponds to substantial deviations of the RF signal from its mean due to large obstacles, which create shadow zones that cause deep fades if a receiver happens to enter them. Although the impact of multipath fading is particularly strong in rich scattering environments such as offices and other indoor locales, outdoor deployments of wireless sensing nodes are not immune to it. Radio waves still get reflected off buildings and other landscape features. Multipath fading and shadowing contribute to the volatility of wireless links and must be accounted for when modelling the wireless channel. When the analysis of a higher-layer scheme (typically medium access and routing algorithms) is carried out, realistic assumptions must be made about the physical layer.

The large-scale path loss is often used to identify an area of successful reception according to the disc model, but this approach is strongly inadequate for the description of wireless sensor networks, as it overlooks the large deviation between the strength of signals measured by receivers equidistant from a transmitter. The Rayleigh fading model (Rappaport, 2001) assumes the absence of a dominant path, whereas it is often the case that sensor nodes are linked by a line-of-sight path; however, its analytical tractability presents

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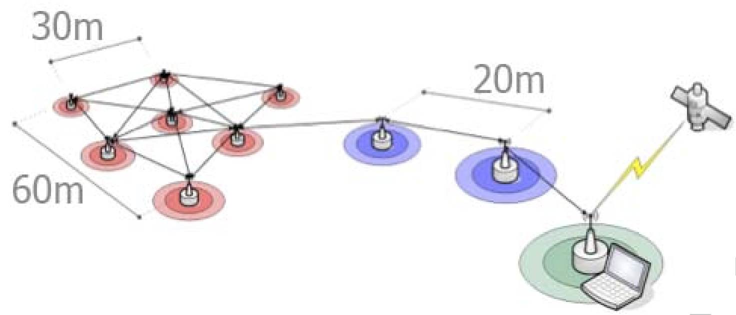

Figure 2: Test case configurations: Distributed sensor network. Here, a mesh topology is considered, with a number of rely nodes that connect the network to the sink.

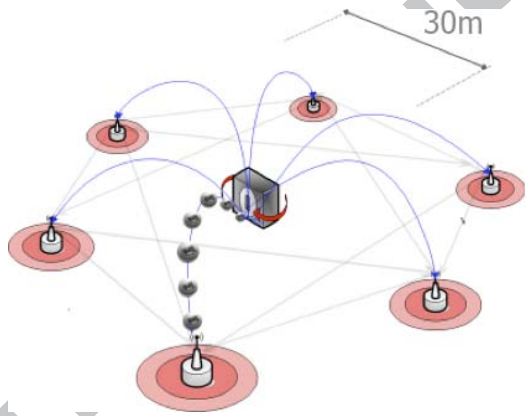

Figure 3: Test case configurations: Networked planetary surface exploration. Here, all nodes can communicate directly with the sink, although alternative paths are possible.

it as a very reasonable compromise between the simplistic disc model and the unwieldy Ricean fading model; moreover, the fact that it assumes the absence of a dominating line-of-sight path makes it a worst-case model.

2. Communication

Two scenarios have been selected because of their different network topologies that offer good examples of distinct conditions. In the first topology, the mesh in Figure 2, a mesh of relays offers extensive connectivity to the sink over multiple hops. The challenges for this topology are manifold:

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- to implement a multi-hop communication strategy whenever there is not a direct connection between the nodes and the sink
- dynamically change the data path in case of changes of the connectivity inside the network (e.g. climate changes, obstacles, node failures, etc.)
- minimise the energy consumption to maximise the network lifetime.

The second topology selected, (Figure 3), offers the possibility to sense an extended area around the lander. Every node can communicate directly with the sink, even though rerouting may be required in case of shadowing effects due to possible incoming obstacles (e.g. rocks falling in the middle of the path). As for the first topology, also in this case it is required to minimise the energy consumption for prolonging the network lifetime as much as possible.

In order to tackle the challenges specified above we have adopted different measures of intervention [2]:

- we have implemented the Arbutus routing protocol (Puccinelli and Haenggi, 2010), whose control plane selects the least cost paths in terms of number of hops, data transfer, and energy consumption (see Section 2.1),
- we have implemented a dynamic acquisition algorithm that is able to tune the sampling frequency of the sensor nodes accordingly with the variations of the sensed parameters, in order to reduce the energy consumption on the node (see Section 3.3),
- a sleep mode strategy has been implemented on the sensor nodes in order to prolong as much as possible the network lifetime. Our strategy consists in putting to sleep wireless sensor and awake them only when data are acquired or transmitted, or on demand (when queried for data).

2.1. Routing protocol

Due to their resource limitations, low-power wireless sensor networks (WSNs) pose considerable communication challenges. One of the most significant is preventing packet loss while maintaining an acceptable goodput. Aside

[2] Due to the nature of the data gathered, data compression issues have not been considered here. However, they should not be underestimated (see e.g. (Pham et al., 2010)).

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from catastrophic problems such as hardware or software failure, packet loss may occur due to channel errors, congestion-induced buffer overflow, and protocol-level inefficiencies. Wireless propagation effects such as large-scale path loss, shadowing, and multi path fading contribute to the attenuation of the signal power. In (Zhao and Govindan, 2003), (Woo et al., 2003), (Zamalloa and Krishnamachari, 2007), it is shown that a transitional reception region separates a region with high connectivity from a disconnected region, and asymmetric links are shown to be common in the transitional region: wireless connectivity is neither Boolean nor bidirectional. Differently from high-end wireless networks such as WLANs or mobile ad hoc networks (MANETs), low-power WSNs typically employ low-end transceivers with a low maximum transmit power (typically $0dBm$), and are therefore completely exposed to the vagaries of RF propagation. Link estimation is instrumental in limiting channel-related packet loss and minimising the number of retransmissions. Channel-related losses are also caused by interference: for instance, CSMA-based MAC layers, common in WSNs, are exposed to hidden node effects. Congestion is particularly severe in WSNs due to their typical many-to-one traffic pattern, which may lead to buffer overflow depending on the network topology. Network protocols may also be responsible for additional losses, for instance due to routing loops and egress drops (the elimination of packets that are erroneously believed to be flawed, such as false duplicates). Incompatibility between protocols pertaining to different layers may also be conducive to a significant performance degradation. An example is the use of a network protocol that requires promiscuous mode operation for link estimation along with a MAC protocol that avoids snooping to save energy (Langendoen et al., 2006).

Many routing solutions have been proposed in the literature, but only a handful of them have been implemented and tested on low-end nodes. In (Lu et al., 2007) a distributed routing protocol that take advantage of multiple node-disjoint paths between the sink and source nodes has been proposed. Its energy efficiency has been demonstrated trough simulations. The most strenuously tested and heavily used solutions are distributed tree-based schemes that target homogeneous networks. In particular, the MintRoute family (Woo et al., 2003) has formed the core of the TinyOS (Hill et al., 2000) network layer over the past years and has recently led to the Collection Tree Protocol (CTP) (Gnawali et al., 2009).

Our focus is on the same corner of the routing design space as the MintRoute family, and we select Arbutus, a routing protocol for data collection applica-

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tions of low-power WSNs that seeks to achieve high reliability as well as to maximise the goodput given the reliability constraint (Puccinelli and Haenggi, 2010). The main principle behind the Arbutus architecture is that routing over a few long hops can be much more efficient than routing over many short hops (Haenggi and Puccinelli, 2005); (Wang et al., 2006). By long hops, we do not mean higher transmit power: the transmit power is assumed to be the same independently of whether a hop is long or short. The hop length is completely determined by the physics of wireless propagation and is qualitatively said to be short or long compared to the hop length expected on the basis of the large-scale path loss. Due to a particularly favourable (or unfavourable) fading state, a hop may be significantly longer (or shorter) than expected from the large-scale path loss (Puccinelli and Haenggi, 2006). Routing over many short hops means always minimising the large-scale path loss, while routing over fewer long hops means leveraging on positive fading states. The Arbutus architecture employs existing tools and recent results along with two main elements of novelty: a tree construction scheme built into the link estimation level that represents the centrepiece of the architecture and provides a practical way to enforce long-hop routing, and the treatment of congestion control as a first-order problem. We build our applications on top of a TinyOS 2.x implementation of Arbutus described in (Puccinelli and Haenggi, 2010), which in turn relies on the standard CSMA-based MAC layer.

Arbutus has been extensively tested, proving its effectiveness in networks of the order of hundreds of nodes (see, e.g., Puccinelli and Haenggi (2010)).

3. WSN Modelling and Simulation

Simulation is a key factor in WSN system design. Since exiting simulators are not flexible enough, in our project we had to construct a reliable power model in order to analyse carefully the energy consumption of the whole networks during its working operations. Thus, the model and simulation activities have been performed starting from the wireless sensor node architecture including the node characterisation, the environment characterisation and eventually the wireless sensors networks architecture, and the communication and routing protocols. Figure 4 illustrates the modelling and simulation activities workflow.

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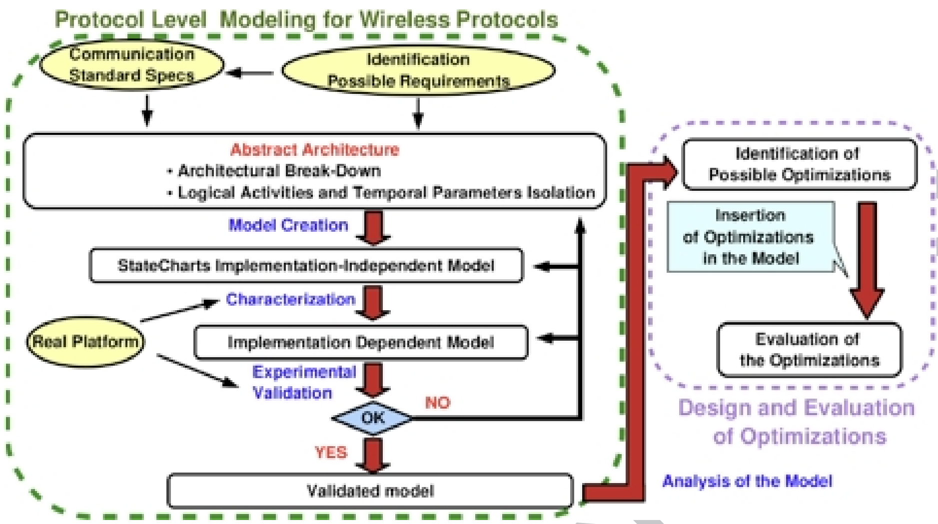

Figure 4: Block Diagram of the Modeling and simulation activities.

3.1. Modelling

In this phase all the characteristics that are relevant for the wireless sensor node and the interaction between the node and the environment, and the interaction among different nodes have been modelled. The model received in input the following parameters:

- node dependent (i.e. antenna and transceiver characteristics, sensors and microcontroller power consumption, ON/OFF transient time and so on);
- environment dependent (i.e. atmospheric condition)
- exploration scenario dependent (i.e. obstacles, distance between nodes, others)

As a function of the above parameters the outputs of the model were the behaviour of the single node in relation to: the chosen node architecture, the interaction between the node and the environment in the specific exploration scenarios, and the interaction among different nodes. The node behaviour was also modelled in relation to some simple obstacles: partially sight obscuration (fading) and totally sight obscuration (fading plus shadowing).

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3.1.1. FSM-Based Protocol-Level Power Modelling

The use of power models is by now a very well established and widely used, in design of wireless networks as well as in most ICT-related design environments. Focusing in particular on wireless sensor networks, a power model allows evaluating management policies and optimisation techniques from design of the radio up to sensor distribution, routing strategies and application-level policies. When suitably validated and characterised, a power model simplifies design procedures as simulation can be used instead of experimental measurements; a model is an instrumental tool for Design Space Exploration. We introduced Protocol Level Modelling (Negri et al., 2004; Mura et al., 2007), extending the concept of functional breakdown to the networking context. Such methodology, further revised and extended in order to be used in a wider set of analysis, is used for this RF-Wipe activity. Protocol Level Modelling allows exploiting the fact that communication between network nodes is regulated by well-defined standards and that therefore, no matter what the particular device used, its behaviour when interacting with other devices is defined in an accurate and device-independent way. Thus, just as a functional-level power can be devised starting from the abstract architecture of a device and then characterised for specific implementations (Negri et al., 2004), a protocol-level power model can be derived in an abstract way from the standards definition, representing node actions and interactions, and then characterised for specific node implementations. Protocol-level modelling is based, on one side, on the fact that a macro action can be decomposed into smaller actions to be executed in sequence and, on the other side, on the fact that it is possible to parameterise certain values inside the model and assign them a numeric value after the characterisation phase. It is thus possible to evaluate optimisation policies with reference to various implementations. Macro-Operations (e.g. Scanning, Data Transmission etc) are modelled as imposed by the standard and result in a sequence of local operations performed by concurrent Finite State Machines (sequences of operations define paths in such FSMs).

The models reflect the layer structure of the protocol: an FSM modelling a higher layer of the protocol describes the Macro-Operations proper to such layer by means of paths through corresponding states, which in turn activate the FSMs at the lower layers of the model that annotate power/energy consumptions. Architectural breakdown is operated so that different components are correlated to the various lower-layer FSMs. Models can be extended

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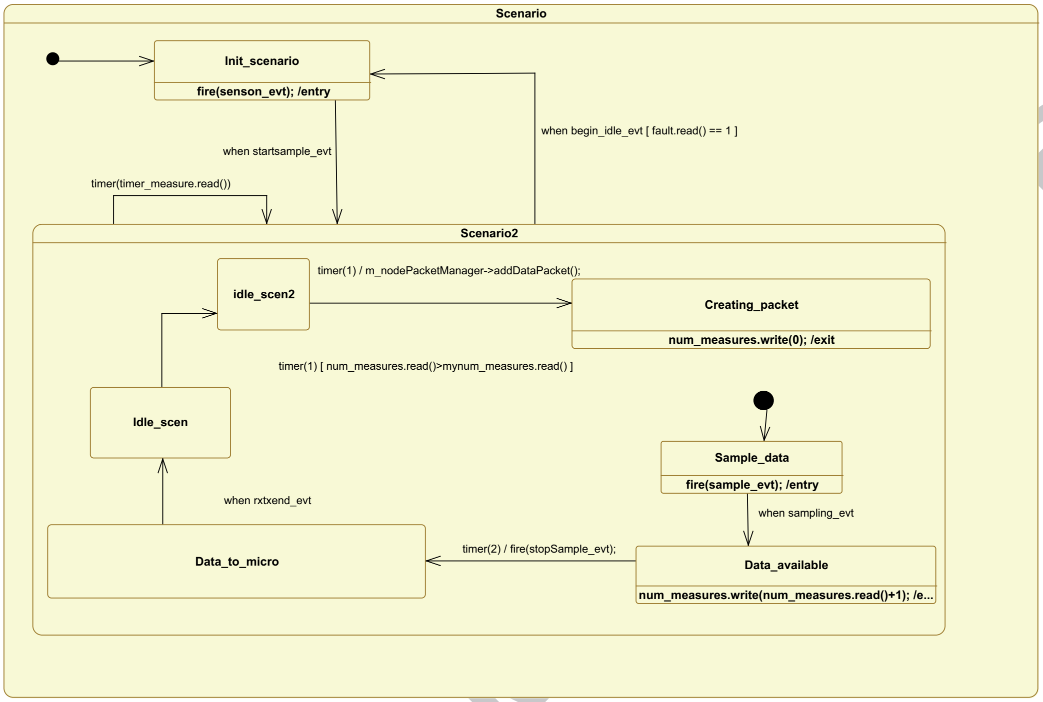

Figure 5: Application Scenario Finite State Machine Diagram

in depth: it is possible to model further layers of a Communication protocol (e.g. Networking, Transport etc) using as a base the layers already modelled. In this case the new layers will invoke behaviour of the FSMs of the lower layers resulting eventually in the appropriate power/energy annotation. When new behaviour is added to a model, this behaviour can be modelled separately and then inserted as a FSM running concurrently in the model. In the case of WSNs we are in general interested in simulating all the operations of the platforms (i.e. including sensing, actuating, processing and possibly other operations), so that analysis and optimisation can be performed up to the application level. Our hierarchical FSM models can be extended in each individual layer: more components (e.g. new sensors, actuators, coprocessors etc) can be introduced as more physical-layer machines. Figure 5 illustrate an example of FSM, namely the Scenario FSM.

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3.1.2. WSN Abstract Architecture

The design of a WSN, in a classical top-down approach, starts from high-level functional as well as non-functional specifications; even before technological choices are made (e.g., the particular microprocessor system to be used for the sensor nodes, the individual device chosen to sense a given phenomenon, etc.) abstract choices such as the protocol to be used, the generic node and overall network structure, etc., will have to be made. An abstract, implementation-independent model thus derived then allows both to validate the high-level concept of the system and to proceed through subsequent design space exploration steps, by identifying critical points, possibly suggesting optimisations that still comply with the initial specifications, evaluating and comparing alternative implementations. Identifying the different possible sources of power consumption at this stage means then associating power consumption not so much with physical components as with activities to be carried out. To keep the notion we used in the corpus of our research we refer to such power consumption sources as Logical Activities (LAs). To better clarify what LAs really are we give an example: if we are considering the radio activities, we may isolate three different sources of Power Consumption namely Reception, Transmission and Idle. The communication standard (which is part of the abstract architecture) fully defines most of the operations of the nodes with strict timing constraints.

3.1.3. Implementation Independent Model

Starting from the Abstract Architecture identified in the previous point the next step of the methodology is the building of an Implementation Independent Model. The modelling style chosen is that of StateCharts (David and Harel, 1987). FSM-based modelling of protocols is a well assessed approach; moving to StateCharts allows us to explain model hierarchy and concurrency, and to easily relate LAs to the abstract model. The macro-architectural breakdown operated in the previous step is instrumental in order to separate the operation of the various components into different concurrent state machines. For the StateCharts formalisms concurrent machines can communicate through events or variables and this mechanism can mimic the connection between various devices in the platform. Orthogonal or concurrent state machines can be used even to simulate the behaviour of the same component in case it is necessary. *Implementation Independence* is a fundamental characteristic of a protocol-level model. Different physical objects complying with the same protocol share common characteristics as generic macro-activities are imposed

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by communication standards. The model referring to such characteristics should be general enough to be used for all the implementations (after the *Characterisation Phase* discussed in the next section). When modelling behaviour of components that is not strictly prescribed by the standards (e.g. the processing activities of a micro- processor in a networked platform), the level of abstraction should remain high and implementation independence be preserved through the use of *Temporal Parameters*.

3.1.4. Implementation Dependent Model

The Implementation Independent Model obtained in the previous step can then be characterised for a particular platform. The second phase of the modelling approach is thus reached, in which quantitative information is associated with the components of the (purely qualitative) abstract model derived before. Two main operations are performed in order to characterise the model:

- The Logical Activities are associated with the corresponding values for the particular implementation. Such values are typically measured through a set of experiments.

- The Temporal Parameters should be substituted with actual values. Experimental analysis as well as use of specific simulators targeted for the particular real architecture can be used to estimate such parameter.

The Implementation Independent Model is initially validated for some platforms, a phase that may lead to either simplify it (e.g., by verifying that some parts of an over-refined model can be collapsed together) or (more seldom) to detail it (by splitting complex logical activities into composition of simpler ones). Having completed this phase, the validated model can be adopted for extensive use, and it becomes possible to characterise platforms based on data from data sheets or emulators for the software part. Afterwards the methodology we propose can be used for *Design Space Exploration*. In this stage the power consumption parametrically assigned to *Virtual Components* can be substituted with a specific value for the corresponding physical component in the particular platform. We also give the possibility of refining, in a later stage, the StateCharts model for particular implementations. As it was said above, while communication activities are generally fully defined by the standard, other tasks of the platform can differ from one implementation to the other. In the platform independent model it is therefore necessary

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to describe such tasks at a very high abstraction level. In case more details are needed for particular analysis/optimisations at this stage the model can be customised keeping the implementation independent part as a kernel and exploding the machines involving not standardised operation.

3.2. Simulation and Validation

During the simulation phase the behaviour of the WSN as a whole has been simulated in the specific exploration scenarios. During each simulation run some of the input parameters were fixed (like the antenna and transceiver characteristics, obstacles positions, energy consumption), while others were modifiable on the run (i.e. atmospheric conditions, intra nodes distances, microcontroller clock frequency, awake and sleep duty cycle, others).

Each node is assumed to employ a transmit power of 0 dBm and to have a sensitivity of -90 dBm, similarly to mainstream experimental platforms (Polastre et al., 2005). For each node pair, the received signal strength is computed by means of ray tracing.

The outputs of the simulation phase were:

- the energy consumption behaviour of the wireless sensor nodes as a function of the environment parameters, the communication parameters, the network topology and the wireless node architecture;
- the profile of the energy consumption distribution in the whole wireless sensor networks during the simulation as a function of the environment parameters, the communication parameters, the network topology and the wireless node architecture;
- definition of the extreme conditions in which the wireless sensors networks is still able to work (max distance between the nodes, worst atmospheric conditions, max number of node failure)
- definition of the wireless network lifetime as a function of the environment parameters, the communication parameters, the network topology and the wireless node architecture, even in the extreme conditions.

All the outputs coming from the previous two phases have been validated with the breadboarding activities. In particular the output coming from the modelling phase have compared with the measurement results obtained with the wireless network implementation. Then, they were adjusted with the breadboard result data and the simulation have been rerun with the new model refined.

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3.3. Set-up 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 optimise the power consumption of the nodes, and
- the performance of the nodes platform selected for the real network implementation.

Power Model. 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 (Agilent 34411A 6,5 digit LXI), 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.

Fig. 6 illustrates the results of one such experiments (real consumption vs a simulated consumption). The blue plot represent 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. The average energy consumed wass 0.0674 $A \cdot sec$ (real) vs. 0.0652 $A \cdot sec$ (simulated).

Sampling. In order to qualitatively verify the correct behaviour of the application that implements a dynamic sampling we deployed a very small network with two nodes and a sink in a star topology. The first node was illuminated for intermittent periods of 5 min with duty cycle of 50% with a varying light intensity values. A Luximeter (Steinegger $1mV/Lux$) was used in parallel of the wireless node. The second node was ventilated with hot air for intermittent periods of 5 min with duty cycle at 50%. A Thermometer (FLUKE 52), 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. The results of these tests are reported in table 3. The

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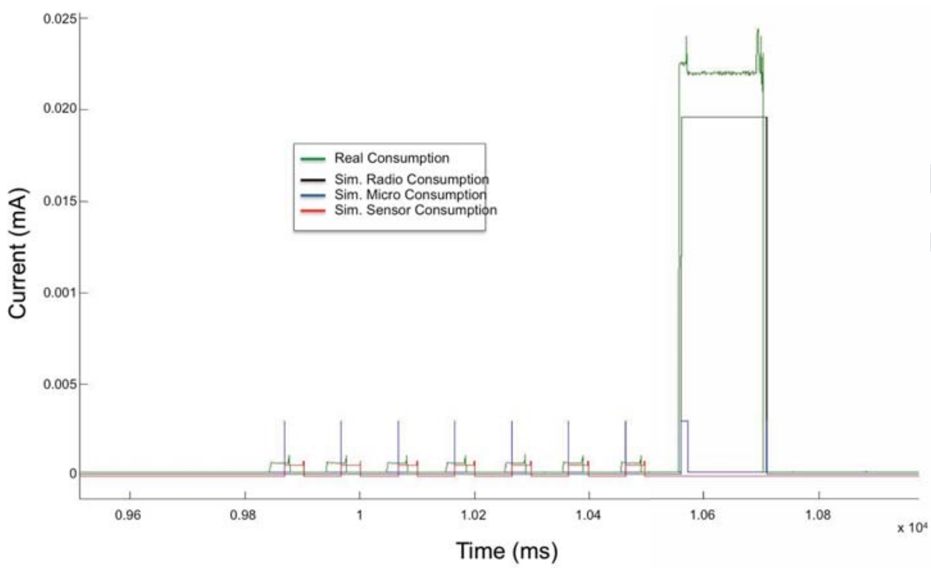

Figure 6: Simulation results: power consumption in simulator vs. real consumption during a periodic task down by the sensor node. The task is the following: the node wakes up, acquire seven samples from the sensor (in this case is light sensor) and then prepare the data packet and send it via the radio and turn off the radio again. The simulation reproduce separately the different current consumption contributions due to the different parts: sensor, micro controller and radio. That means that for the comparison with the real current consumption the three contribution have to be summed up. The small difference (around 2mA) during the transmission phase is due to the LED consumption (used only for signalling that the sensor was transmitting) on the sensor boards that was not considered in the simulator.

first line reports the values related to the case of constant sampling with the maximum sampling interval of 1s, which is fast enough for gathering even fast changes in light. The second line reports the values obtained with dynamic sampling. Dynamic sampling reduces the energy consumption by as much as 94% with a loss rate below 15%.

Performance. Finally, we simulated the two different scenarios objective of this work, in different working conditions: sample and transmit the acquired value every minute and put then the node in sleep mode, for a period of one hour; adding and or subtracting nodes in order to check the capability of the network to react accordingly; simulating changes in the environmental

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Table 3: Dynamic sampling vs constant sampling

	Number of Samples	Normalized Energy	Loss Rate
Constant Sampling	2250	100%	0%
Dynamic Sampling	133	5.91%	14.77%

conditions by adding and then removing obstacles. In all tests the network has demonstrated to behave and react correctly to changes.

In conclusion, the results of the laboratory tests 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.

3.4. Outdoor field tests

The key objective was to design a robustness and reliable system, able to provide the relevant data required. It had to adapt its behaviour to the environmental conditions, operating efficiently in any kind of planetary scenario and minimizing the power consumption.

Thus, a set of 23 outdoor field experiments were carried out in order to assess the performance of the network in real operational conditions. They were performed along one year (it includes rainy and sunny days; cold and hot ones; windy and calm situations) in different scenarios, including both urban and field terrains [3].

Both topologies described in Section 2 were considered during the test, focusing the experiments in their specific problems. Each one of the 16 first test was focused in one specific aspect of the WSN behaviour (e.g. nodes inclusion/removal, topological changes, presence of interferences or obstacles). The rest of experiments tried to evaluate the performance of the system subjected to different problems combined. Special attention was paid to the Arbutus routing protocol, in order to verify its optimum route election and the reconfiguration capacity.

The operational metrics were based on i) packet delay time, ii) packet loss ratio, iii) network reconfiguration time, iv) power consumption and v) unusual event recognition time (for the sunset, sunrise etc.), being possible to summarise the test in 7 different groups:

[3] In Andres Morate's vineyards (Belmonte de Tajo, SPAIN) and in the CAR UPM-CSIC facilities (Madrid, Spain) respectively

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1. Reception at the sink in different circumstances: As the communications are quite dependent from the environment, the correct communication inside the network has been tested in different places and weather conditions. As previously said, both populated and countryside scenarios have been tested, during winter and summer. Rainy and sunny conditions were present. Also, the presence of other equipment that have caused interference and malfunctions in the nodes.
2. System adaptability to environment conditions. Since power saving is one of the main priorities in the project (and also in the WSN topic in general), several experiments were carried out to evaluate the suitability of the dynamic adaptable algorithms. They assessed the adaptive behaviour, checking that its performance is correlated with the environmental conditions. In this sense, it was verified that when unusual events arose (both natural or artificial), the acquisition frequency increased (i.e. the sample time depending on the parameter's magnitude inertia end evolution). The data acquisition was also monitored during smoother changing conditions like sunset and sunrise, observing the appropriate response according to the illumination level.
3. Performance during long periods. As far as reliability is one of the most critical aspects to consider, the temporal behaviour was tested exhaustively, being also appropriate for check the power consumption. Sets of 48 hours - 1minute-acquisition-frequency tests were carried out to assess the time evolution and the device stability (either considering machine cycles, external events/interruptions and batteries performance). The showed that the performance of the network remains the same, obtaining similar packet lost ratios and power consumptions below the expectations
4. Performance in presence of obstacles. As previously said, robustness is one of the main goals of the system. That is why the reliability in presence of obstacles (both static and dynamic, positives and negatives) was carefully assessed. The tests included different obstacles, supposing their density less than 10% of the terrain surface; different sizes (maximum volume was 10 cm^3 10x10x10cm) and several materials (metal, wood and cardboard).

   Furthermore, the experiments were carried out using different terrain

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with different characteristics: sand [4], grass, concrete and pavement were taking into consideration, including slopes lower than 10%. The experiments proved that the system is able to work properly in all these situations, having not significant packet looses (less than 1%).

5. Robustness to failures. It was required the net to be able to manage malfunction in some nodes or connectivity loss. These problems can be external or internal, by anyhow their solution is closely related to re-routing capacity: when one node or one link goes out of service, the rest of the network have to reorganise itself as a new mesh. During the tests, some randomly chosen nodes (max. 3 nodes at the same time) were suddenly switched off, for periods of less than 5 minutes, and then on again, breaking pre-established links during variable periods of time. As it is possible to appreciate in Figure 7, in every configuration the net was able to reorganise itself and and the rest of the nodes continued with its normal execution (except when it was physically impossible because one or more nodes were completely isolated).

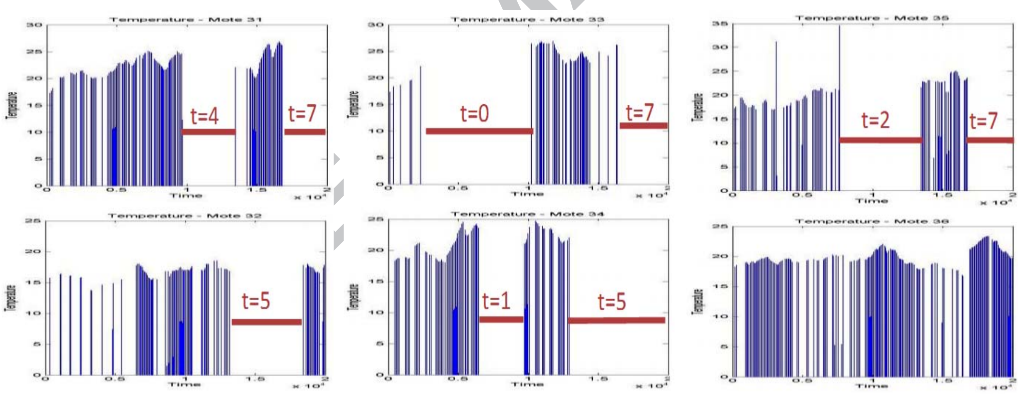

Figure 7: Example of robustness test. During random periods, some random nodes where switched of (first five plots). Nevertheless, the sink received the data of the furthest node during all the test (last plot).

Furthermore, subsequent experiments were done also adding nodes. It was proved that the network was able to reorganize itself in order to integrate the new sensors. Besides, it was also verified that the routing protocol was able to detect the new elements and reorganize

[4]Sand thickness lower than 1 cm in sandy fields)

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Table 4: Key performance metrics.

Metric	Value
Packet loss rate	< 0.01
Average transmission count per hop	1.73
Duplicate suppression rate	0.99

the routes according to the new topology. The access-time time to the channel evolved as expected according to the simulations and was also proved that the inclusion of new nodes provided more alternatives paths for communication -which supposes an increment on the network's performance-.

6. Performance when mobile sink. In the start topology (Second scenario), it has been verified that even moving the sink, the connectivity is guaranteed. The experiments proved that when displacing freely this node around the area covered by the WSN (50m max displacement from its original location), the network is adapted to continue with the operation. No delays or changes in the baud rate were detected, with the exception of the time required for performing the new links in the mesh when rerouting.
7. Robustness when relocation of nodes. The nodes composing the net were displaced o reallocated in order to test the dynamic capabilities of the routing protocol. In the displacement, the nodes were moved in a 3m-radius area from their original location, verifying that the communication was not lost. Instead, in the reallocation tests, the nodes were moved inside the mesh but changing relevantly the topology of the net. It was proved that the routing algorithm re-defined dynamically the links among nodes, generating new paths and maintaining every node communicated.

The results derived from the these tests allow us to draw the conclusion that the system is capable of achieving the desired performance in all the above described aspects, providing the needed characteristics of fault tolerance and adaptability. The results of the field tests compared favorably with the expected performance based on published results achieved in public access testbeds (Puccinelli and Haenggi, 2010), which are summarized in Table 4. Most notably, under standard propagation conditions, the residual packet loss rate is below 1% and is mainly due to false link layer acknowledgements.

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The analysis and processing of the data recorded by the sensor network, compared to the ground truth data acquired with classical instrumentation has shown a satisfactory correlation between the environmental data acquired (temperature, humidity and visible light). Small drifts were detected, but in general were left out thank to the effect of the multi-measure acquisition (median filter of 5-10 values in every acquisition).

4. Deployment system

Node deployment is not a mainstream topic in the well-investigated field of WSNs (Gajbhiye and Mahajan, 2008). In many applications, deployment is a highly controlled process because nodes can be laid out manually. Unfortunately, this is not true for scenarios like volcanoes, natural disaster locations, or planetary exploration.

In these kind of scenarios, and particularly for Planetary Exploration (PE), robotic means are the ideal and perhaps the only option. Several approaches can be found in the bibliography. (Bickford et al., 2005) analyses different methods to perform the deployment, splitting them among ground, aerial and atmospheric systems.

Aerial systems are appealing due to their high mobility and independency from terrain conditions, but extreme environmental conditions such as heavy winds and surface dust storms make then unsuited for the planetary scenario (Corke et al., 2004). Besides, their small payload capacity and autonomy would allow their use only in reduced local areas.

Deployment during atmospheric entry provides a huge actuation area and energy efficiency but does not enable any kind of planning since the deployment is completely random. This problem has been studied in (Bartolini et al., 2011).

The ground deployment provides an acceptable compromise: a ground mobile unit provides better robustness and reliability, as well as a higher payload and power capacity. The path planning and control required is complex but provides higher accuracy and resolution. Hence, a ground mobile unit (GMU), defined as a wheeled rover, was selected.

4.1. System requirements

Within the ground deployment systems, several alternatives are available. They were evaluated according with these five parameters:

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- Mobility: The distance to be covered per day, the size of the obstacles to be cleared or the range of movements considered should be taken into account (Suzuki, 2010).
- Navigation: The layout of the network and how the ground unit places the nodes may be pre-planned or decided on-the-go. In this sense, both on-line and off-line planning schemes should be discussed (Luo et al., 2005).
- Accuracy: The placement requirements in terms of precision and repeatability must be treated, distinguishing among located, random and semi-random deployments (Xu et al., 2010; Younis et al., 2006; Kulkarni et al., 2011).
- Priority: The deployment task might be the main mission of the robotics means or just a collateral activity of the PE mission.
- Distance/Access: The possibility of placing the nodes at a certain distance from the GMU should be considered, in order to avoid non-passable or dangerous areas.

Nevertheless, they are closely related among them: As far as accuracy is concerned, both the precision on placement and the accuracy in the deployment must be taken into account. The fist aspect to consider refers to the rover's own positioning. Present planetary exploration missions do not achieve a good accuracy -in Earth's terms ($\simeq 10m$)-, so a high precision in the deployment cannot be expected. Besides, the presence of holes (e.g. craters), steep slopes or big rocks adds uncertainty to the location estimation.

As a second aspect in the system accuracy, the precision of the physical deployment must be also considered, since the errors derived from a robotic arm, a vending system or a remote deployer (i.e. a launching system) are completely different. However, even if a nailing system is clearly more precise, the characteristics of the terrain described before makes suitable the use of remote placing method in order to improve the general mobility and robustness of the system. This makes possible to overcome obstacles and avoid hazardous situations, allowing also to cover wider areas and access locations unreachable by other means. As a counterpart, it requires to define ranges and distances, complicates the mechanics and increases the complexity of the navigation process.

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In this regard, the mission's path planning has to deal with terrain's characteristics. Since previous information is usually available -collected using satellite imagery or in other earlier missions- both on-line and off-line methods are possible. Off-line path planning allows to guarantee the optimisation of the route and the WSN layout. It also avoids the intensive computing on-board, freeing computational resources for the on-board low level controller. In contrast, its flexibility is clearly inferior, not being able to manage dynamic situations properly. Anyhow, the choice of one or other of these alternatives is clearly defined by the network topology and the precision on its placement, since higher levels of accuracy and optimisation could be only provided using off-line planning.

The priority of the mission must of course also be considered: if the deployment is considered as a stand-alone task, its freedom and adaptability is higher than if is subjected to other specifications. In case the deployment is considered as a secondary activity carried out during the accomplishment of a higher priority mission, its mobility is restricted and its navigation subjected to plan routed. Only minimum deviations from the primary mission could be satisfied (Sanz et al., 2011).

Considering all these aspects (see Figure 1), a robotic system was designed, implemented and tested.

4.2. Mobile deployment engine

As Figure 8 shows, the system is composed of four main elements, that implement the functionalities described in the previous subsection.

The first component is the autonomous rover (see Fig.8-1). It is a four wheeled drive Autonomous Guided Vehicle, capable of operating on rough terrains with a heavy payload capacity. It provides the long range displacement while maintaining the stabilisation and performance required. It is also in charge of carrying the deployment system, supplying the energy required and the communication resources needed.

The second element is the remote deployer. It allows, from the fixed location of the rover, reaching a wide circular area where the nodes cab be placed, regardless the presence of obstacles or the terrain's orography. The deployment system is configured as a pitching node-launching machine (see Fig.8-3). It propels the nodes by means of a continuous rotation wheel, operated by an electrical DC motor. The wheel supplies the nodes with tangential acceleration and velocity. The launcher is fixed at a 45° position in the *pitch* axis in order to maximise the distance of the parabolic launch,

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as well as to balance the rolling effect and the impact strength of the nodes. Nodes' target locations are defined in polar coordinates, where the α angle is specified the orientation axis (pan) angle of the launcher's base and the distance r is set by adjusting the launching speed, controlling the voltage supplied to the spinning wheel's motor. The maximum theoretical range r achievable is of 50m.

The connection between both components is performed using a damping connection base (see Fig. 8-2). It has been specially designed to decouple the rover from the deployment system. This base is built with two resistant polymer plates joined by means of four muffling legs that provide the launcher enough stability when spinning or when going across slopes. The platform controls the yaw angle of the launching system by means of an electrical servomotor, which provides a range of ±90°. It uses a bearing system to facilitate the rotation.

Figure 8: Deployment system components (left). (1) rover; (2) damping connection base; (3) launching system; (4) node feeder. Right: the implemented system.

The other element related with the nodes is the node feeder (see Fig. 8-4). This element stores the encapsulated nodes and provides them to the launcher when required, synchronising the process with the launcher speed and the orientation system. It use a mechanical actuator base on the helix effect. The feeding process takes less than a second (800ms per capsule, from the command reception to the node launching, derived from the capsule fall rate).

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Finally, the last part in the system concerns to the nodes themselves and their handling. The motes are encapsulated with spherical plastic covers, in order to allow a suitable fitting of the nodes to the launching system, as well as to protect the sensor from the impacts caused during the deploying. The rough texture of the capsules maximise the accuracy in the placement process, while their leaky structure make them capable to absorb impacts without damage their content. Furthermore, the equidistant holes on their surfaces achieve no interferences in the acquisition processes, obtaining an uniform measurement of environmental variables.

4.3. Deployment system test and validation

The deployment system has been exhaustively verified through a series tests aimed at assessing its accuracy, repeatability and precision. Both static and dynamic (with the rover stationary or moving) launches have been done, with different combination of distances and angles. Both Figure 9 and Figure 10 present a basic set of experiments to assess these parameters. In the first case, a static deployment were evaluated with series of ten launches targeting different ranges, where was observed an increasing accuracy (from 40 to 10cm). Nevertheless, despite of being more accurate at further distances, the repeatability decreases with the distance (from 20 to 40cm) compensating the precision deviation. All this performance -that continues in the second case- is illustrated in Table 5. Alternatively, Figure 10 illustrates the dynamic experiments, where instead maintain the target, the aim is changing constantly. They have result in the same conclusions, with the exception of the precision, that has been decreased significantly in the dynamic case. Nevertheless, they both satisfied (and even exceed) the requirements imposed by the mission: range greater than 20m, precision and repeatability under 0.5m and stability at different ranges ($< 5\%$ variation) (For further details see (Team, 2010))

Moreover, the node displacement after the deployment has been estimated according to the terrain properties, as well as the capsule resistance to impacts and the maximum absolute ranges of the system. Finally, the performance when following some patterns or spatial distributions has been considered (Fig. 11).

General results were considered satisfactory, obtaining a mean accuracy higher than 0.28m and repeatability of 0.32m in the static test. As expected, the precision obtained in the dynamic mode is significantly lower, obtaining 56.96cm (accuracy)/ 37.77cm (repeatability) for small angles ($< 45°$)

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Table 5: Static deployment results according to the range selected

Metric	Requirement	Values			
Range (m)	> 20	10	15	20	Max.
Mean value (m)	–	9,612	14,636	19,685	23,005
Precision (m)	< 0.5	0,3888	0,3641	0,316	0,0822
Repeatability (m)	< 0.5	0,2369	0,2911	0,3536	0,3991
Max distance between any pair of nodes (m)	< 1.5	0,5991	0,6946	0,85	1,0323
Max distance between the mean value and the furthest node (m)	< 1	0,3991	0,3656	0,4815	0,542
Mean distance to mean point (m)	< 0.5	0,208	0,272	0,3018	0,3401
Mean distance to target (m)	< 0.5	0,4205	0,4087	0,3989	0,3523

and 133.95cm/37.82cm for greater ones (see Fig. 12). The maximum range achieved was 30m, and the maximum distance between nodes was 0.79m.

with the same weight of the motes (23g + batteries). Nevertheless, It is important to highlight that impact test were performed in order to verify the the performance of the system, and none of the motes suffered any damage due to the launch or the impact with the surface. Also, capsules with different weights and CoG were considered, obtaining variations always smaller than ±50%.

5. Discussion and Conclusions

In this work, we have focused on the application of WSNs to space exploration with the purpose of assessing their potential application for future planetary exploration missions.

From a space application standpoint, 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 and shorter mission programmatic.

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

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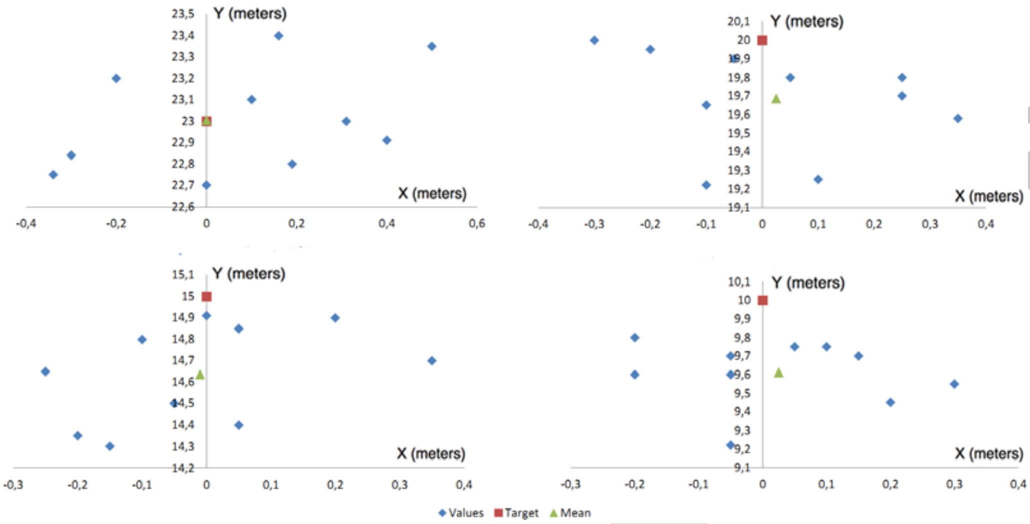

Figure 9: Results of the tests carried out to evaluate the repeatability and accuracy on static deployment. Series of ten launches were carried out, maintaining the angle but increasing the range (10, 15, 20 and 25m). The red squares represents the targets for each series, while the blue rhombus depict the real positions obtained in the tests. The green triangles are the average locations obtained.

addition, the on-site presence of sensors web could 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.

A variety of scenarios have been considered, and two of them have finally been chosen as reference for the study: a distributes sensor web and a networked planetary surface exploration application. Such scenarios were chosen because of their interest for ESA, and as they allow testing two typical network configurations.

In order to optimise the network's performance for the scenarios at hand, we have worked on three fronts: we have designed a routing protocol, a dynamic acquisition algorithm and a sleep mode strategy that optimise battery lifetime and goodput.

In order to assess the effectiveness of the proposed system a power model have been developed taking into account the different aspects of the architecture involved. Tests with real nodes have confirmed the goodness of the

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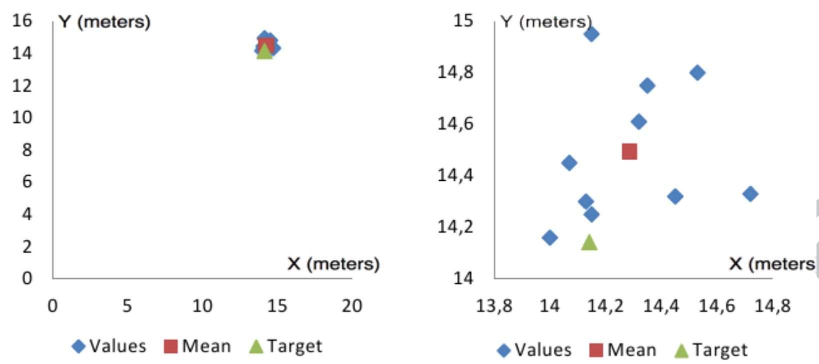

Figure 10: Results of the tests carried out to evaluate the pattern-based static deployment performance. The red squares represents the targets for each series of five launches, while the blue rhombus depict the real positions obtained in the tests. The green triangles are the average locations obtained in each series. Left: Axial distribution. Target: Orientation $= 0°$(*fixed*), Distance $= 10, 15, 20$ meters. Right: radial distribution. Target: Orientation $= -10°, -5°, 0°, 5°, 10°$, Distance $= 15$ meters (*fixed*).

model, that can be thus used for future simulations in different scenarios.

An extensive outdoor campaign has been carried out, demonstrating that the system we have developed could in fact be used in the reference scenarios. The WSN is capable of following environmental changes optimising power consumption (e.g. sample time adjusted depending on the inertia of the measure parameter) and can work during large periods of time, without cuts, saturations or overflows. the WSN has shown excellent behaviour also in dealing with variations of the configuration (relocation, loss or addition of new nodes) and also with moving nodes.

The scenarios have been breadboarded using a limited number of nodes. However, the results obtained can be scaled to networks with up to the order of hundreds of nodes, which is the number of nodes with which the routing protocol has been tested. This, of course, depends on the particular topology and sampling rate needed, since in some configurations the sink is obviously a bottleneck. Given the typical distance between nodes, we can conclude that an area of the order of hundreds of squared meters could be effectively covered by a WSN distributed instrument. Energy harvesting methods, such as solar panels equipped nodes, would greatly increase sensors lifetime, although in this study we have focused of power consumption.

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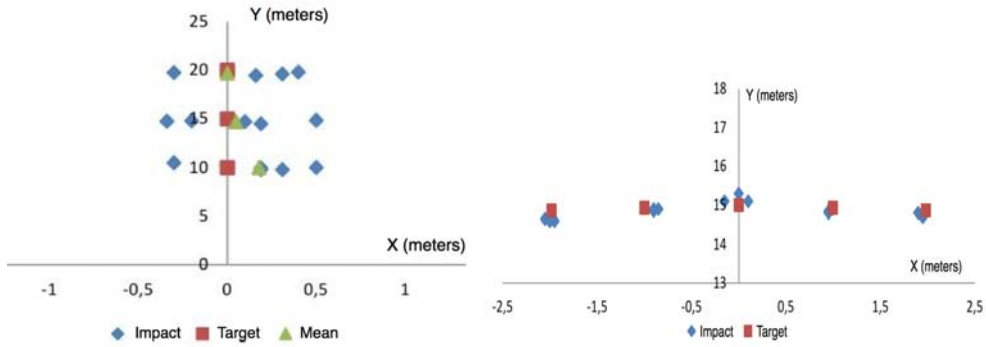

Figure 11: Results of the tests carried out to evaluate the pattern-based static deployment performance. The red squares represents the targets for each series of five launches, while the blue rhombus depict the real positions obtained in the tests. The green triangles are the average locations obtained in each series. Left: Axial distribution. Target: Orientation = $0°$(*fixed*), Distance $= 10, 15, 20$ meters. Right: radial distribution. Target: Orientation $= -10°, -5°, 0°, 5°, 10°$, Distance = 15 meters (*fixed*).

We have also demonstrated the feasibility of the deployment of WSNs using robotic means as a rover platform. Of course, launching systems depend on the peculiar characteristics of the planet or celestial body at hand (e.g. gravity, atmosphere). However, the results obtained can be easily generalised taking such factors into account in the computation of the launch parameters (speed, angle etc.). The precision obtained allows an accurate enough placement of the nodes (either automatic or remotely-controlled), further optimising the web's performance. The mobility provided by the rover allows extending the range of action and therefore the area covered by the WSN, or creating corridors connecting different areas of interest.

From the results of the simulations and tests we can conclude that the WSN "distributed instrument" concept is actually feasible for space exploration scenarios: it provides a reliable and effective way to monitor the environment for the purposes of the envisioned applications, lowering overall mission costs and providing the benefits desired.

The variety of scenarios and applications discussed in this work, and the results of the field tests allow foreseeing a great potential of WSNs in space applications, widening the range of possible scientific objectives, many of which would be difficult – or even impossible– to achieve with classical tech-

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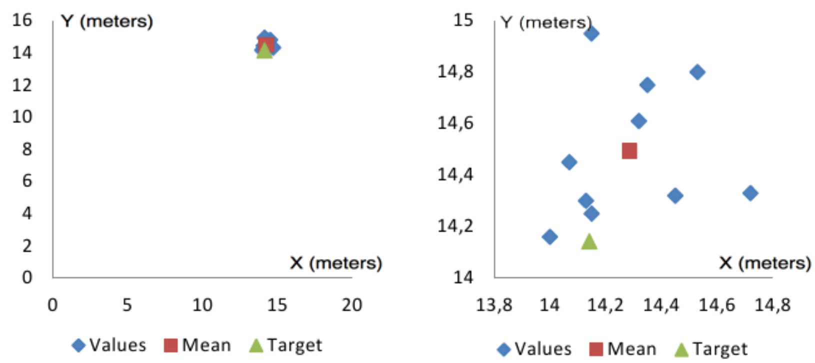
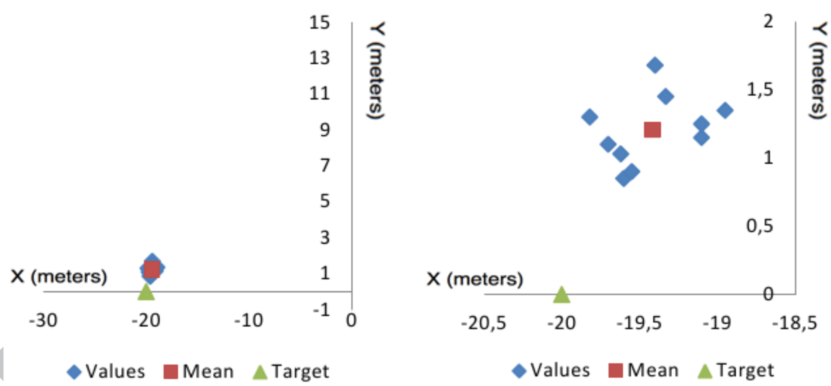


(a) Dynamic test. Target: Orientation = 45° (*Small angle*), Distance = 15 meters



(b) Dynamic test. Target: Orientation = 90° (*Big angle*), Distance = 20 meters

Figure 12: Dynamic tests results. The left column presents the general views, while the right one depicts a detailed views of the same test.)

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nology.

Acknowledgements

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Highlights:

-The use of WNS as distributed instrument has great potential for planetary exploration as far as reliability, spatial and temporal sampling, reduced payload weight and power consumption

-WSNs in space applications widen the range of possible scientific objectives, many of which would be difficult to achieve with classical technology

-Launching nodes from a mobile robot provide a feasible and effective deployment system

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