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OPPORTUNITIES AND CHALLENGES OF WIRELESS SENSOR NETWORKS IN SPACE

R. Sun
Chair of Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, The Netherlands, R.Sun@tudelft.nl

J. Guo
Chair of Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, The Netherlands, J.Guo@tudelft.nl

E. K. A. Gill
Chair of Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, The Netherlands, E.K.A.Gill@tudelft.nl

Challenges and opportunities of wireless sensor networks (WSNs) in space applications are presented. The investigation of internet protocols, ad hoc routing and commercial-off-the-shelf (COTS) wireless communication protocols for efficient and reliable network design is addressed. In order to facilitate the analysis, several application scenarios of space-based WSNs are given, including autonomous formation flying, very-small-satellite cluster/swarm, fractionated spacecraft, onboard sensor network and surface vehicles for planetary exploration. Criteria that contain network scale, link range, degree of dynamics, data rate, power consumption, time intensive requirement, and degree of cooperation are proposed in order to classify applications and choose the most potentially applicable technologies. Different levels of challenges to implement each application are also compared.

I. INTRODUCTION

A wireless sensor network comprises a number of tiny, resource-constrained, cooperative, and mostly intelligent sensor nodes that randomly deployed in the area of interest. The prosperous development of terrestrial WSN gives huge impetus to their applications in space. Many space engineers and researchers regard WSN as a powerful future technology, as it offers a new paradigm for space monitoring and exploration at multi-point with high resolution, high redundancy, and high flexibility.

Compared to the terrestrial applications, the implementation of space-based WSNs involves challenges and innovative opportunities. The stringent space environments with characteristics such as high mobility, undesirable perturbations will influence the operation of WSNs significantly. The wireless communication between two nodes in the network will rely on inter-satellite link or intra-satellite link, whose establishment and stability are impacted by the satellite orbit and attitude, antenna configuration, link range, mobility or the layout of spacecraft. Therefore, it is important in this paper to exclusively investigate of the similarities and differences between terrestrial and space-based WSNs, and propose the available technologies and resources that can be potentially applicable in space. The technologies including internet protocols, ad hoc routing, and COTS wireless communication protocols need to support the network to accomplish reliable interact among nodes, self-organization and reconfiguration of the formation, tolerance of dynamical addition and removal of sensor nodes, or even inter-networking with other future space networks.

In order to facilitate the analysis, several application scenarios of space-based WSNs are proposed:

- Autonomous formation flying;
- Very-small-satellite cluster/swarm;
- Fractionated spacecraft;
- Onboard sensor network ;
- Surface vehicles on the Moon, Mars and other planets or asteroids

Each point aforementioned is distinctly different from each other. This paper distinguishes these scenarios by the proposed criteria, summarizes their implementations using the most potentially applicable technologies, and makes a comparison based on different levels of challenges.

II. SIMILARITIES AND CHALLENGES WITH TERRESTRIAL WSN

II.I Similarities

Space-based WSNs share many of the characteristics with the terrestrial WSNs. Resource constraints is one of their similarities. The nodes in most of the terrestrial WSNs are charged by battery, which makes the power saving to be the most important part in node design and network architecture design. Relaying the message through intermediate nodes is an effective solution. Similarly, due to the limitations on mass, power, and cost, small satellites may not have sufficient power to directly exchange data with the ground station, but upload the message to more-powerful network nodes (i.e. master satellite is responsible for data-gathering and communication with the ground station).

The network architecture is another similarity that can be divided into several different phases during the lifetime of a sensor web, specifically the network deployment, configuration and operation. Deployment may be a one-time activity. Terrestrially, it is often practical to place the sensor nodes by hand or scatter them from an unmanned aerial vehicle. In space exploration applications, if one satellite is served as a sensor node, multiple satellites in a signal launch vehicle are possible to be launched together. On the other hand, deployment may also be a continuous process with more nodes being deployed at any time during the use of the network, for example, to replace failed nodes or to improve coverage at certain interesting area, which is more practical for space applications. For example, NASA's Earth Science Constellation is coordinating a number of different satellites into a train-like arrangement to provide near simultaneous observations of the same area of the earth [1]. The satellites in the train-like array are launched one by one, and still rely on ground-based data fusion, cannot communicate with each other. However, this is only a first step of satellite sensor web. If the satellites are designed a priori to communicate and be cooperative, the network can be established. The new nodes have the abilities to autonomously configure themselves into the network, while the network can recognize the new nodes during the network operation.

Furthermore, inspired by the node's modularity feature in terrestrial applications, space-based WSNs will facilitate system design and shorten development time by designing the sensor node in a modular approach. The nodes could have the following main components:

- Sensor unit: largely depends on the mission scenario and scientific objectives.
- Microprocessor: different level of software would run on the microprocessor, such as signal conditioning, data analysis, localization calculations, clock synchronization, communication protocol operation and power management.
- Communication unit: enables signal transmission and receiving. Specifications (i.e. full duplex/ half-duplex, frequency allocation, data rate, bandwidth, and the support for multiple access) will depend on the mission requirements.
- Antenna: omni-directional or directional
- Power supply: battery or energy harvesting (solar energy).

For a specific application scenario, not all of these components are required. In some cases, some units can be eliminated or integrated with other parts in the spacecraft (i.e. the work of a microprocessor can be replaced by on-board computer).

II.II Differences and Challenges

Network scale

Terrestrial WSNs normally consist of hundreds even thousands of nodes. If the communication range of each node is limited, the nodes may use multi-hop communication to send their data to the destination. This requires a complex routing strategy to ensure time or energy optimized. However, the current network scale in space applications is much smaller (<100 nodes). This simplifies the complexity of data routing, but on the contrary, data paths may be not sufficient to guarantee the network robustness.

Mobility

Mobile nodes in terrestrial WSNs require ad hoc network methods to communicate. In ad hoc network, nodes are assumed to move unpredictably, and therefore procedures must be introduced to handle the random dynamics of the topology. On the other hand, in space-based sensor networks, satellites usually have their own fixed orbits and move along the known trajectories. The information of predictable orbits can help the sensor nodes to make a more effective and precise decision of where and when to communicate with the neighbour nodes.

Inter- or intra-satellite communication

The communication between two nodes in space-based WSNs will rely on inter-satellite links or intra-satellite links.

Inter-satellite links enable the satellites to exchange information and share resources while reducing the traffic load to ground. Its establishment and stability are impacted by i.e. the satellite orbit and attitude, antenna configuration, mobility, and link range. Unlike the terrestrial WSNs, the relative position and orientation of the nodes in space is determined by their orbits and attitudes; Long ranges exist between adjacent nodes. These pose more challenges to the physical layer design and network protocol selection.

Intra-satellite links wirelessly connect a number of onboard sensors or actuators to reduce wired harnesses and connectors inside a spacecraft. Such networks are more similar to the terrestrial WSNs because the nodes in the networks have relatively fixed position and short link range. The network design should furthermore consider the layout of the satellite, minimum mass and power consumption and redundancy.

Precise positioning and control

In many space applications, the nodes in the network should determine or be supported by some additional attributes, such as position determination, or clock synchronization. For example, for the Time Varying Gravity Field Mapping (EX-5/Grace Follow-on), position knowledge in the nanometer level will be required to provide high spatial resolution (<1cm) [2]. Another example is Magnetospheric Multiscale Mission (MMS) mission, which requires precise ranging between two satellites in order to make accurate measurements of the magnetic and electric fields [3]. Such formation flying missions with multiple coordinated spacecraft are good platforms for the demonstration of satellite-based sensor networks. The collective behavior of all the satellites in the formation will determine the quality of the sensor network. In addition, in a formation flying, a certain satellite (similar to the gateway, as an intermediary between the sensor network and the external networks) may be needed to establish the link with the ground station, while other satellites keep the formation in a precise manner by autonomous on-board positioning and control.

Reliability

Space environment has some special characteristics such as vibration, thermal, radiation, high velocity mobility and undesirable perturbations. They will influence the selection of electrical components and the stability of communication links. COTS solutions used in terrestrial WSNs can not be inherited until they have been tested in space environments. The undesirable perturbations can change the orbit of satellites over time. Even if the changing is slow, it still makes the multiple mobile nodes in the network forming a dynamic network topology and influences the network protocol selection. A more challenging effect in space environment is that the objects in orbit change their orientation or attitude based on the perturbations from solar pressure, gravity gradients, magnetic fields, and aerodynamic drag [4]. This may be a serious issue for space-based WSNs because inter-satellite communication is only possible when both link endpoints are pointed within antenna beamwidths, which may require careful control of satellite attitude or change to an omni-directional antenna or use multiple antenna solutions. For intra-satellite communication, this issue will not be that serious.

III. TECHNOLOGIES AND RESOURCES POTENTIALLY APPLICABLE TO SPACE-BASED WSN

Some wireless COTS technologies and resources are potentially applicable to space, such as Internet protocols, Ad hoc networking, and standard IEEE wireless communication protocols.

III.I The Internet Protocol (IP)

The power of IP to the satellite lies in its global addressing and datagram delivery, which standardized the way that the ground and the satellite or inter-satellite interact. IP based technology can also simplify the inter-networking with other future space networks. IP technologies have been demonstrated by several space missions via the satellite-to-ground links. UoSAT-12 was the first known test of using standard IP to an orbiting spacecraft. UDP/IP, NTP and FTP were successfully completed within UoSAT-12 [5]. UWE-1 as an educational Cubesat also verified several communication protocols and applications like AX.25, TCP/IP, UDP/IP, TFTP, and HTTP [6]. A much more advanced technology — mobile IP has been tested on space shuttle (CANDOS). It realized automatically setting up routing tunnels to send uplink traffic to the correct ground network or TDRSS relay satellites for uplink [5].

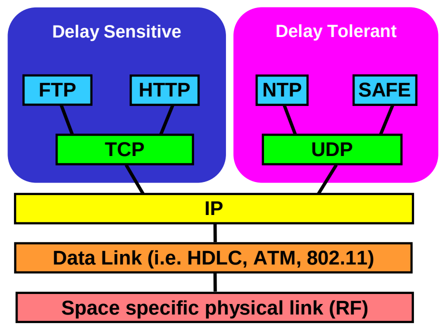


Fig. 1: IP protocol based on OSI model

Fig.1 gives the common Internet version based on the Open System Interconnection (OSI) model. In the physical layer, radio frequency (RF) link is the common choice for space networks. The initial challenge is to identify a data link framing mechanism that supports IP while also performing well over RF links used by space missions. High-level data link control (HDLC) framing is a good choice because it has been used in space communication systems for over 20 years [5]. Several IEEE wireless communication protocols also have IP support, such as 802.11, 802.16. TCP/IP is a reliable delivering protocol because it requires a two-way link in order to get acknowledgement from the receiver. Therefore, TCP/IP is delay sensitive and can not be used in such a network with very long separation distances. UDP/IP is a “send-and-forget” protocol, which means that there is no acknowledgement sent back or handshaking. This characteristic makes UDP/IP well suited for uni-directional and delay tolerant link. In other words, UDP/IP requires less delay or exhibits better throughput, but more probability of missing the packets than the TCP/IP [7]. Another advantage of UDP/IP is that it supports the Network Time Protocol

(NTP) that can be used for clock synchronization within 100 milliseconds.

The selection of TCP/IP or UDP/IP in space-based WSNs will depend on the trade-off between time constraints and reliability requirements. In a distributed satellite mission who imposes strict time constraints, especially in a formation where the satellites need to frequently exchange navigation data via inter-satellite links, less propagation delay may maintain the satellites in a more precise relative position and orientation, and subsequently UDP/IP can be the solution. On the other hand, if the loss of some sensor data may adversely affect the scientific success of a mission, TCP/IP will be selected to guarantee high data reliability.

III.II Ad Hoc Networking

The terrestrial mobile ad hoc network is a mobile mesh network with a number of self-configuring devices connected by wireless links. Ad hoc networks are autonomous. They cannot assume or rely upon pre-existing infrastructure. The nodes must identify their neighbours and determine routes within the network. Most terrestrial ad hoc routing protocols are designed to deal with rapid topology changes. However, some of the space-based WSNs scenarios do not have a very high degree of topology change but will change slowly (i.e. when nodes failure), the assumptions embodied in ad hoc routing protocols should be modified to a relative simple version according to the requirements in space.

Possible scenarios that need the support of ad hoc routing protocols in space-based WSNs include:

- The neighbour discovery upon initial deployment;
- Formation reconfiguration;
- Fault "lost in space" conditions;
- The ability to allow for the placement of sensors with a great freedom as the impact of the addition or removal of sensor nodes on the overall configuration is minimal;
- Inter-networking with future space networks.

III.III IEEE Series Wireless Communication Protocols

The primarily concern of the selection among several wireless COTS protocols for sensor web is the range between adjacent nodes. The candidates for relative long range inter-satellite links are Wi-Fi (IEEE 802.11) and WiMAX (IEEE 802.16), and for relative short range intra-satellite links are ZigBee (IEEE 802.15.4), Bluetooth (IEEE 802.15.1) and WiMedia (IEEE 802.15.3). Fig. 2 gives the range span of each wireless standard, associated with their achievable data rates.

Zigbee standard is ultra low power with sleep mode. That characteristic makes it attract more attention than Bluetooth for intra-satellite communications currently [8]. The data rate of Zigbee is low, but already enough for housekeeping data and some ADCS data in small satellites.

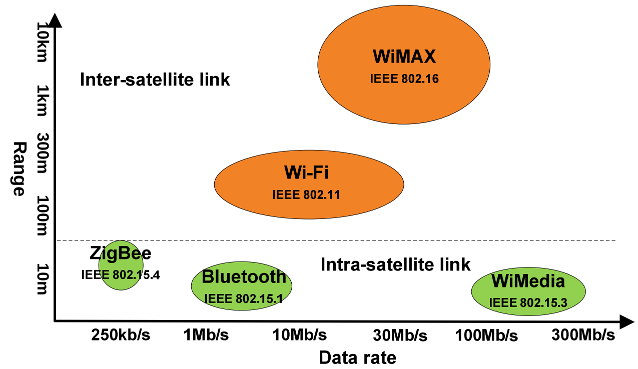


Fig. 2 Specifications of several potential wireless COTS network standards for space-based WSNs

Also the family of IEEE 802.15.3 (WiMedia) standard seems to be very promising for high data rate, high QoS (Quelity of Service) intra-satellite communications, especially when data streaming applications exist.

WiMAX is a very competing standard for very long distance or very high data rate communication in wireless protocol market. It also has many features that the inter-satellite communication networks could make good use of, such as extensive support for QoS, high mobility, full native IP support, OFDM and high physical layer efficiency [4].

Compared to WiMAX, Wi-Fi is a much more established standard. Although it is designed for terrestrial applications for outdoors distances of only 300 meters, a modification for increased range version for inter-satellite links is addressed by Sidibeh, K. [9]. Clare, L. P adapts the Wi-Fi multiple data rate capability to the space environment and incorporates the Wi-Fi MAC protocol to support precision formation flying control across the various phases of mission operations, ranging from initial random deployment to precision formation and formation reconfiguration [10].

Network features (especially MAC functions to reduce the number of collisions), bandwidth, power consumption, EMC requirements, mobility, reliability, robustness and implementation complexity are the factors to be considered before using any of the wireless standards in the applications of space-based WSNs.

IV. SPACE APPLICATIONS

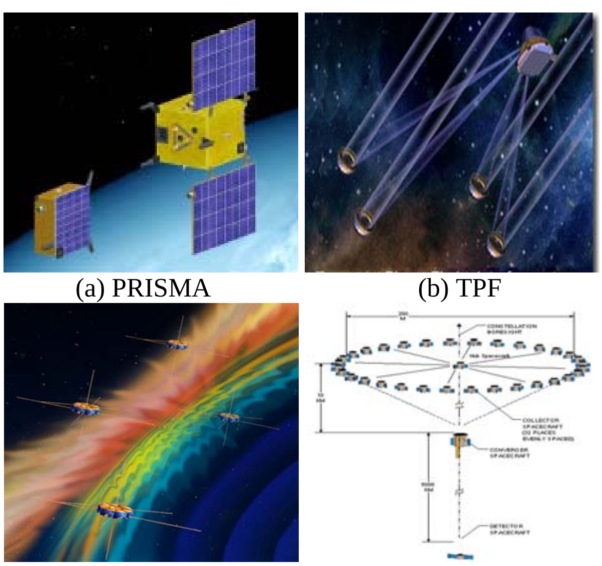
IV.I Autonomous Formation Flying

A spacecraft formation, different from a constellation, includes two or more spacecraft in a tightly controlled spatial configuration. Autonomous formation flying poses more requirements to relative navigation and control because the typical maneuver cycle for maintenance of the formation may be too short for ground-control and thus many require a fully autonomous on-board control approach with the help of inter-satellite links [11].

Autonomous formation flying is a good demonstration platform for satellite sensor network. As the network scale is relatively small, multiple access technologies in the physical layer (i.e. FDMA, TDMA and CDMA) can be considered to guarantee the channel sharing and collision avoidance instead of using complete complex wireless communication protocols. The technologies highlighted with regards to sensor networks include:

- Inter-satellite links
- Inter-satellite ranging
- Real-time coordinated observations
- Precise relative positioning and control
- Clock synchronization
- Communication and navigation synergies

A series of formation flying missions have been flown or proposed with establishment of inter-satellite links and high demands on inter-satellite ranging accuracy. This includes the PRISMA mission that is the first demonstration of autonomous formation flying with S-band RF-based metrology at centimeter-level ranging accuracy [12]. TPF (Terrestrial Planet Finder) [13], MMS (Magnettospheric Multiscale Mission) [14] and MAXIM (MicroArcsecond X-ray Imaging Mission) [15] are other examples that rely on inter-satellite link technologies to ensure mission success.



(a) PRISMA (b) TPF

(c) MMS (d) MAXIM

Fig. 3 Examples of formation flying missions with inter-satellite links [12,13,14,15]

Apart from mission specific applications, the technologies used by autonomous formation flying can be served as important verifications in the development of a fully functional, reliable and large scale satellite sensor networks, because they not only enable autonomous formation keeping, but also allow for a reduced ground segment, and with that enhanced system robustness and real-time operations.

IV.II Very-Small-Satellite Cluster/Swarm

Using numerous cheaper micro-, nano- or even pico-satellites in a cluster/swarm for multipoint exploration is a challenging but very attractive idea. Cluster/swarm can get a large area coverage and unprecedented high resolution, can go to places that are difficult to reach or too dangerous for standard spacecraft [16]. Organizing cluster/swarm as a sensor web via inter-satellite links has many advantages:

- *Power saving*: the power consumption can be conserved by reducing the transmit power and relaying the message through the closer intermediate nodes.
- *Single ground link*: a single ground contact with a more powerful member in the network, while other nodes solely rely on the inter-satellite links. This application is especially suitable used in deep space, where not all of the satellites have the power to communicate directly with the ground station.
- *Data fusion*: on board distributed computing can reduce the amount of data that needed to be transmitted to the ground
- *Robustness and redundancy*: the number of nodes in cluster/swarm is relatively large, which determines that the scalability and robustness of the network is high, and redundant routing paths and nodes exist.

The good examples of cluster/swarm in space are OLFAR mission proposed by two universities in the Netherlands and ESPACENET project undertaken in UK.

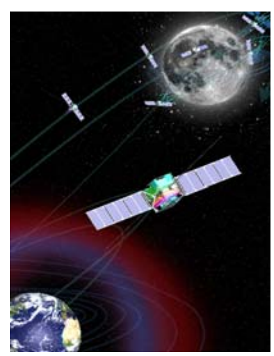


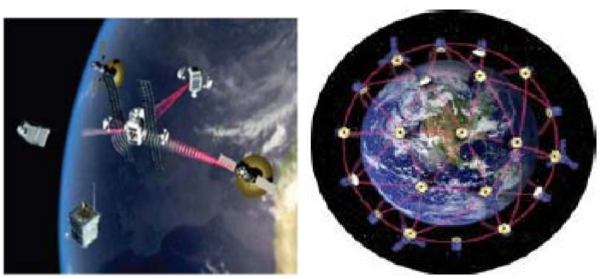
Fig. 4 OLFAR mission

OLFAR (Orbiting Low Frequency Antennas for Radio Astronomy) mission will operate as a coherent array of approximately 50 cubesats within a 100km virtual aperture [17]. As the data correlation must be done in space, distributed processing with centralized downlink transmission is the preferable option. OLFAR mission is in the moon orbit. The satellites will not be launched together, but separately move to the moon one by one to join in the existing operational network, as illustrated in Fig. 4. Inter-satellite communication and self-configurable networking will be the greatest challenging part in OLFAR mission.

ESPACENET project is under investigation to develop a pico-satellite sensor networks to demonstrate technology advances in space, including modified IEEE802.11 wireless standard for inter-satellite links, distributed computing and reconfigurable system-on-a-chip (SoC) design. Its aim is to develop an ad hoc network with pico-satellites in LEO [18].

IV.III Fractionated Spacecraft

Fractionated spacecraft, as shown in Fig. 5 is a revolutionary concept. Unlike constellations or formations, the generalized concept of it is to break a large monolithic spacecraft into smaller heterogeneous modules, which perform distinct functions and interact through wireless communication links [19].



(a) An example of fractionated spacecraft

(b) Global fractionated infrastructure

Fig. 5 Examples of fractionated spacecraft [19,20]

In this special wireless network, each module can be regarded as a node. If necessary, the elements of the ground segment can also be treated as nodes. Some characteristics presented in sensor networks are beneficial to fractionated spacecraft, such as:

- *Flexibility*: Options to add modules, remove modules, replace modules, or reconfigure spacecraft architecture throughout development and operational life. The later added features can also extend mission functionalities.
- *Mass saving*: Wired cables are eliminated, and data handling subsystem is replaced by wireless communication network.
- *Requires very high communication reliability*: In fractionated spacecraft where the individual nodes are very valuable and may become useless if their inter-module communication system fails, so the reliability of the communication system is very important.

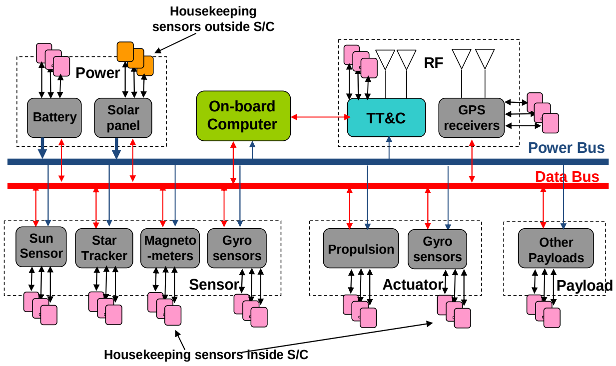
Apart from the networking challenges, wireless power transfer is another hard nut to crack. Its current technology is still in the infant stage. In 2007, a physics research group in MIT realized an experiment of wirelessly powering a 60W light bulb with 40% efficiency at a 2 metres distance using two 60 cm-diameter coils. Therefore, we have the reason to conclude that the link range in the network for fractionated spacecraft will be restricted to a short distance (<1km) because of the limitation of wireless power transfer technology in the near future.

IV.IV Onboard sensor network with Intra-satellite links

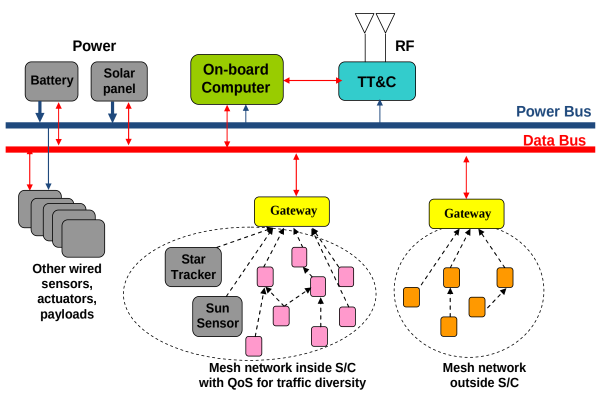
WSN within a spacecraft is applied in order to eliminate wiring harnesses and connectors, and enhance the robustness and functionalities of the mission. Wireless sensors can also be used on ground during AIT activities. This kind of sensor network is very similar to the terrestrial WSN in the following characteristics: fixed positions relative to the spacecraft, short link range, and low power consumption. To this end, Zigbee standard with sleep mode is very suitable for its application. However, when considering the details of how to apply Zigbee to intra-satellite links, several other points that will be tightly coupled to network architecture should be paid attention. They include:

- *Traffic and flow diversity*: In the case of a typical spacecraft, the candidate wireless sensors have different data traffic types, i.e. payload data, house keeping data, and ADCS sensors and actuators data traffic. Different traffic types impose various requirements on the data handling system. Greater traffic diversity may increase the need for the network to provide QoS assurances to the different classes of traffic.
- *Gateway*: For onboard sensor network, gateway acts as an intermediary between the network and external on-board computer (OBC). It is responsible for network organization and can also aid in message routing and sometimes could offload certain processing from less-powerful network nodes. However, Gateway is the single point of failure. Potential faults of gateway greatly influence the implementation of the whole network. In order to increase the gateway reliability, it is better to connect the gateway and OBC by wires.
- *Layout of spacecraft and sensor placements*: The layout of spacecraft and sensor placements determine if line-of-sight communication is possible. In most cases, the obstacles make it impossible for some nodes to “see” the gateway, but relay via the intermediate nodes. In addition,

some nodes located outside the spacecraft (i.e. temperature sensors on the antenna booms, or on the solar panels) may require another gateway because wireless signal can not pass through the shell of the spacecraft.



(a) An example of traditional onboard data handling subsystem, hundreds of housekeeping sensors distributed inside or outside the spacecraft

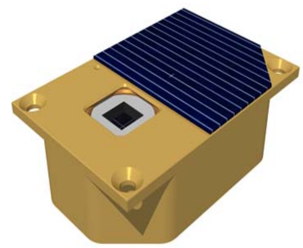


(b) An example of wireless onboard sensor network to replace wiring harnesses and connectors. The candidate wireless sensor nodes include relative-low-data-rate housekeeping sensors and relative-high-data-rate ADCS sensors (take sun sensor and star tracker for examples). QoS assurances may be needed to the different classes of traffic. Housekeeping sensors inside and outside the spacecraft may require different gateways.

Fig. 6 Comparison of traditional onboard data handling subsystem and wireless onboard sensor network

Fig. 6 illustrates the conceptual design of wireless onboard sensor network, and makes a comparison with the traditional onboard data handing subsystem. The candidate wireless sensor nodes in Fig. 6(b) are relative-low-data-rate housekeeping sensors (i.e. temperature, pressure, and vibration sensors), and relative-high-data-rate ADCS sensors (i.e. sun sensor, star tracker). Some wired links also exist, in such a way that the basic function of spacecraft and its reliability can be guaranteed.

Till now, both the RF-based and optical intra-satellite links have been demonstrated in space. Delfi-C3 nano-satellite is the first ever in-orbit demonstration of autonomous wireless sun sensors (AWSS) [21]. A wireless RF link using a modified COTS transceiver operating at 91.5MHz is achieved. NANOSAT-01 presents an in-orbit experience of optical wireless links between a 3-axis magnetometer and OBC [22].



(a) Autonomous wireless sun sensors (AWSS)

(b) NANOSAT-01

Fig. 7 In-orbit experiments of intra-satellite links [21, 22]

IV.V Surface Vehicles On The Moon, Mars And Other Planets or Asteroids

In 2004, a British landing spacecraft on Mars "Beagle 2" got lost. The failure of this mission showed the inherent hazard using a single centralized system in planetary exploration context. WSN presents a good solution because of its sufficient redundancy, and gains more and more interest resent years. WSN enables mapping over a large area or volume and for a long period of time. The nodes on the planets or asteroids are stationary or move very slowly. The link range between two nodes could not be very long because the terrain of planet surface may be rocky and obstruct the sight of nodes.

Compared to the space application scenarios aforementioned, utilization of WSN for planet or asteroid exploration still has some other distinctive challenges, including:

- *Sensor node deployment and landing*: The nodes may be dispersed by a spacecraft/ Lander/ Rover. After their dispersion they are free falling towards the planet's surface. The nodes deployment technique would have a strong impact on the network architecture.
- *Self-localization*: After deployment, the exact placement of individual sensor nodes may be imprecise and difficult to predict, which makes self-localization technique is needed. In addition, the possible network topologies cannot be accurately determined in advance. That

requires the network to be configured and organized autonomously.

- *Relay data back to Earth*: the same orbiter that delivered the nodes to the planet can also act as a relay to forward the acquired data back to Earth.

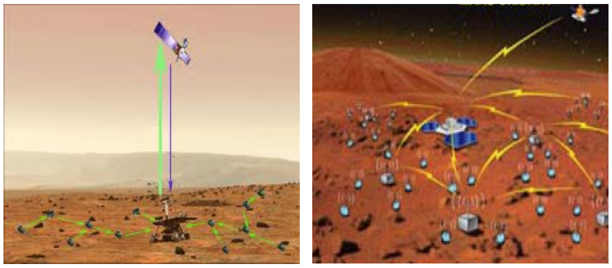


Fig. 8 Examples of WSN for planetary exploration [23]

V SUMMARY OF DIFFERENT APPLICATIONS

For space-based WSNs, each scenario aforementioned is distinctly different from each other. Different application scenarios are likely to impose different requirements and demand different networking technologies. To facilitate the analysis, we give criteria to distinguish these scenarios, shown in Table 1.

The selection of criteria is based on two levels: (1) From the high level system engineering perspective, the purpose of a certain mission with multiple satellites determines whether or not the inter-satellite or intra-satellite link is needed. Link range, network scale and degree of dynamics are the fundamental triggers to meet the mission scientific or technical requirements, and therefore serve as the first level criteria. A more straight depiction is given in Fig. 9. (2) The second level is related to what kind of data to be exchanged among nodes. Navigation data is necessary to support onboard autonomy in formation flying. Science data are normally transmitted in order to facilitate distributed space-based computing, especially when not all satellites have the power or time to downlink data back to Earth, but instead, to relay data via more capable satellite in the scenario like very-small-satellite cluster/swarm and surface vehicles on planets. Besides, housekeeping data (or satellite health and status data) with a low volume will be the primary concern for the scenario of onboard sensor network. Therefore, data rate, power consumption, time intensive requirement and the degree of cooperation has been chosen as the secondary criteria to classify WSNs' space applications.

Criteria / Applications	Link range	Degree of dynamics	Network scale	Data rate	Power consumption	Time intensive	Degree of cooperation
Autonomous formation flying	100m-30km	Low dynamics (topology does not change frequently)	Small or Medium (2-20 nodes)	Low or medium (<1Mbps for navigation, time, orbit information data)	Medium	Yes (navigation and control data are frequently transmitted for maintenance of formation autonomously)	High
Fractionated spacecraft	<1km	Low dynamics (topology is fixed, but robustness enables old modules to be replaced by new ones)	Small (<10 nodes)	Medium (<1Mbps for time intensive data, i.e. command & control)	Medium	Yes (Real-time monitors modules status and gives command & control data)	High
Very-small-satellite cluster/swarm	<1km	High dynamics (no fixed formation exists/ random flying)	Large (>20)	Low or medium (depends on the degree of cooperation)	Low	No	Medium
Onboard sensor network	<10m	No mobility	Large (10-100 nodes)	Low (<250kbs for housekeeping data; <1Mbps for other AOCS sensors)	Very low	No	Low
Surface vehicles on planets or asteroids	<1km	No mobility or low dynamics	Medium or Large (10-100 nodes)	Medium or high (Science data collection)	Low	No	Medium

Table 1. Criteria used to classify space-based WSNs application scenarios.

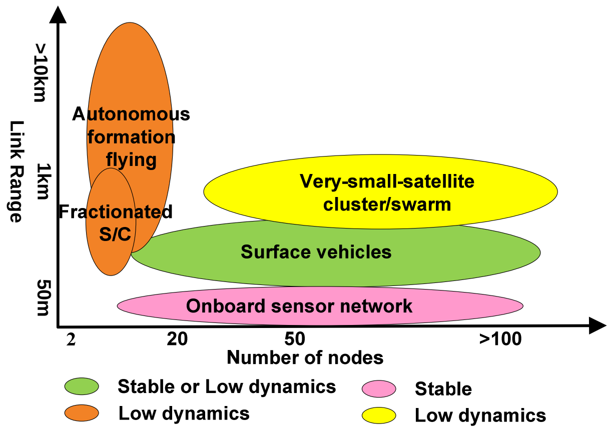


Fig. 9 Category of space-based WSNs application scenarios in terms of link range, number of nodes and the degree of dynamics

Table 2 explains what degree of each potential technology is supportive to each criterion using symbols "+ +, +, o, -, - -", with the meaning that the technology is satisfactorily supportive, supportive but some modifications may need, not related, not supportive, contrary to the specific criterion, respectively. Examples of "+ +" and "- -" is explicitly explained here.

(1) WiMax is a wireless protocol designed for long range and high data rate communication, while Zigbee is perfectly suitable for low power consumption, low data rate communication as discussed in section III.

(2) Multi-hop routing is a solution for large network scale because point-to-point direct connection among such large numbers of nodes is onerous. It is also applicable to communicate over long distances that are greater than the normal transmit power can support. However, for some missions with strict time constraints, multi-hop is a killer because expect for signal propagation, it occupies much more time on the data relay which will depend on the number of traversed nodes (processing, queuing).

Criteria \ Technologies		Available COTS technologies							
		Multi-hop	IP	Ad-Hoc	IEEE Wireless Communication Protocols				TDMA /CDMA /FDMA
					802.15.4 (Zigbee)	802.15.1 (Bluetooth)	802.11 (Wi-Fi)	802.16 (WiMax)	
Link range	Long (>=1km)	+ +	o	o	-	-	+	+ +	o
	Short (<1km)	-	o	o	+	+	+	-	o
Degree of dynamics	High dynamics (Rapid topology changes)	+	o	+ +	o	o	o	o	- -
	Low dynamics (Network reconfiguration when some nodes added or dropped)	+	o	+	o	o	o	o	o
Network scale	Large (>20 nodes)	+ +	o	o	o	o	o	o	-
	Small or Medium (<=20 nodes)	-	o	o	o	o	o	o	+
Data rate	High (>=1Mbps)	o	o	o	-	+	+	+ +	o
	Low (<1Mbps)	o	o	o	+ +	+ +	-	-	o
Power consumption	Low power consumption	+	o	-	+ +	+	-	-	-
Access to terrestrial WAN	Yes	o	+ +	o	o	o	+	+	-
Time intensive	Yes	- -	o	-	o	o	o	o	+ +
Degree of cooperation among nodes	Highly cooperative	+	o	o	o	o	o	o	+
	Low cooperative	o	o	o	o	o	o	o	o

Table 2. Criteria of potential applicable technologies for space-based WSNs. Different symbols "+ +, +, o, -, - -" give the degree of how the technology support each criteria, with the meaning that this technology is satisfactorily supportive, supportive but some modifications may need, not related, not supportive, contrary to the specific criterion, respectively.

(3) Traditional multiple access technology TDMA/CDMA/FDMA with its fixed time/code/ frequency dividing makes it suitable for time-intensive situation, but not applicable when the topology changes rapidly in high dynamics situations.

(4) Ad-hoc routing is designed for high dynamics.

Technologies / Applications	Available COTS technologies								Undeveloped technologies needed to support specific scenario
	Multi-hop	IP	Ad-Hoc	IEEE Wireless Communication Protocols				TDMA/ CDMA /FDMA	
				802.15.4 (Zigbee)	802.15.1 (Bluetooth)	802.11 (Wi-Fi)	802.16 (WiMax)		
Autonomous formation flying	-	+	+	-	-	+	+	+ +	Precise relative navigation
Fractionated spacecraft	-	+	+	-	-	+	+	+ +	Wireless power transfer; Clock synchronization; Very high reliability of data transmission
Very-small-satellite cluster/swarm	+ +	+	+ +	-	-	+ +	+	-	
Onboard sensor network	+	o	o	+ +	+	-	-	-	
Surface vehicles on planets or asteroids	+ +	o	o	+	+	+ +	-	-	Node deployment and landing; Self-localization
$\sum$	+ + +	+ + +	+ + + +	0	-	+ + + +	+	+	

Table 3. Potential applicable technologies for different space application scenarios of WSNs. Different symbols "+ +, +, o, -" mean that this technology is strongly recommended, applicable but not the most suitable one, not needed, not suitable to be used for the specific application, respectively. The sum of symbols for each technology can show whether or not this technology has a wide applicability for space.

Based on the analysis in Table 1 and Table 2, we give the summaries in Table 3 of the potential applicable technologies for different space application scenarios. Different symbols "+ +, +, o, -" mean that this technology is strongly recommended, applicable but not the most suitable one, not needed, not suitable to be used for the specific application, respectively. For each application, we can choose the technologies with symbol "+ +" as its potential solution. The sum of symbols for each technology in the last row can give us the information whether or not this technology has a wide applicability for space. For instance, Wi-Fi and ad-hoc have the highest prospects in space applications, while Zigbee and Bluetooth work well only at a small range of applications such as onboard sensor network due to their low distance and low data rate fundamental characteristics.

Undeveloped technologies are also listed in Table 3 with the attempt to summarize which application is achievable using the current available COTS technologies, and which one needs other technologies for further research in space use. In order to give a comparison of the challenges of each application, we extract the chosen COTS technologies and undeveloped technologies from Table 3, grade them at different levels of challenges in Table 4. Conclusions are given that fractionated spacecraft is most challenging one, while onboard sensor network is relatively easy to implement using the current technologies.

VI. CONCLUSIONS

WSN offers a new paradigm for space monitoring and exploration. Space-based WSNs share many of the characteristics of terrestrial WSNs, such as source constraints, considerations on network deployment, configuration and organization, as well as the modular property of the node. On the other hand, it also poses new challenges. The communication between two nodes will rely on inter-satellite link or intra-satellite link. The stringent space environments including high mobility and undesirable perturbations also influence the network design significantly.

The implementation of WSN demands exclusive investigation of network architecture design and protocols for optimized operation in space. Internet protocols, ad hoc routing and IEEE series wireless communication protocols are potentially applicable, however, require us revisit the underlying assumptions in order to modify them into mission-qualified version.

Although the space application of WSNs is significantly different from mission to mission, some common characteristics can be addressed in terms of network scale, link range, degree of network dynamics, data rate, power consumption, time intensive requirement and degree of cooperation. For the large scale network that contains hundreds of sensor nodes, complex network multi-hop routing algorithms are needed. Zigbee is suitable for short range, low power, low data rate intra-satellite link, while Wi-Fi and WiMAX can be used in high data rate, long range inter-satellite communication. The degree of network dynamics ranges from low dynamics such as network reconfiguration when some nodes added or dropped to high dynamics in the case of rapid topology changes. The selection and modification of ad-hoc routing algorithm should meet different degrees of network dynamics. For the time intensive situations, traditional multiple access technology TDMA/CDMA/FDMA is preferable than commercial wireless protocols.

Based on the current technologies, the applications of space-based WSNs like onboard sensor network, autonomous formation flying are relatively easy to implement, however, fractionated spacecraft and surface vehicles for planetary exploration is very challenging.

Technologies at different levels of challenges \ Applications		Autonomous formation flying	Fractionated spacecraft	Very-small-satellite cluster/swarm	Onboard sensor network	Surface vehicles on planets or asteroids
Multi-hop	1			X		X
Ad-Hoc	2			X		
IEEE 802.15.4 (Zigbee)	1				X	
IEEE 802.11 (Wi-Fi)	1			X		X
TDMA/CDMA/FDMA	1	X				
Precise relative navigation	1	X				
Wireless power transfer	5		X			
Clock synchronization	3		X			
Very high reliability of data transmission	2		X			
Node deployment and landing	3					X
Self-localization on planets	2					X
$\sum$		2	10	4	1	7

Table 4. Technical solutions for the applications of WSNs in space with different levels of challenges. Based on the current technology development, the level is graded from 1 to 5 to describe the degree of implementation from easy to difficult.

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