Naftali (Tuli) Herscovici
AnTeg
52 Agnes Drive
Framingham, MA 01901 USA
Tel: +1 (508) 788-5152
Fax: +1 (508) 788-6226
E-mail: tuli@ieee.org

Christos Christodoulou
Department of Electrical and
Computer Engineering
University of New Mexico
Albuquerque, NM 87131-1356 USA
Tel: +1 (505) 277-6580
Fax: +1 (505) 277-1439
E-mail: christos@ece.unm.edu

Wireless Sensor Motes for Small Satellite Applications

V. Lappas¹, G. Prassinos¹, A. Baker², and R. Magnuss³

¹Surrey Space Centre
University of Surrey, Guildford, Surrey, UK

²Surrey Satellite Technology Ltd
Guildford, Surrey, UK

³European Space Agency
Nordwijk, ESTEC, Netherlands

Abstract

Motes are low-cost COTS (commercial off-the-shelf) microchips, which integrate a processor, onboard sensor, RF communications link, and a power unit. High levels of power efficiency can be achieved with the use of the IEEE 802.15.4 protocol for communication between the motes, allowing long-term periods of operation for motes and reducing the power requirements of a spacecraft. The article examines the feasibility of using sensors for harness reduction between satellite subsystems, and for inter-satellite networking capabilities between satellite swarms.

Keywords: Satellite communication onboard systems; satellite communication; satellite vehicle power systems; interconnections; wireless LAN; sensors

1. Introduction

Spacecraft manufacturing is largely a manual operation, with high costs and long lead times. Harnessing or electrical interconnections form a large part of the spacecraft, contributing mass and requiring more assembly, integration, and testing as spacecraft complexity increases. Having harnessing account for more than 10% of the platform cost and up to 15% of the dry mass are common fractions in spacecraft manufacturing and design. Small spacecraft use a plug-and-play CAN bus data architecture, offering

cost savings through standardized cards and interfacing, against higher-mass point-to-point connections used in large spacecraft. Sensor networks developed for the terrestrial industry can be physically arranged or arranged in an ad hoc fashion using new wireless protocols, such as the ZigBee, which can self-organize into a communicating network [1].

Spacecraft platforms are highly complex systems. Harness and electrical interconnections of spacecraft components require a high level of assembly integration and testing. The use of wireless monitoring nodes can potentially minimize the use of wires, with

wireless connections leading to a significant reduction in the harness. Several industries use wireless sensor devices (motes) to monitor automotive subsystems, control lighting, and monitor movement for security systems. Such sensors can form a mesh, or can form point-to-point ad-hoc networks [1, 2].

Motes are wireless micro-sensors that combine a low-power micro controller, an RF transceiver, and power supply with one or more attached or embedded sensors. They often use eight-bit microcontrollers, and have a few kilobytes of onboard flash memory to store the program used from the mote.

Motes are being researched for intra-spacecraft communication, to replace wires between spacecraft subsystems, and for inter-spacecraft communication, offering communication among spacecraft flying in formation or as an ad-hoc swarm. Onboard computer functions, such as housekeeping sensor readings, could be replaced by mote networks, which can also support data routing from other subsystems.

Low-cost small satellites use the CAN (Control Area Network) protocol to provide a communication link among different subsystems. Although CAN has been tested on previous satellite missions and is proven to perform very well, it has a limited data rate and comes with a harness overhead. Harness reduction can result in a reduction in complexity for construction of a spacecraft, as well as in a sizeable reduction in the total mass, especially for small spacecraft. Further mass reduction can occur due to elimination of electronic interference boards on subsystem electronics. For example, a CAN interface for a star tracker or a battery-charge regulator has a mass of 100-200 g. By using a MICA2DOT [3] wireless micro-sensor, the mass could be reduced to 10 g, including the battery cell (Figure 1). The data rate of CAN is limited to 32 kbps, but the MICA2DOT has a higher baud rate of 38.4 kbps, with a fraction of the mass. Motes using directional antennas have the capability to transmit up to 250 kbps and have a mass of less than 30 g, excluding the battery. Using a mesh topology of motes inside a satellite, we could create a robust network with almost zero harness.

For power- and mass-limited satellites – such as the Surrey 1 kg Palmsat spacecraft [4] – cooperative clusters of the spacecraft can form a low-power, low-cost, robust data-handling solution. In the case of several satellites flying in formation, a “communication web” will be formed, which offers efficient communication among the satellites.

2. Small Satellite Requirements

Such networks have specific requirements in order to be suitable for space applications, which are summarized below:

- *Minimum mass and power consumption.* Small mass results in a total spacecraft mass reduction, lowering the overall cost of the mission. The power consumption needs to be kept to a minimum to minimize additional needs for batteries, solar cells, battery-charge regulators, and other power subsystems.
- *Minimum complexity.* During spacecraft assembly, extended tests need to be carried out to confirm correct operation and connectivity of the different subsystems, resulting in increased cost and assembly time for the

spacecraft. By minimizing complexity, the overall cost of the mission can be substantially decreased.

- *Minimum cost.* By using mass-produced miniature commercial off-the-shelf motes, and thus replacing expensive custom space hardware, cost can be minimized.
- *Maximum reliability and lifetime.* Using a larger number of micro-sensors to form a self-healing robust network, instead of increasing the networks’ reliability itself, increases reliability, redundancy, and lifetime.
- *Maximum performance.* Miniature commercial off-the-shelf motes are being developed with more-capable data rates than the current CAN networks (32 kbps).
- *Radiation tolerance.* Especially for long-distance deep-space missions, radiation hardening of the electronic components needs to be tested.

Additional features of the wireless network include embedded data security, built-in routing/networking, and long lifetime of operation.

The intra-spacecraft network requirements are influenced by the distribution of the motes inside the spacecraft. For a small spacecraft (Palmsat or a nanosatellite), due to its small size the distance between each individual mote is small, resulting in minimum loss of signal strength (Figure 2a). For larger spacecraft, it is likely that additional power will be required from the motes in order to transmit at higher power, as the motes will be positioned further apart, in different, separated compartments (Figure 2b). The case for intra-spacecraft communication networks is similar.

For inter-spacecraft networks, network requirements are influenced by the distribution of the spacecraft within the swarm. The distance between the spacecraft is the main network-design factor. The range between the motes is influenced by the power available for transmission, the technology used, and the antenna. Higher power can result in longer range, but from a spacecraft perspective, it is required that the network be as power efficient as possible. Mesh networking as offered by ZigBee provides a solution, by routing data from satellite to satellite with several data hops, decreasing the required range of transmission between satellites, as depicted in Figure 2 [1].

Figure 3 shows an example with six satellites flying in formation. The distance between satellites 1 and 3 is d_1 , which is considerably larger than d_2 (the distance between satellites 1 and 2). Using mesh networking, satellite 1 can transmit to satellite 3 through satellite 2, decreasing the required range from d_1 (large) to d_2 (small).

3. Wireless Motes for Small Satellites

The wireless sensor nodes have specific requirements, which are limited by the wireless technology used and available power. Wireless nodes are likely to be powered either from battery cells or from the spacecraft itself. Several wireless standards exist, each one for a certain application field. For example, Wi-Fi, based on the IEEE 802.11n standard, is mainly for laptop and desktop computer networking, while Bluetooth, based on IEEE 802.15.1, is

Figure 1. The Xbow MICA2DOT mote [3].

Figure 2a. The mote configuration within a small spacecraft (6.6 kg nanosatellite).

Figure 2b. The configuration of motes within a 300-kg mini-satellite (the red dots indicate the nodes).

Figure 3. The multi-data-hop mesh routing for a spacecraft formation.

used for low-speed, short-range communications, e.g., between mobile phones and hands-free headsets. WiMAX, based on IEEE 802.16, is field tested to provide the last mile for broadband connectivity where cable and DSL are too expensive to be installed. WiMedia, based on IEEE 802.15.3, uses Ultra-wideband (UWB), aiming to replace cables between set-top boxes and display monitors. Although covering most of today's market needs, all of these technologies require a lot of power, making them unfavorable for space applications, where power consumption is important.

Considering the spacecraft requirements for intra-spacecraft and inter-spacecraft networking, a low-power, low-cost solution was proposed. ZigBee, based on the newly developed IEEE 802.15.4 standard, offers a simple networking solution. Nodes operating under ZigBee will self-organize to form a communication network inside and outside of the satellite. Each individual node will communicate with its neighboring nodes, forming a mesh network topology capable of accommodating up to 65,000 nodes on the same network [5]. Creating this mesh network, nodes which are not in range can communicate with each other by allowing packets to multi-hop to their final destination through intermediate nodes. This can theoretically extend the range of ZigBee networks to infinity, provided that nodes exist in between, not more than 100 m from each other. The packets will then hop from node to node until they reach their final destination. ZigBee does not require more processing power than an eight-bit microcontroller with onboard flash. ZigBee requires a low-duty cycle, and offers the ability to put 802.15.4 radios to sleep, which is the key to small power consumption. For example, consider the MICA2DOT (MPR510CA) [3] mote, which requires 24 mW active power and 3 μ W standby power, with a duty cycle of 0.1%, supplied by a 3 V 750 mAh battery cell. This will have a lifecycle of 27,780 hours, which is equivalent to three years and two months. Comparing this to the power requirements of Wi-Fi and Bluetooth, which can operate from a few hours up to a few days at the maximum, ZigBee has a clear advantage over these technologies.

ZigBee has a low data rate compared to other technologies, with maximum rate of 250 kbps when operating at 2.4 GHz with the use of directional antennas, making ZigBee suitable for intra-spacecraft communications. The MICA2DOT (MPR510CA) [3] mote has four channels and operates at 433 MHz with a maximum baud rate of 38.4 Kbaud, but it is expected that for a mesh network, the rate can be decreased by a factor of 10. Comparing with the existing CAN hardware, which offers a maximum rate of 32 kbps, the performance of ZigBee for intra-spacecraft communications is acceptable. ZigBee is a low-cost and long-lifetime standard for wireless communication, fully complying with the requirements of

a low-cost low-mass solution. Table 1 shows different wireless technologies under consideration for space-mission applications.

4. Formation Flying Application

Formation-flying (FF) technology enables many small, inexpensive spacecraft to fly in formation and gather scientific data by operating as a "virtual satellite." This "virtual satellite" concept lowers total mission risk, increases science data collection, and adds considerable flexibility to the missions. Satellites flying in formation will autonomously react to each other's attitude changes, requiring minimum intervention from the ground. Formation-flying satellites have the ability to collect data that was not feasible to collect from a single satellite, such as stereo images, or data from the same location from different angles.

Spacecraft payloads often have competing and conflicting requirements on a satellite's design. To achieve the highest rate of success, several additional redundant systems are included onboard the satellite, which impose additional overhead on the design and manufacturing processes. By separating the scientific instruments among the satellites of the formation, we can minimize the risk of the mission from total mission failure to instrument failure. Further to a mission failure, there is the potential for replacing the failed satellite with a new one.

Each satellite of the formation will be considerably smaller, lighter, simpler, simpler to manufacture, and mass produced to decrease the mission cost to a minimum. Formation-flying algorithms are primarily concerned with the maintenance of the relative location of the satellites in the formation. Each satellite will have its own attitude-determination and control system (ADCS), and all the usual subsystems, such as power and onboard computer (OBC), but the scientific payloads required for the mission will be distributed among the satellites. Each satellite needs to communicate with every other satellite to combine data readings from the instruments and the sensors, and to transmit that data to the Earth ground station.

A satellite cluster operating as a "virtual satellite" is a group of satellites within very close range of each other (100 m). Using distributed architectures for the different payloads among the satellites of the formation, and by using one satellite as the executive controller for transmitting data to the ground, we require a wireless bus among the satellites for data transmission, with higher data rates compared with CAN (Control Area Network). The required data rate of a nanosatellite like SNAP-1 [4] for a bi-directional CAN bus is 32 kbps, while the motes based on IEEE 802.15.4 used for testing offer a rate of 38.4 Kbaud at 433 MHz, with the capability to increase this rate to 250 Kbps with directional antennas at higher operating frequencies. The satellite having the executive controller on board will be responsible for transmitting the data captured from the formation to the ground station with an S-band RF downlink. Assuming a formation of several SNAP-1 satellites, the downlink data rate would be 38.4 kbps, or 76.8 kbps maximum.

Apart from ZigBee, WiMAX was examined for inter-satellite communication. WiMAX offers a much larger range, and its bandwidth requires excessive amounts of power, compared with ZigBee. For satellite-cluster missions, where distances between satellites are small and data-rate requirements do not exceed the requirements of a CAN bus, ZigBee was preferred for simplicity

Table 1. A comparison of wireless technologies.

	Wi-Fi	Bluetooth	WiMAX	ZigBee
Type	WLAN	WPAN	WMAN	WPAN
IEEE	802.11 a/b/g/n	802.15.1	802.16	802.15.4
Standards	Wi-Fi alliance	Bluetooth SIG	WiMAX forum	ZigBee Alliance
Range	100 m	10-100 m	50 km	30-100 m
Bands	2.4 GHz	2.4 GHz	2.5 GHz, 3.4 GHz	2.4 GHz, 866/900 MHz
Data speeds	11-54 Mbps	1 Mbps	280 Mbps	20-250 Kbps
Operation lifetime	Few hours	Few days	Mains powered	Up to years
Network topologies	Point-to-multipoint (star)	Ad-hoc	Point-to-multipoint, mesh	Mesh, point-to-multipoint (star), cluster tree

and efficiency. WiMAX is a technology considered for planetary colonies, currently conceptually planned for moon landings.

5. Conclusion

Wireless motes are currently being used for many intelligent, low-power applications in many areas of the electronics industry, such as the automotive industry. Wireless links can prove to be useful for spacecraft applications, particularly for small satellites. Savings in harness mass and the capability of employing motes for both intra- and inter-spacecraft applications makes the use of this technology very attractive. The advantages and challenges of using wireless motes for small satellites have been examined. Practical work currently in progress indicates the promise of near-term implementation of wireless motes on small satellite missions.

6. References

1. J. A. Guitierrez, E. H. Callaway, and R. Barrett, *IEEE 802.15.4 Low-Rate Wireless Personal Area Networks: Enabling Wireless Sensor Networks*, New York, IEEE Press, 2003.
2. V. Gupta, M. Wurm, M. Zhu, M. Millard, S. Fung, N. Gura, H. Eberle, and S. Shantz, "Sizzle: A Standards-Based End-to-End Security Architecture for the Embedded Internet," *Pervasive and Mobile Computing Journal*, 1, 4, December 2005, pp. 425-445.
3. MICA2DOT datasheet, Crossbow Technology Inc., <http://www.xbow.com/Products>, accessed April 24, 2006.
4. C. Underwood, V. Lappas, A. da Silva Curiel, M. Unwin, A. Baker, and M. Sweeting, "Using 'PalmSat' Pico-Satellite Technologies to Meet Mission Scenarios," 55th International Astronautical Congress, Vancouver, Canada, October 2004, IAC-04-P.5-A.01.
5. ZigBee specification sheet, www.zigbee.org, accessed February 2, 2006.