Wireless Intra-Spacecraft Communication: the Benefits and the Challenges

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***Abstract*— In this paper we present a systematic study of how intra-spacecraft wireless communication can be adopted to various subsystems of the spacecraft including C&DH (Command & Data Handling), Telecom, Power, Propulsion, and Payloads, and the interconnects between them. We discuss the advantages of intra-spacecraft wireless communication and the disadvantages and challenges and a proposal to address them.**

I. Introduction

No one making spacecraft today would argue in favor of hydraulics over fly-by-wire, but the argument to replace hydraulics with fly-by-wire technology in military and commercial aircraft was a long and hard fight. Ultimately, the benefits of weight and redundancy won the day for fly-by-wire.

Intra spacecraft communications is now in the same sort of battle contesting the benefits of wireless against the familiar (though heavy, bulky, and awkward) cable interconnects. It is somehow emotionally appealing to think of a copper wire connecting two points - what could go wrong with that? Well, add up the reliability of connectors - pin by pin - two connector assemblies per cable segment, interconnections, spares, orientation to ameliorate G forces, and annealing to prevent spring forces when it is heated and cooled. Add in the mechanical isolation requirements, and sectional seal challenges. The desirability of cables gets a little tarnished.

Precedents in favor of wireless for important strategic and uninterruptable communication date back to the early part of the 20th Century - when wireless was considered an improvement over wires which could be cut or damaged in times of war or by acts of nature.

Wireless is unfamiliar, as far as experience, for intra-spacecraft communication, however. Our modern experience with cell phones leaves us a little concerned over the day to day reliability. It was not always that way - consider broadcast FM radio - providing highly reliable coverage. If that kind of reliability is possible on intra-spacecraft communication, then why not use it?

II. Benefits of Wireless over Wired Datapaths

What are the benefits of wireless data interconnection? What are the design constraints and what are the performance promises that can be made? Benefits of wireless for intra spacecraft communication include reduced weight, multilevel redundancy, adaptivity, n path to n path switching capability - the possibility to add, delete, or re-purpose circuits on the fly, mechanical and electrical isolation, predictable balance/weight distribution, and the ability to coordinate data silences for science experiments. Taking each of these one at a time:

A. Flexibility

Expansion flexibility, in a cabled environment comes from allocating space and weight to spare leads, connector terminals and power. Adding a few circuits to a hard line after the cables have been made, the mechanical interconnections determined and the cable harnessing and mounting design impacts cost, schedule, reliability and is possibly a launch stopping exercise. To avoid this, cabled assemblies in military equipment may be required to provide 10% spares - one additional wire for each 10 wires in a harness. Spacecraft designs often include cables that are simply cut and thrown away at launch and different stages of the mission. There will be design limits to wireless path flexibility as well - but the cost of designing in spare capacity that is double or triple the forecast need is small, and the weight increase is negligible. To add spare circuits in the wireless domain is to allow for wider bandwidth, or more channel frequencies, and to provide the logic for accessing them.

B. Adaptivity

Adaptivity is an inherent benefit of wireless datapaths between modules and subsystems. Multi-string redundant spacecraft system are prohibitively expensive due to the fact that all resources in the system require cross-strapping to all redundant strings in the system. Wireless connectivity allows the cross-strapping to become almost free. In addition, any resource that can be re-used for different purposes at different stages of the mission can be freely re-purposed. For example, a flight

computer used for landing a lander can be re-purposed to do the job of a science computer after the landing has succeeded.

C. Redundancy

Redundancy in a wired situation requires multiple cables. A 100% redundancy requirement means doubling the number of wires and connections and providing the switching circuits to be able to transfer or arbitrate between paths.

Redundancy in the wireless domain will occur through redundant transmitters and receivers - but the weight increase is measured in milligrams, not kilograms. Furthermore, with path flexibility provided by frequency agility and protocol agnostic systems, such as Software Defined Radio architectures, multiple independent redundancies can be provided for each and every data path, if desired.

D. Interference

Initially, the idea that cabling can be shielded, and the shielding tested provides the mission designer with a sense of confidence that interference from datapath communications can be kept below a pre-defined level, assuring success.

The cost, in terms of weight, bulk and mechanical stability of shielding is high, however, and the level of interference from wired cables is *never* going to be zero.

Wireless communication in spacecraft will generate a certain amount of noise in the spectrum that they use. Since no scientist will accept engineering noise, deterministic or not, in their science data, we must come up with the means to completely notch out EM emssions on the spectrum that is used by science instruments and other critical avionics.

Existing methods that completely notch out emissions already exist. Time Division Multiple Access (TDMA) is a coordinated wireless situation where it is a relatively simple matter to have complete "radio silence" for controlled periods while performing sensitive science experiments. Signal shielding is then confined only to the housings of the electronic assemblies. New technology development (see Section V) in the area of spectral control will also lead to new methods that can avoid critcal spcetrum completely and allow continuous interference-free wireless operation.

III. Data Paths in Spacecraft Electronics System

Intra-Spacecraft Wireless Communication is a very generalized term, and it could have different meanings to different people. To a scientist, who can never have enough science instruments, wireless communication means less mass and volume in cables and therefore more instruments. To a spacecraft avionics system engineer, wireless communication gives him the ability to freely cross-strap components that would have require a large amount of cables that were not in the mass budget. To an avionics subsystem design engineer, the reduced number of physical I/Os means reduced time in getting his hardware out of manufacture and testing. To an ATLO (Assembly, Test, and Launch Operations) engineer, the sheer amount of savings in connector mating and demating means savings in time and possible mis-mates that would have damaged hardware. The spacecraft system is not a homogeneous set of interconnects, some parts of it can benefit from wireless communication more than others.

A. Spacecraft System Intercomm

The Spacecraft System Intercomm is the interconnect between almost all subsystems of a spacecraft. Typical uses include time synchronization and timing sensitive status and control messages to and from the C&DH [1, p. 100]. In most JPL-designed spacecraft, this role is fulfilled by the MIL-STD-1553 bus. The physical layer of the MIL-STD-1553 bus is a high-voltage differential signal with a peak voltage of 18-27 Volts [2, p. I-34]. The signal requires large transformers on each node, as well as termination resistors at each end of the bus. The bus uses a shielded "Triax" (3 conductors) cable, usually in pairs for a second redundant bus.

The transformers, transceivers, and the special connectors required for this bus can amount to a rather large surface area of the board utilizing the bus. The bus is also very inefficient in terms of transfer speed versus power used. A wireless interconnect can also address these shortcomings, with the added benefit or free cross-trapping. However, unlike Payload interfaces, a failure in the Spacecraft System Intercomm is potentially "mission-ending". For this reason, the role of Spacecraft System Intercomm should not be a near-term goal of intra-spacecraft wireless communication until the technology can be matured in other aspects of the spacecraft less susceptible to potential failures. In the meantime, a new generation of wired system bus technologies are being developed at JPL [3] to address the aforementioned shortcomings.

B. Payload/Sensor Interconnects

Payload subsystems such as science instruments communicate with spacecraft avionics typically for access to Telecom to send information back to earth. The current state-of-the-art JPL design is a synchronous serial data link. Missions such as MSL (Mars Science Laboratory) with a proposed payload of 11 instruments [4], each requiring at least one separate serial data link to the avionics, the potential weight-savings should not be ignored. In a separate smaller scaled mission, the Phoenix lander (built by Lockheed Martin Space Systems with instruments from JPL), the instrument count still numbered 6 [5]. Figure 1 shows an example of how much these cables can amount to in terms of mass and volume.

While we cannot accurately calculate the total number of signal wires required to operate each instrument without access to proprietary information, we can provide an educated guess. Each synchronous serial link require at least three signals to operate: Clock, Frame, and Data, with an additional flow control signal to avoid buffer overruns. Multiply this number by two to get the bidirectional link required for avionics to communicate with an instrument effectively, and we arrive at the number eight. We can also assume that differential signals are used by inter-module data links, which implies two wires per signal. This brings our total number of wires to sixteen per instrument, not including power lines and the signals that each

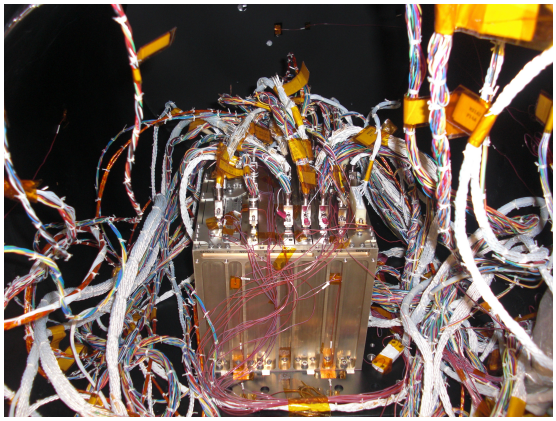

Fig. 1. Avionics Cables from a Subsystem

instrument would require on its own. With this information we can run a tally for some of the recent Mars missions (see Table I). Some estimates of weight can also be derived from the wire count as well, based on lab data collected during MSL bench tests. Take MSL's Payload cable for example, at 620 grams/meter not counting connectors and shielding, a mere 10 meter cable will weigh in at 6.2 kilograms. A wireless replacement for these wired interconnects will result in significant weight savings.

Mission	No. of Instruments	No. of Wires	Weight
MSL	10	160	620 grams/meter
Phoenix	6	72	280 grams/meter
MER	6	72	280 grams/meter

TABLE I
MARS MISSION INSTRUMENTS COMPARISON

In missions that require redundant avionics, wired interconnects between the redundant avionics and the single-string payloads need to be cross-strapped, as well. This gives wireless payload interconnects an additional advantage because wireless interfaces are inherently cross-strapped, therefore do not require a duplicate link.

An initial investment in wireless interconnects for science payloads is well-suited, given that connection between science payloads and the rest of the avionics are less critical for mission success, as long as the problem of interference is solved. At the same time, the weight-savings and the free cross-strapping capability make it a very attractive alternative to wired interconnects. In fact, we believe that these interconnects should be the first test object of a wireless experiment.

C. Payloads/Sensors Interconnects in Hard-to-Reach Places

Some missions require sensors that are mounted on hard-to-reach surfaces or at ends of long beams. We consider these a special category of interconnects due to their location and the special care needed for wired interconnects to reach them. One such example is the external MEDLI instrument (MSL Entry Descent and Landing Instrument) is a collection of 14 sensors located on the heat shield of the spacecraft. [6] These instruments are hard to reach by the main avionics computer via cables due to their unique location, and as a result, instrument data has to be relayed by special means different than other instruments. Instruments such as MEDLI are ideal candidates for being made wireless interconnects. The benefits here include: drastically reduced engineering complexity, reduced weight, and ease of detachment after the heat shield is thrown away.

D. Telecom Interconnects

The Telecom interconnect that we discuss here refers to the data link between the telecomm subsystem and the C&DH subsystem. In terms of the electrical signals and the low-level protocol used, these links are almost identical to the payload interconnects discussed earlier in Section III-B.

The Earth to Spacecraft communication is a low data rate circuit, compared to other intra-spacecraft circuits, and is one that can be easily coordinated with on-board wireless to enhance sensitivity or avoid interference, if necessary.

The continual operation of these interconnects are crucial to the operation of the spacecraft. But a short outage is not necessarily "mission ending." In additionally, due to its similarity to the Payload interconnects, the wireless technology developed for the Payload interconnects can be proved by future missions and applied to the Telecom interconnects after the performance and reliability are characterized and understood. Therefore, we consider Telecom Interconnects another good condidate for experimenting with wireless communication.

E. Ground Operations (Integration, Test, Assembly, and Launch)

Ground operations is somewhat of a separate topic from spacecraft design. However, it is an integral part of making a spacecraft fly. The ground operations from integration, test, assembly, to launch operations will also enjoy the some benefits from the adoption of wireless communication. Wireless communication reduces the chance of mis-mating connectors and causing damage to hardware. Flight hardware will require less connections to the GSE (Ground Support Equipment), and therefore easier to perform integration and testing.

Figure 2 shows one of the avionics boxes connected to its GSE racks for bench testing, the sheer amount of connectors (as many as 30 connectors per box) that must be connected introduces potential for human errors in mis-mating connectors. Using wireless communication for just a fraction of the interfaces can reduce the chance of mis-mating and increase the efficiency of integration and testing.

IV. THE CHALLENGE

The main unaddressed challenge of using a wireless system in past JPL flight projects is Electromagnetic Interference (EMI). All spacecraft subsystems are required to pass both the EM emissions and the susceptibility tests which differ from mission to mission, based on the environment and the design of the spacecraft.

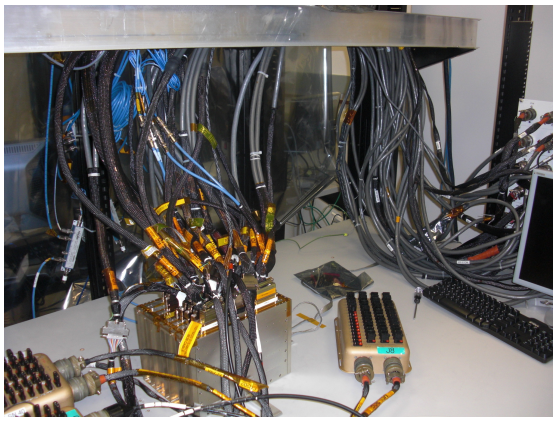

Fig. 2. GSE Cables during Bench Test

Commercial wireless solutions do not address this challenge because the commercial wireless industry does not have the same kind of requirements as the space industry. This challenge must be addressed by technology development initiatives in the space industry.

V. The Solution

A common "serious-joke" among receiver designers is that they want all of the digital communications frequencies to be located *above* their operating channel - so that harmonic interference does not affect them. While subharmonic interferences can occur, they are usually the result of higher frequencies and a non-linearity generating a heterodyne to a frequency lower than the main signal sources.

With a wireless system trunking, most of the data path communication, spectral control can be used to avoid critical frequency bands, or the communications can share those frequencies using time orthogonality (being off when the science measurement is made, and on when the science is off).

Spectral control includes locating emitters on frequencies away from protected channels, isolation in time and frequency, and active emission masking. Active masking is the process of "pre-distorting" a modulation to have predetermined areas of no signal. Pulse width and pulse frequency, for example, control the location of nulls and the separation of spectral lines in a pseudo-noise modulated (Direct Sequence Spread Spectrum) signal. Technology exists to allow relatively complex patterns of nulling - in a manner similar to classical filter design.

The authors developed a proposal [7] for a system to demonstrate the ability of a spread-spectrum wireless interface to mask its emissions and work alongside other spacecraft systems that are susceptible to EM (electromagnetic) interference. The proposal calls for the system to be tested in a test setup identical to one that is used by current JPL missions to characterize its EM footprint. If this proposal is given the go-ahead, it will lead the way in showing that wireless communication is a serious technology that can be used in a space environment.

VI. Conclusion

Wireless communication comes with its burdens: being a source of interference for other components of the spacecraft, being susceptible to interference caused by other components of the spacecraft as well as the environment, and the additional footprint occupied by the transceiver. All of these disadvantages can be mitigated by engineering or technology development.

Spacecraft avionics architecture with wireless communication enjoy reduce weight, increased flexibility, better redundancy and fault protection, and reduced complexity. If we can develop and mature the technologies to address the interference problem, wireless communication technology will enable new innovative spacecraft designs that enjoy all of the above benefits.

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