Intra-Spacecraft Wireless Link and Its Application to Spacecraft Environmental Tests

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(Received July 28th, 2015)

Replacement of the wire harnesses for data transfer used in a spacecraft with wireless links could reduce mass, enhance design flexibility, and simplify spacecraft integration tests. We have proposed a method for applying wireless link technology to the onboard data network of a spacecraft. In this paper, a commercial wireless device supplied by Oki Electric Industry that was developed for information and communications technology applications was assessed for this purpose. We conducted experiments and simulations to investigate its link performance in a spacecraft test model. Although a stable link between devices is established wherever the wireless device is placed inside the model, we observe a maximum space loss of 50 dB and estimate that an additional 40 dB design margin is required to cope with the fluctuating power level uncertainty arising from frequency channel choice and component location variance within the model. We also used the device to perform wireless sensor data transfer in spacecraft ground tests and determined that the device was suitable for such applications.

Key Words: Wireless Link, Intra-Spacecraft, Bus Lines, Ground Test

1. Introduction

Replacing wire harnesses for data transfer with wireless links could improve many facets of space activity performance.1,2) The easiest way to achieve this would be to directly import wireless standards such as the IEEE 802.1 and 802.2 families into the spacecraft. However, obtaining successful results using such a simple approach is difficult. Past examples of wireless communications applications, such as wireless LAN in the International Space Station, biotelemetry for astronauts,3) and structural monitoring of hard-to-reach locations,4) were to duplicate similar functionalities on the ground for manned missions and were designed to be used under astronaut’s oversight; applying such systems to unmanned missions, as we are proposing in this paper, is a different problem.

We are interested in developing an intra-spacecraft wireless link system to be applied to a data network of spacecraft bus instruments. Aside from issues of electromagnetic compatibility, adopting existing wireless standards faces problems in terms of radio frequency (RF) wave propagation inside the spacecraft.5,6) The interior of a spacecraft is shielded by metallic walls and behaves like a cavity, which can severely degrade the link capability of existing standards and make the design process to apply them much more complicated. To solve this problem, developing a wireless scheme with measures to resist echo-rich environments is necessary. According to our previous work,5) frequency diversity and delay spread control are inevitable for such spacecraft-based wireless link systems.

In this paper, we introduce a wireless module originally developed for information and communications technology (ICT) equipment, such as vending machines.7,8) RF propagation in a spacecraft is actually similar to such ICT equipment applications. In both cases, RF signals must travel in a narrow and small space enclosed by metals spread and produce multi-internal reflections. Based on our belief that an ICT device might also work in a spacecraft environment, we picked one developed by Oki Electric Industry for our study.

We experimentally investigated propagation and link performances of the Oki wireless module in a spacecraft model (a mock-up made as a structural test model of the REIMEI satellite, which was launched in 2005). Using ANSYS HFSS, we then numerically simulated propagation inside the model to better understand the results and compensate the experimental results. Based on these experiments and simulations, we discuss the capability of the device in our application.

Finally, we introduce preliminary results obtained by applying the module to spacecraft ground (vibration) tests. In previous ground tests, the cabling for monitoring sensors has proven to be a problem; this has created a great demand for the replacement of such cables with wireless links. As such, the results of this study represent an important advance.

2. Scope of Intra-Spacecraft Wireless Link

The scope of this technology is the replacement of cable interconnects between spacecraft subsystem components with wireless links. Here, both bus and payload subsystems are considered. We can also consider applying our results to sensor monitoring in spacecraft ground tests.

In Table 1, we summarize the bus data rates needed to carry out various missions. The data flow of onboard components is classified into three categories: telecommand, housekeeping (HK), and payload data. Though HK and payload flow is one-way, the telecommand flow needs answerback. The RS-422, IEEE 1553B, and SpaceWire10) based on wire interconnects have traditionally been used to implement data...
systems in Fig. 1 equals 38, and adding additional 20% spare channels, we obtain a maximum of about 45 channels requiring accommodation in our wireless application.

To summarize, the subject of this paper is a wireless link covering a data rate of up to 1 Mbps to be used for transmission of telecommand, HK, and payload data over more than 45 channels between subsystems linked in a star topology configuration with a data handling unit at its center.

3. Benefits of Intra-Spacecraft Wireless Link

The first benefit of using wireless links is the significant reduction in the use of wires. Table 2 lists the percentages of cable mass per total dry mass for several spacecraft. This figure is around 6% for a medium-class spacecraft ranging from 200 to 400 kg and can rise to greater than 10% for a small spacecraft of less than 100 kg or a large spacecraft of more than 1000 kg. Considering the empirical fact that one-third of the cable mass consists of data lines, we can expect a reduction of around 2% (between 4 and 8 kg) of a medium-sized spacecraft’s mass. However, the allowable mass of wireless modules introduced should be smaller than the lost wire mass to obtain the benefits of mass reduction.

Flexibility of spacecraft design is another benefit. The allocation of subsystems in a spacecraft is strongly influenced by factors other than performance optimization. Owing to wiring process constraints, components connected with a minimum loss must sometimes be placed far from each other on different boards of the spacecraft body. It is advantageous in such cases to use wireless interconnects as these generally ease integration constraints. By doing so, the limited space within the spacecraft can be used more efficiently. It is also possible to minimize the extra mass placement needed for mass balance because flexibility can allow for prior adjustments. However, this might not be fully possible in our case owing to remaining power lines.

Simplification of assembly, integration, and validation (AIV) operation is yet another beneficial factor. The fitting of each cable between component connectors takes a long time because hundreds of connectors are used in a spacecraft. Often, some of the connectors will not be appropriately mated, resulting in interruptions in the AIV process and seriously schedule delays. The use of wireless links reduces this risk and eases the AIV process; it is for this reason that we apply wire-
Table 3. Specifications of the wireless module under test.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>4.7 g</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Max. 66 mW</td>
</tr>
<tr>
<td>Size</td>
<td>36 mm(w), 21 mm(d), 11 mm(h)</td>
</tr>
<tr>
<td>Frequency band</td>
<td>2.4 GHz ISM band</td>
</tr>
<tr>
<td>Telecommunication scheme</td>
<td>Single carrier, FSK, FDMA</td>
</tr>
<tr>
<td>Transmission power</td>
<td>−10 to 0 dBm</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
<td>−90 dBm</td>
</tr>
<tr>
<td>Transmission data rate</td>
<td>2 Mbps, 1 Mbps, 250 kbps</td>
</tr>
<tr>
<td>Channels</td>
<td>73Ch</td>
</tr>
<tr>
<td>Maximum occupied bandwidth</td>
<td>1 MHz/Ch</td>
</tr>
<tr>
<td>Receiver dynamic range</td>
<td>More than 50 dB</td>
</tr>
<tr>
<td>Support for link establishment</td>
<td>Auto frequency coordination function in enclosed environment</td>
</tr>
</tbody>
</table>

The third factor is transparency for utilization. This means that the substitution of wireless for wired interconnects should be done so as not to change the current method for developing subsystems. On the users’ side there should be no need to develop new interfaces for adopting new technology; hence, the wireless module should work with any existing link layer network protocols used in the spacecraft. Although we will not discuss the integration of our wireless module with higher layers of protocols further in this paper, it is a significant issue.

5. Device under Test for Intra-Spacecraft Wireless Link

The specifications of the wireless module under test are listed in Table 3 and the device is shown in Fig. 2. The module, which is the latest version of device introduced in Ref-9), was originally developed for ICT applications and was not made for space use. As such, we utilize this module only to evaluate how it could work inside a spacecraft. Properties such as radiation tolerance will be taken into account separately and not discussed in this paper.

The specifications in Table 3 meet our requirements described in Section 2. The device is compatible with a maximum 1 Mbps transmission data rate and can accommodate more than 50 channels. The bidirectional star topology is configurable using one module each for transmission and reception occupying different channels.

This device realizes the robustness requirements of Section 4 by implementing a frequency coordination scheme9) that enables each module to have its own data table on the received levels of every channel used in the network. The access point is the transmission module at the hub of the wireless network. Comparison and coordination among the tables of the module determine the channel allocation in the network. Through this negotiation, each channel keeps a received level high enough to establish stable links inside the spacecraft. Because the propagation condition inside a spacecraft is usually invariable once its construction is completed, a one-time coordination on the ground is generally sufficient and repeated coordination is unnecessary each time the spacecraft is turned on. Hence, the channel allocation in this scheme is static. In cases where frequency alone does not solve the allocation problem, an option to add time-domain multiple access also exists.9)

The other requirements discussed in Section 4 were the compactness and the usability of the module. Although it was designed for use on the ground, the device in Fig. 2 is sufficiently small. It is important that such compactness be attainable for future flight models. The usability of the module is still being worked out and will certainly be solved before our flight model development.
6. Test Results Using a Spacecraft Structural Test Model

Figure 3 shows the mock-up spacecraft used in our tests. It was originally built as a structural test model of the REIMEI[12] satellite and has dummy mass bulks and a board structure to separate the interior into two rooms. One reception antenna is fixed at the position indicated in Fig. 3. We also place transmission antennas at 17 positions inside the model. Using these 17 pairs of transmission points, we measure RF wave propagation within the model using a network analyzer (Rohde Schwarz ZVT8). The antennas are prototypes we developed for wide bandwidth measurement covering 6 through 20 GHz. Each is a linearly polarized monopole antenna fabricated on a substrate and having an omnidirectional pattern.

We obtained propagation loss and coherence bandwidth (defined as 90%) from these measurements. The measured results are shown in Fig. 4. The markers in these plots correspond to the 17 measurement points, which are categorized into two groups. One group corresponds to line-of-site (LOS) propagation. In this group, the transmission and reception antennas are placed on the same side of the model’s separation board. In the other group, the antennas are on different sides of the board and are dominated by non-line-of-site (NLOS) propagation.

The propagation loss in Fig. 4 (a) is plotted as a line-of-sight distance between the transmission and reception antennas. The further this distance, the higher the loss. The dependency on distance for the NLOS group is not as clear as for the LOS group; loss in the former group, while obviously large, is less than 50 dB. The difference of loss between the LOS and NLOS groups is within 20 dB. We also see wiggling by as much as 20 dB in the LOS group and a fluctuation of 5 dB in the NLOS group as a frequency dependency averaged in time from 2,400 to 2,500 MHz. These fluctuations are apparently caused by the structure of spacecraft body. In addition to these variations, a ±20 dB noisy fluctuation before averaging from interference is also seen in both the LOS and NLOS groups. Hence, a further degradation of 40 dB must be taken into account in the total loss needed for link estimation.

Coherence was investigated to estimate the transfer data rate limit inside of the model. From Fig. 4 (b) it is seen that coherence bandwidth is greater than 4 Mbps and that there is a sufficient margin for the 2 Mbps specification in Table 3. There is therefore no need to add an equalization process under this condition. We can conclude from the coherence bandwidth measurement that level alone needs to be considered in designing links using this module, suggesting a hoped-for high degree of link simplicity.

Using ANSYS HFSS, we also performed a simulation on a spacecraft model to compensate for the shortness of the measurement points. The simulation model is as shown in Fig. 5; our simulation model differs from the structural test model in that the components of the latter are dummy-mass bulk objects while those of the former are realistic flight objects. Figure 6 shows an example of our simulation results, a YZ cross-section of Fig. 5 depicting how a 2.4 GHz signal emitted from a transmission antenna spreads into the model. In this simulation, complete shielding and no leak of RF waves outside the model are assumed for simplicity. The transmission antenna is also modeled as an omnidirectional antenna. We must still reconsider the matching condition for the antennas to enable more accurate and absolute quantitative comparison with the experimental results from Fig. 4; however, it is sufficient to discuss the relative difference of typical levels between two separated rooms, which reads within 20 dB in Fig. 6.
Camera

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thermal vacuum conditions. In such spacecraft the number of

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We also investigated the possibility of using our module in

expanding these results to a general spacecraft environment.

Finally it is notable that these are simply particular results

obtained using a single spacecraft model. The simulation dis-

played in our spacecraft model under the requirements of Section 2, level

is the only factor that needs to be taken into account for link
design. The averaged received signal level between modules
inside the model is as indicated in Fig. 4 (a). Furthermore, a

greater than 40 dB margin for enabling link establishment

should be maintained in order to protect the links from level
fluctuation owing to interference. In other words, this margin is
required to cover potential loss owing to position and fre-
cquency allocation uncertainty within the module. Corre-
spondingly, the sensitivity specified in Table 3 equivalently
becomes −50 dBm instead of −90 dBm in our case.

Finally it is notable that these are simply particular results
obtained using a single spacecraft model. The simulation dis-
cussed in this section is certainly a useful and effective tool in
expanding these results to a general spacecraft environment.

7. Application to Ground Tests

We also investigated the possibility of using our module in
spacecraft ground tests of vibration, thermal equilibrium, and
thermal vacuum conditions. In such spacecraft the number of
wires required for monitoring can reach as many as several

hundred. Replacing these with wireless links has therefore
been an attractive option, but no effective solution for doing so
that can work in any spacecraft environment has been found. We
believe that our wireless module has the potential to solve this
problem.

To test this, we performed a simple experiment (See Fig. 7)
in which we placed the reception antenna shown in Fig. 3
outside the model while varying its distance to the model. This
is the same configuration as, for instance, the vibration test
wherein measured data are transferred from within a spacecraft
to the outside. The path loss and coherence bandwidth were
again obtained experimentally. A greater than 2 Mbps link
from multiple points inside the model to the external point was
successfully established at up to 7 m in distance. No polariza-
tion-dependent phenomenon was observed in the transmission
antenna in this experiment. Hence, the wireless links seemed to
be stably established from any module inside of spacecraft
wherever and in whatever direction they were placed.

However, further adaptation of the module is necessary for
its practical use in ground tests. Necessary channel numbers,
transfer rate per channel, and demand for power supply natu-

rally differ depending on the nature of the tests. These factors
differ so much that the module would probably have to be
customized for each test; furthermore, the performance of the
module must also be modified to fit to a user’s requests.

We also conducted a test in which the module alone was
fixed on top of the vibration test machine (See Fig. 8). A paired
receiver module was placed on top of a table 3 m away from
the test machine. The inset of Fig. 8 shows a random vibration
condition imposed to the module. We applied random and
sinusoidal vibrations adopted from HAYABUSA2 and sound-
ing rocket missions; in each case, transmission was successful.

8. Conclusion

We have proposed a method for replacing wires for the bus
lines of a spacecraft with wireless links. We first clarified what
performance and functionalities are required for this purpose in
Sections 2 and 4. Then, in Section 6, we experimentally proved
that the wireless module for ICT applications developed by Oki
Electric Industry is quite suitable for our purposes and that it
performs in our spacecraft model in the same manner as origi-
nally designed. Combining experimental results with the
simulations, we preliminary obtained a link design requirement
of a 40 dB margin on the received level to secure robustness in
the link design discussed in Section 4. However, further in-
vestigation is necessary to extend our particular results ob-
tained for the spacecraft model used to general specifications
for any spacecraft. For this purpose, the simulation method
used in Section 6 will be effective. Our preliminary test results
also indicate that the device is promising for implementing
wireless links for spacecraft ground tests.

Acknowledgement

The authors would like to thank the REIMEI project team for
granting permission to use the structural test model of the
REIMEI satellite in our experiments and for providing nu-
Numerical structural data for our simulations.

Fig. 7. Application to ground tests for spacecraft.

Fig. 8. Wireless link test under the vibration condition required for spacecraft.

References

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