

Power Line Based LAN on Board the NASA Space Shuttle

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Abstract – Today in the construction of vehicles, ranging from automobiles, to ships, to aircraft, to the Space Shuttle, separate cabling is used to establish the underlying physical layer of a local command and control network. As LAN technology and associated networking protocols continue to advance, local command and control networks will evolve toward broadband local networks, supporting a proliferation of sophisticated devices and software-based applications. Without exception, vehicles have a power distribution system based on metallic conductors of some type. It would be advantageous to make this power distribution network perform double-duty, as an infrastructure supporting both power delivery and broadband digital connectivity. We study the possibility of re-using existing power cables on board the NASA Orbiter (also known as the Space Shuttle) for providing a backup LAN based on power line (PL) communications. We analyze (from a communications point of view) wiring and grounding practices on board the Space Shuttle with the goal of studying the theoretical performance of a PL modem operating on the existing PL infrastructure of the Space Shuttle. In particular, the channel transfer function of a typical PL link on board the Space Shuttle will be calculated and its theoretical capacity evaluated.

I. INTRODUCTION

An expected LAN environment on-board a spacecraft, including computers, data storage, servers, instruments and subsystems, all interconnected via Ethernet, FDDI and IEEE 1394 networking technologies is described in [1]. For many smaller space vehicles, such as satellites and unmanned probes, the on-board LAN will be fixed and optimized to the mission of the craft. But for larger manned vehicles, such as the NASA Space Shuttle, the Space Station and new designs, commercial high-speed LAN technology will be increasingly utilized.

The main backbone of manned space vehicles will likely be fiber-based, due to the light weight, high bandwidth and high noise immunity. However, fiber is somewhat inflexible, in that cabling has to be carefully installed and terminated on relatively sophisticated connectors which are subject to contamination and damage. Moreover, in mission-critical scenarios, a back-up network is required in case the primary LAN fails. This is likely to be a requirement for all new spacecrafts. Although networks can have built-in redundancy, such as a dual fiber backbone with automated protection switching, certain failures can still disable entire portions of the network. The best back-up networks are stand-alone, with complete redundancy and space-diversity of underlying media. Use of the power distribution network would provide

this space diversity, since standard engineering practices normally call for segregation of power and communication cables (or, this could be made an explicit requirement during construction of the craft). There are several other advantages in re-using an existing cabling infrastructure: no new wire installation, minimal additional weight to be taken into orbit (basically, the modem electronics but not the cabling), and the possibility of networking virtually all systems (since all use power) at the cost of adding only the modems (and not the cabling).

II. SYSTEM ARCHITECTURE AND CHALLENGES

As depicted in Figure 1, all systems on the Space Shuttle are powered by three fuel cells (FC), 28 Vdc nominal and structure grounded [2]. There are three DC and three AC redundant and isolated buses, any two of which can be tied together. AC power is obtained by static inverters, 3-phase, 4 wire wye connection, 115/200 VRMS at 400 Hz (neutral connected to structure ground). 1-wire and 2-wire (twisted pair) conductors with impedance ranging between 50 to 100 ohms are used to carry DC power, whereas 3-wire (75 ohm) cables carry AC power. Several levels of multiple branching are present, so that many levels of bridged taps over bridged taps are present in the PL links connecting two nodes.

Although the presence of three DC and three AC redundant and isolated buses provides some diversity that can be exploited by the PL system, there are also many challenges to overcome.

Fuel Cell (FC): the electrical model at low frequency is a capacitor with very high capacitance, therefore FCs basically act as shorts. This causes network segmentation: nodes in the front (nose section) of the Space Shuttle will not be able to communicate with nodes located in the back (tail section) or with nodes located close to the FCs.

Common mode: many connections are made with 1-wire conductors, so that signals use the ground itself (Shuttle's structure) as a return path. This is a very noisy configuration for telecommunications signal that induces common mode propagation. The presence of common mode currents on a cable does not inherently degrade the integrity of differential mode data signals. However, if mechanisms exist where energy can be transferred from common mode to differential mode, then the common mode current can become a dominant interference signal. This phenomenon is called mode conversion or mode coupling. Strong coupling between modes occurs at a few points in the space vehicle, most notably at the

points where 1-wire and 2-wire conductors are spliced together.

Topology changes: remote power controllers (RPCs) control several branches and may commute depending on the operating conditions of the Space Shuttle. Therefore, the link topologies between communicating nodes are time-varying.

III. FREQUENCY TRANSFER FUNCTION CALCULATION

Several approaches have been followed for characterizing the PL channel (PLC) [3]-[6]. In particular, an interesting approach is to describe the PLC as if it were affected by multipath effects [4], [5]. The multipath nature of the PL channel arises from the presence along the PL link of several branches and impedance mismatches that cause reflections. Although this approach has been proven to describe to some extent signal propagation along PL cables, the multipath model is an intrinsically incomplete description of the PLC and presents several disadvantages: resonant effects due to parasitic capacitances and inductances are not explicitly taken into account; there is a high computational cost in estimating the delay, amplitude and phase associated with each path; particular wiring and grounding practices are not included in the model. Furthermore, the multipath approach is based on a parametric model where the many parameters can be estimated *only after* having measured the PLC impulse response, thus limiting the capability of "a priori" channel modeling. The unavailability of a model that *fully* describes signal propagation along PL cables led the PL community to often reach overly pessimistic conclusions: the PLC is impossible to model *a priori*, does not allow for the superposition of effects, and has very little or no determinism embedded in it [7].

Previous approaches share a common deficiency in that they are only able to partially describe the underlying physics of PL signal propagation and, therefore, do not allow the unveiling of general properties or any embedded determinism of the PLC (see, for example, [12]). For this reason, we will use more accurate models for the PLC [13] to calculate a "typical" frequency transfer functions between nodes (e.g., sensors, computers, etc.) communicating on the space vehicle. In the next Sub-Section A, we will describe the general approach we followed for modeling the PLC using a multiconductor transmission line theory approach, and then we will particularize the model to the case of the Space Shuttle in Sub-Section B.

A. A Novel Approach Based on Multiconductor Transmission Line Theory and Modal Decomposition

Power cables used for single-phase indoor wiring are in general comprised of three conductors in addition to the ubiquitous earth ground. These include "hot" (black), "return" (white), and safety ground wires, all confined by an outer jacket that maintains close conductor spacing.

A three-conductor cable supports six propagating modes (TEM approximation); three spatial modes (*differential*, *pair* and *common* modes) each for two directions of propagation.

The *differential mode* (or balanced mode) current I_{dif} represents an "odd-mode" with current confined to the white and black wires and is generally the desired signal. The *pair-mode* (or longitudinal mode) current I_{pr} represents an "even-mode" with current flowing between the safety ground wire and the white/black wires "tied together". The two modes I_{dif} and I_{pr} are well confined to the cables and consequently exhibit low attenuation. The third *common mode* current I_{cm} represents overall cable current imbalance, which creates a current loop with earth ground. The differential mode current is almost always the functional current responsible for carrying the desired data signal along the line. It is possible to excite only a differential propagating mode along a TL by differential signaling. However, if there are imbalances or asymmetries between the conductors, common mode components may arise even when the conductors are differentially driven.

Building on a successful model for signal propagation in multi-pair category 5 UTP links [8] utilizing modal decomposition [9], the new approach described in [13] takes into account important grounding practices imposed by the United States National Electrical Code (NEC). Multiconductor Transmission Line theory (MTL) analysis involves breaking down a system of N conductors and a ground into N simple transmission lines (TL), each of which corresponds to a mode of propagation. Therefore, signals at the input of an MTL are broken down into modal components and sent down the proper modal TLs. For the particular case of three-conductor PL cables, it has been found that only two of the three modes of propagation are dominant [13]. One of the main advantages of the proposed approach is that it allows us to compute *a priori* and in a deterministic fashion the transfer function of any PL link by using transmission matrices, as is routinely done for the twisted-pair environment. To achieve this result, an equivalent circuit for the two dominant propagating modes along the cables is derived using MTL decoupling techniques. This will lead us to a model consisting of two coupled circuits representing the propagation and interaction of the two dominant modes. In particular, the first circuit accounts for differential-mode propagation while the second circuit accounts for the excitation and propagation of the pair-mode, which is the second dominant mode and arises prominently with certain grounding practices. This second circuit represents what we refer to as the "*companion model*." These two circuits are coupled through a transformer located at the principal point of mode coupling, i.e. the ground bonding. The presence of mode coupling and the excitation of the pair-mode have been neglected in previous studies.

The two circuit models obtained on the basis of MTL decoupling theory (the *differential* and the *companion* circuits) can also be represented in terms of cascaded two-port networks (2PNs) strongly coupled through a single transformer. Once the equivalent 2PN representation is obtained, it is possible to represent the PL link by means of transmission, or ABCD, matrices, exclusively. This approach

will allow us to compute *analytically* and *a priori* the transfer function of any indoor PL link, including in the model the topology and the specific wiring practices. Finally, as shown in [13], it is possible to mathematically prove that one of the consequences of a 2PN modeling is that the PLC, regardless of its topology, is isotropic, i.e. exhibits the same transfer function from either side, under the sole condition that the output impedance of the transmitter is equal to the input impedance of the receiver. It is worth pointing out that this symmetry property cannot be proven using the *Reciprocity Theorem*, which states that any transfer function with the dimension of impedance or admittance remains unchanged if the points of excitation and response are interchanged. In fact, the Reciprocity Theorem holds for transfer functions with the dimension of a transimpedance or a transadmittance and does not hold for dimensionless transfer functions. Similar considerations also apply to the telephone channel [10].

B. Application of the PLC Model to the NASA Space Shuttle

The general approach based on multiconductor transmission line theory developed in [13] can be simplified for the case at hand since we do not have 3-wire cables, but only 1-wire and 2-wire ones. Therefore, in our case, the only modes that are present are the differential and the common modes.

For our calculations, we will use the topology shown in Figure 2 which may well represent a possible topology of the PL link between nodes A and B. Note that there are cables with different characteristic impedance Z spliced together.

We make fairly mild assumptions when computing the frequency transfer function: splices between 1-conductor and 2-conductor PL cables introduce negligible mode coupling, differential signaling is used to communicate, and FC are somehow by passed. These assumptions imply that we neglect common mode propagation and excitation, and this can be considered nearly equivalent to underestimating the noise.

The calculated frequency transfer function is shown in Figure 3. The transfer function of any PL link on the Space Shuttle is likely to contain several notches due to the many and multiple bridged taps present in the topology. Channels that exhibit transfer functions such as the one shown in Figure 3 introduce strong Inter-Symbol Interference, thus requiring powerful nonlinear equalization techniques⁽¹⁾, combined with adaptive modulation and precoding techniques.

IV. CHANNEL CAPACITY CALCULATION

In order to calculate the Shannon capacity, we also have to define a noise model. We chose a pessimistic model (90% worst case as reported in [11]) typical for indoor power line networks (Noise Model A) and an even more pessimistic one (Noise Model B) obtained by increasing Noise Model A by 20 dB:

– Noise Model A: $-25 \cdot \log(f) - 94$ dBm/Hz, f in MHz;

– Noise Model B: $-25 \cdot \log(f) - 74$ dBm/Hz, f in MHz;

Other parameters used in the calculations are here listed:

– Coding gain: 5 dB;

– Margin: 6 dB;

– SNR gap: 9.75 dB;

– Maximum spectral efficiency: 10 bits/s/Hz;

– Bandwidth: 1-30 MHz.

On the basis of these parameters and assumptions, the Shannon capacity is plotted in Figure 4.

V. CONCLUSIONS

On the basis of our study, we found the following:

- Traditional PLC models are not suited to model the Space Shuttle PL environment.
- FCs likely create network segmentation, and means for by passing them are necessary.
- The Space Shuttle cable layout differs significantly from well-known topologies found in telecom networks and residential power lines.
- Noise may be considerable due to structural grounding, splicing between 1-wire and 2-wire cabling (common and pair mode excitation), and interference.
- Relative to the channel transfer function, attenuation is not problematic, but there are many frequency notches in the band of interest. Choice of modulation and coding schemes is critical.

Although a measurement campaign to obtain accurate noise models on the Space Shuttle are necessary to accurately assess achievable throughput, this preliminary study shows that throughputs of several tens of Mbps may be achieved at reasonable transmission power levels.

VI. REFERENCES

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⁽¹⁾ Due to the many frequency notches present in the PLC, linear equalization cannot be used because it would give rise to severe noise enhancement phenomena, a very serious drawback in a noisy channel such as the PLC.

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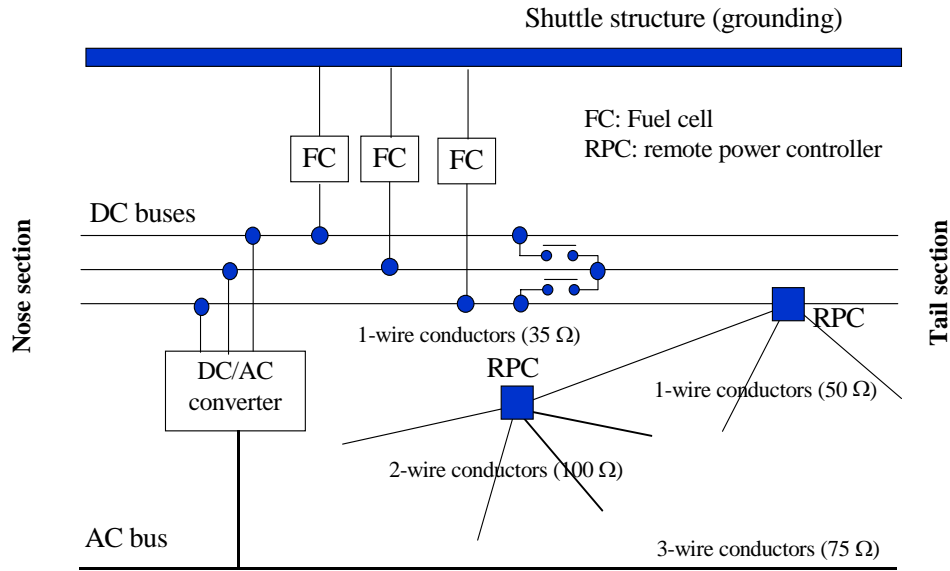


Figure 1: Power cabling on board the Shuttle.

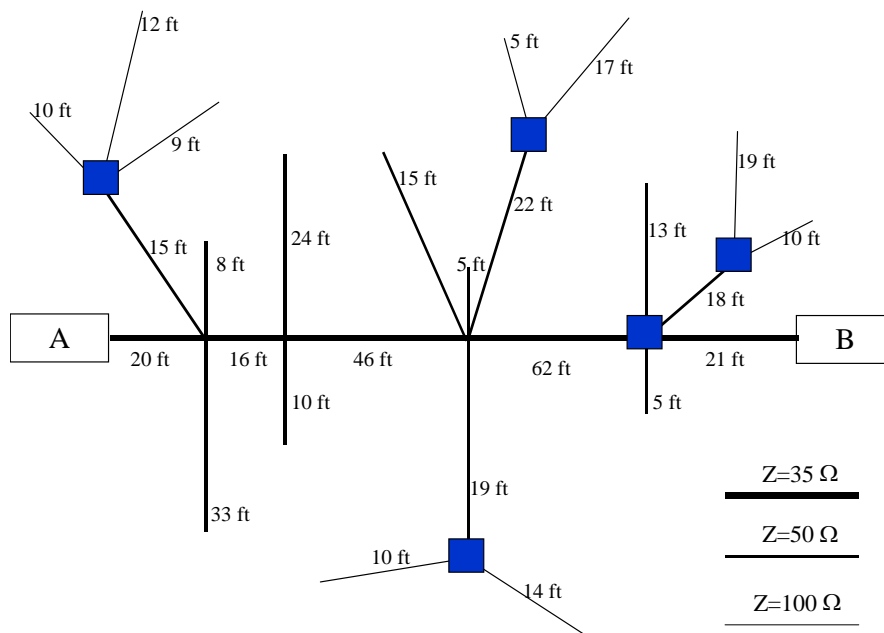


Figure 2: A realistic topology used for frequency transfer function and capacity calculations.

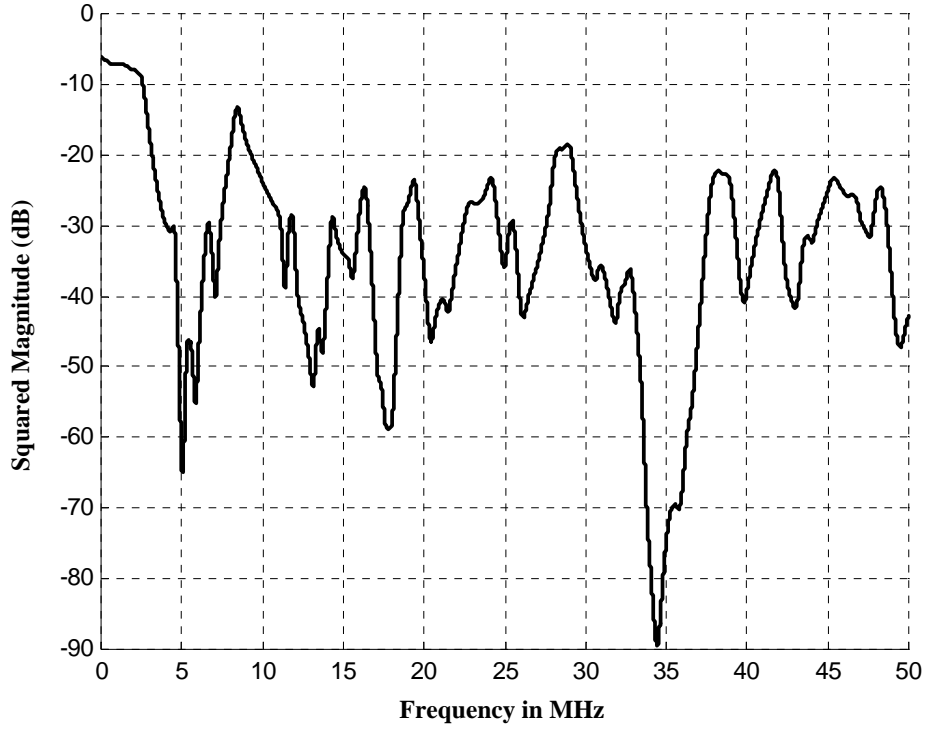


Figure 3: Frequency transfer function between A and B (see topology in Figure 2).

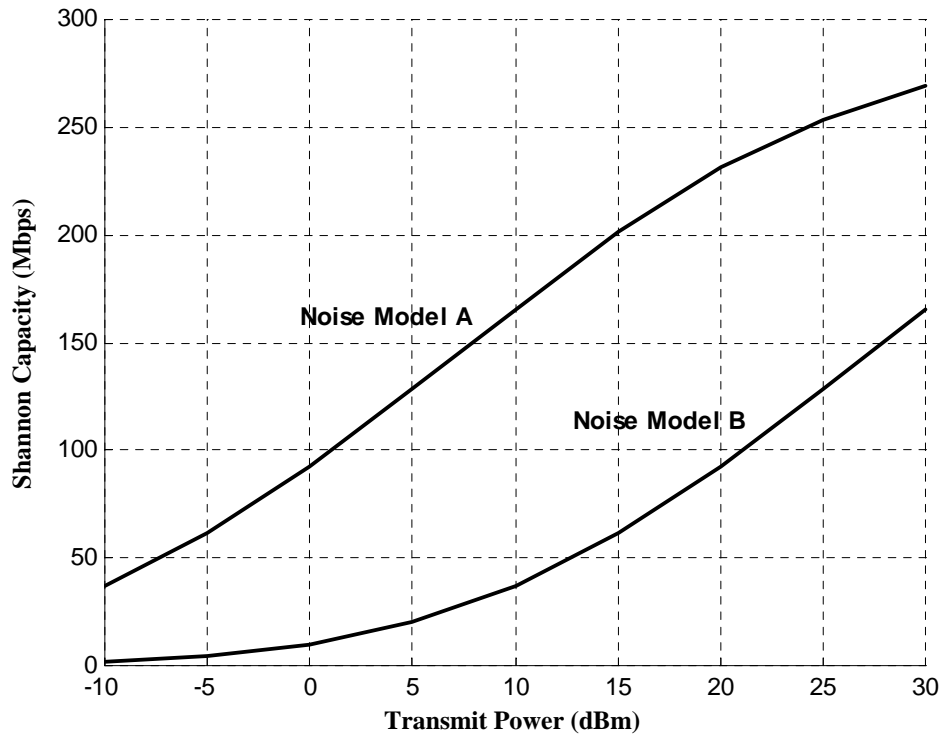


Figure 4: Shannon capacity of the channel with the transfer function in Figure 3.