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Performance of Centrifuge Data Acquisition Systems Using Wireless Transmission

ABSTRACT: Centrifuge testing requires transmitting data collected in a moving, increased-acceleration environment to a data acquisition system. Typical transmission methods include analog and digital data transmission through slip rings. However, these methods have often limited the accuracy of the measured data as well as the number of instruments that can be used in a test. A wireless ethernet data acquisition system was implemented for a centrifuge in this study. Using a computer equipped with a wireless ethernet card inside the centrifuge allows increased throughput while maintaining control of the centrifuge test by an external computer. Such a computer workgroup connected with wireless ethernet provides high throughput of noiselessly transmitted data. This approach allows a significant increase in the number of channels, and thus instruments, that can be used in a test when compared with other digital communication standards. An evaluation of the performance of this system indicates that the data throughput of the wireless system is consistently higher than conventional hard-wired serial communication systems, but depends on the g-level, transmission direction, and type of wireless card.

KEYWORDS: centrifuge, data acquisition systems, wireless communication, slip rings, digital transmission

Notations

DAS:	Data Acquisition System
dBm:	decibel referenced to one mW
EMI:	Electromagnetic Interference
GUI:	Graphical User Interface
HD:	Hard disk
IEEE:	Institute of Electrical and Electronics Engineers
LAN:	Local Area Network
MB:	Megabyte, 1 million bytes
PCI:	Peripheral Component Interconnect
PCMCIA:	Personal Computer Memory Card International Association
RAM:	Random Access Memory
VI:	Virtual Instrument

Introduction

Significant improvements have taken place in data acquisition systems (DASs) and in the quality of measurement instruments used in geotechnical testing. However, such advances have been limited in the case of centrifuge testing because of the moving environment of this experimental technique. Indeed, progressing instrumentation technology has significantly reduced the sources of noise and systematic errors to an extent that measurement now relies heavily on the quality of data transmission from the centrifuge model to an external recording computer. Consequently, the transmission characteristics of DASs have restrained the amount and quality of the collected data. The objective of this study is to evaluate the performance of several DAS configurations in a centrifuge environment. In particular, wireless transmission is implemented to reduce measurement dependence on the transmission method and to broaden the number of instruments that can be used to monitor centrifuge models. This study provides an overview of existing centrifuge data acquisition systems and their data transmission methods, highlighting the advantages and disadvantages. The characteristics of a recently implemented wireless transmission system are then presented. Based on the results of a series of benchmark evaluation tests, an analysis is provided of the transmission quality and data throughput of the wireless transmission system in relation to conventional DASs.

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Overview of DASs for Centrifuge Testing

Figure 1 summarizes different data transmission architectures for centrifuge DASs. Data transmission can be either analog or digital. While the analog acquisition of data is typically performed in real-time, digital acquisition can be done in either real- or delayed-time. Finally, real-time digital systems may be either serial or wireless.

Characteristics of Analog DASs

The sensors in geotechnical testing programs (e.g., pressure transducers, LVDTs, thermocouples) convert a physical phenomenon (e.g., pressure, displacement, temperature) into a continuous electrical signal, usually voltage. A DAS is then used to transmit the analog data signal to a recording computer. To decrease random error introduced during transmission, a signal conditioner is often used to amplify and filter the data signal before the signal is transmitted to the recording computer. Finally, the recording computer digitizes and stores the continuous data signal as a physical measurement for future analysis.

The data signal in an analog DAS is a continuous sensor output that corresponds to the measured physical phenomenon (Schmid 1970). The most common analog DAS configuration involves locating the recording computer outside the centrifuge. Since a continuous cable cannot be used to connect the sensor within the centrifuge to the external recording computer, slip rings located on the centrifuge axis are used to transmit the sensor signals outside the

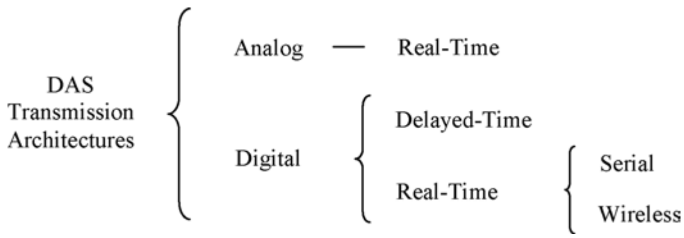

FIG. 1—*Alternative DAS data transmission architectures.*

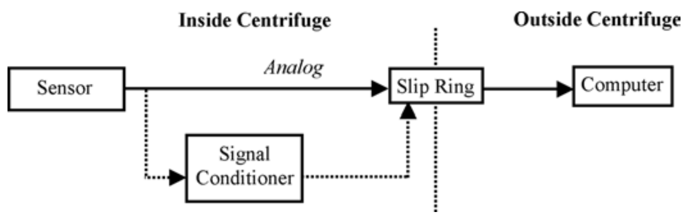

FIG. 2—*Block diagram for an analog data acquisition system.*

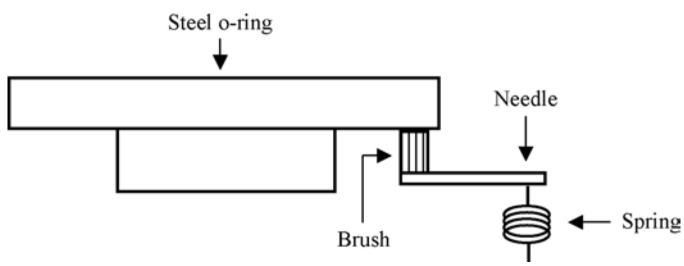

FIG. 3—*Schematic of a centrifuge slip ring.*

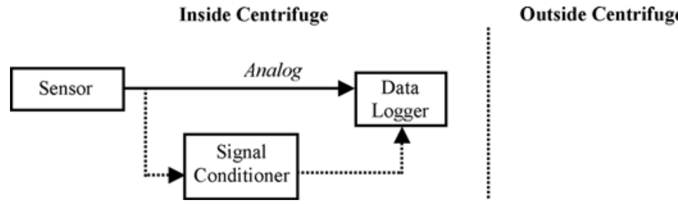

FIG. 4—*Block diagram for a delayed-time digital data acquisition system.*

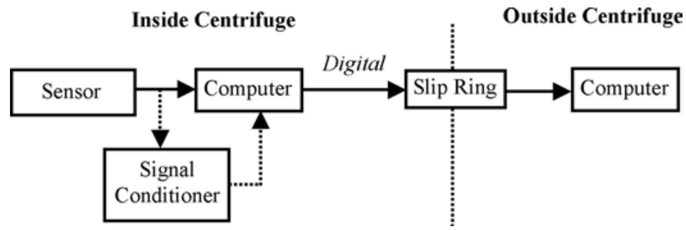

FIG. 5—*Block diagram for a real-time digital serial data acquisition system.*

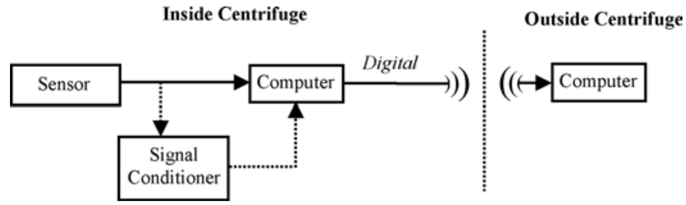

FIG. 6—*Block diagram for a real-time digital wireless data acquisition system.*

centrifuge (Fig. 2). Typical slip rings used in centrifuge apparatuses include four components: a stainless steel O-ring linked to the centrifuge rotation axis, a needle, a brush attached to the end of the needle, and a spring that compresses the needle-brush assembly against the stainless steel O-ring (Fig. 3). Each slip ring forms an electrical contact that defines an isolated electrical path that constitutes an analog instrumentation channel (Dief et al. 1998). Thus, the number of channels available is directly related to the number of slip rings installed on the centrifuge axis (i.e., one channel cannot be shared by two instruments simultaneously).

Characteristics of Digital DASs

Digital DASs include an analog-to-digital converter that receives the analog signal generated by a sensor, digitizes the signal, and finally sends the digitized data to the recording computer. A digital signal is characterized by a sequence of electrical pulses (bits) valuing at one of two set voltages (Tugal 1982). In this way, a digital signal can encode the physical measurement made by a sensor. Digital encoding significantly reduces the random noise introduced by data transmission through slip rings because the digitized data can be only one of two values, rather than a continuous range as the analog data.

A digital DAS for centrifuge testing may involve several design configurations. One of these configurations, a delayed-time digital DAS, involves replacing the external recording computer with an internal data logger. As described by Nelissen (1991), the data logger regularly digitizes and records the measurement during the test, and the data is downloaded from the data logger for later analysis once the test is completed. Figure 4 presents a typical configuration for a delayed-time digital DAS.

An alternate design is a real-time digital serial DAS, which uses two computers for data transmission to provide real-time monitoring during testing. A recording computer is installed outside the centrifuge, while the second computer is installed inside the centrifuge. The internal computer is located near the axis of the centrifuge to minimize stresses under increased g-levels. This computer digitizes the data signal and transmits the digitized signal through the slip rings to the recording computer using a communication standard such as RS-232 (Buchanan and Wilson 2001; Boyle et al. 1998; TRDI 1998). Figure 5 presents a schematic view of a real-time digital serial DAS.

Another design configuration is real-time digital wireless DAS, which also provides real-time monitoring during testing by using two computers. Also in this case, the analog signals generated by the sensors are digitized by an internal computer, just as in a real-time digital serial DAS. However, instead of using a serial communication, the computer transmits the data signals wirelessly to the external computer via a stationary receiver outside the centrifuge (Fig. 6).

Analysis of DASs

Although analog DASs (Fig. 2) minimize installation complexity, their transmission method depends on the performance of the slip rings. An equivalent electrical circuit for a stack of slip rings is illustrated in Fig. 7*a*. The rotating contacts in the slip rings may add noise ($v_{noise}(t)$ in Fig. 7*b*) to the data signal, often degrading signals prepared by the signal conditioner. In addition, the

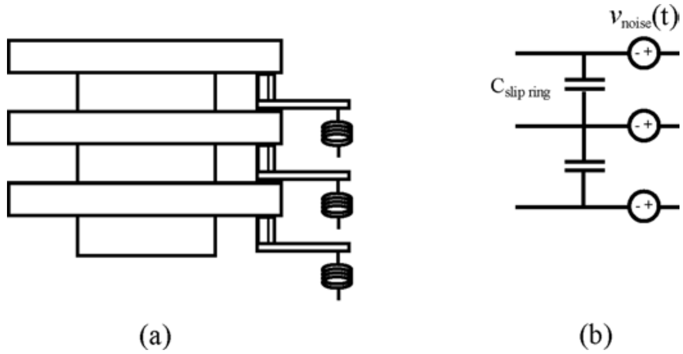

FIG. 7—*Equivalent electric circuit for a stack of slip rings: (a) slip ring stack; (b) equivalent electric circuit.*

capacitance ($C_{slip\text{-}ring}$ in Fig. 7*b*) between different slip rings may erode the signal strength and quality by introducing cross-talk (i.e., by passing one signal into another). The magnitude of cross-talk increases with increasing capacitance and with frequency content. The data signals may be particularly compromised when they are sent though slip rings that are adjacent to those carrying power into the centrifuge equipment because high-power affects the data signals. Slip ring friction and capacitance may also affect the control signals sent to an instrument located inside the centrifuge. In addition, each electrically isolated signal requires two slip rings to complete a circuit, which increases equipment cost requirements for tests involving electrically isolated sensors. The noise added by the slip rings may increase due to the wearing of the components. Thus, an analog DAS is adequate for tests in which the instrumentation is not sensitive to noise (i.e., provides a strong measurement signal). Consequently, an analog DAS cannot support high-sensitivity sensors or digital imaging without pre- and post-transmission signal conditioning.

While avoiding the pitfalls associated with the use of slip rings, delayed-time digital transmission (Fig. 4) may lead to problems associated with static testing or "blind in-flight testing." That is, measurements from the sensors cannot be monitored in real-time because the data is not transmitted out of the centrifuge, which increases the difficulty in test control and feedback. Also, the storage capacity of data loggers is smaller than that in traditional computers, limiting the test duration or complexity of the centrifuge model instrumentation.

Real-time digital serial transmission may provide improved performance over analog transmission, but it may involve throughput limitations. While the noise added by the slip rings does not affect the digital signal, communication standards such as RS-232 impose bandwidth limits on data rate and precision. For example, Buchanan and Wilson (2001) note that transmission rates for RS-232 cannot exceed approximately 19 600 bits/s (or 2.45 kilobytes/s where one byte is eight bits). For a given precision, a certain amount of bytes is required to encode fully the measured reading (Garrett 1981). Thus, higher precision requires an increased volume of transmitted data, which limits the number of sensors. Also, the inter-slip ring capacitance plays a larger role at higher transmission rates, which may further degrade the data signals.

Real-time wireless data transmission (Fig. 6) may successfully combine the independence from slip rings (as in the delayed-digital DAS) with the noiseless data transmission of digital DASs and increase the communication bandwidth. Wireless transmission minimizes the noise in data transmission by avoiding the use of slip rings. Finally, wireless technology offers a significant increase in bandwidth, allowing for more precise measurements and an increased number of instruments. Considering the advantages of this system, a DAS configuration based on real-time digital wireless transmission was implemented for this study.

Equipment Description

The real-time digital wireless transmission system implemented for this study uses an internal signal conditioning unit, an internal computer with a wireless ethernet Personal Computer Memory Card International Association (PCMCIA) card, an external wireless receiver (commonly known as a wireless hub), a local area network (LAN) switch, and an external computer with a Peripheral Component Interconnect (PCI) ethernet card (Buchanan and Wilson 2001). The PCMCIA card and the wireless hub conform to the Institute of Electrical and Electronics Engineers (IEEE) 802.11b wireless communication standard (Muller 1995) and transmit data at 11 megabits/s (Mbps) using a 2.4 GHz carrier. The LAN switch is a standard model capable of communicating at 10 or 100 Mbps.

The two computers exchange information in a workgroup, with the external computer controlling the internal one. Using the ethernet connection, a remote control program imports the desktop of the internal computer into the desktop of the external computer. The user can then command the internal computer to run a data acquisition program using the external computer during a test. The data acquisition program, or virtual instrument (VI), is specifically tailored for each test. The measurements are taken by the signal conditioner, which is controlled by the VI using a graphical user interface (GUI). The GUI is used to display measurements in a graphical format, to save the recorded data to the hard disk, and to give commands to the hardware and instrumentation inside the centrifuge. Also, the user can program the VI to create a web page that displays the measured data and provides the experiment controls. Consequently, a web browser running on the external computer can point to the web page created by the data acquisition program, import the VI's GUI, and give the user full control over the test remotely.

The signal conditioner chassis and the internal computer were installed close to the centrifuge axis to minimize the centripetal forces experienced during testing. Data acquisition modules slide into the signal conditioner. Consequently, the chassis was oriented so that the induced centripetal forces act parallel to the modules, preventing their bending. The computer was similarly aligned to protect the motherboard and the disks of the hard drive.

The internal computer chassis contains the centrifuge computer, the wireless transmission card, a data acquisition card that interfaces with the signal conditioning unit, and an oscilloscope for multipurpose uses. The signal conditioning unit includes twelve slots for sensor modules, providing good data acquisition versatility. For example, the configuration is currently using twenty sensors simultaneously (four load cells, eight LVDTs, and eight thermocouples). The internal computer's oscilloscope module permits the use of frequency domain reflectometry probes or other types of instrumentation for wave spectrum analysis.

The procedure for data collection involves running the respective VI in the computer located inside the centrifuge and recording the measured data on the computer located outside the centrifuge. As an example of the required throughput, a GUI involving five pore-pressure transducers and three load cells, collecting measurement every 5 s, generates a 735 kB data file after 3 h of testing.

An advantage of this system is that it can be easily upgraded to accommodate the advances in transmission as new generations of wireless ethernet technology develop. Specifically, only the

PCMCIA card and the wireless hub would need to be replaced to upgrade the system.

Performance Benchmarks

An important objective of this study is to document the performance of a real-time digital wireless DAS under normal and increased g-levels and to compare this performance with that of a traditional serial DAS using the slip rings. The configuration of the serial system is indicated in Fig. 5, and the configuration of the wireless system is indicated in Fig. 6. Four wireless systems manufactured by different companies were evaluated. The link quality can be quantified by measuring the number of lost or corrupted data packets. The wireless link quality and signal strength (in mW) were measured for every 5 *g* of acceleration to monitor the performance of the wireless connection.

In addition, the testing procedure involved quantification of wireless data throughput from the computer located inside the centrifuge to the computer located outside the centrifuge (download testing), and vice-versa (upload testing). Downloading and uploading procedures were carried out both from Random Access Memory (RAM) to RAM and from Hard Disk (HD) to HD. In this way, the ability of the internal computer's HD to sustain stress could be evaluated. Subsequently, throughput measurements were taken using a serial connection between the two computers (i.e., through the slip rings). All tests were carried out under normal, 40, and 80 *g* in order to evaluate the potential noise generation and throughput degradation as a function of increased acceleration.

Throughput was measured by copying a 33 MB file using a file-manager program. The file size is sufficiently large to maintain wireless transmission at full-load for almost 7 min. Data throughput was measured during 5 min of continuous data transfer and by defining average values over 30-s intervals.

Results of the Performance Evaluation

Figure 8 presents a typical measurement of two characteristics of the wireless link (link quality and signal strength) as a function of applied g-level. They are presented as a percentage of the initial (strongest) condition. The results show that both link quality and signal strength are essentially independent of the g-level.

Preliminary benchmarking results of the wireless throughput obtained in this study were alarming for two reasons. First, the wireless transfer rate was always less than the serial transfer rate. Second, the wireless data throughput consistently degraded by a factor of ten or more during the first minutes of network traffic for any acceleration. Both were caused by the comparatively low standard RAM of the internal computer. As observed in Fig. 9, increasing the RAM of the internal computer from 64 to 256 MB leads to increased and stable transfer rates. Inadequate RAM results in low throughput because the internal computer does not have sufficient memory resources to perform the wireless transmission tasks.

Figure 10 shows the wireless data throughput under an acceleration of 80 *g* for one type of wireless card (Brand C) compared against the serial data throughput. The acceleration was held constant with time for the different data transfer styles (RAM-RAM and HD-HD). As shown in the figure, the wireless transfer rate does not decrease with time, suggesting that increasing the RAM of the internal computer eliminates the time dependency of the system. In addition, the HD of the internal computer is not noticeably affected by increased *g*-levels because the transfer rates of the RAM-RAM and HD-HD trials are approximately constant. As also seen in Fig. 10, wireless uploads (transmission from the external to the internal computer) are consistently faster than wireless downloads (transmission from the internal to the external computer), while serial transfer rates are approximately constant regardless of the transfer direction. Wireless uploads are faster because the transmitting side (the wireless hub) has two antennas. Since the field strength is doubled, the generated signal is easier for the wireless card to receive. On the other hand, downloads are slower because the transmitting side (the wireless card) has a single antenna, which generates a comparatively weaker signal than is received by the wireless hub. The

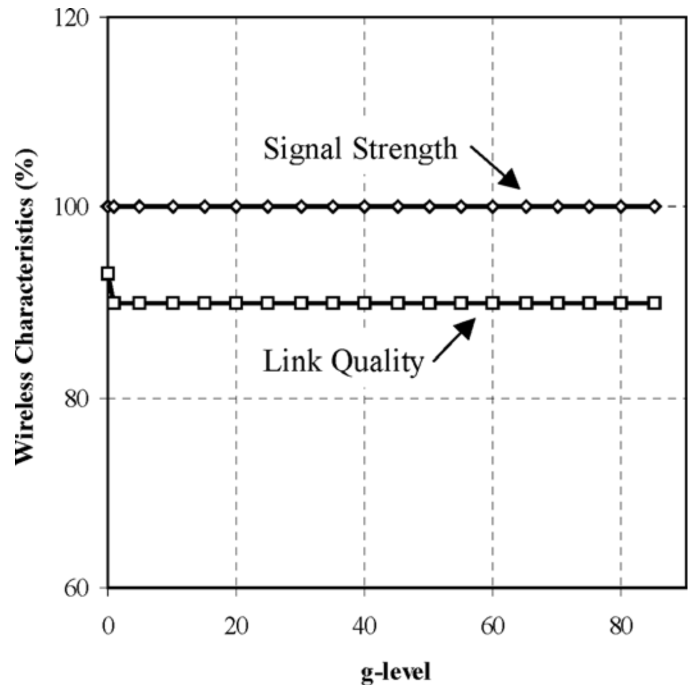

FIG. 8—*Wireless link quality and signal strength.*

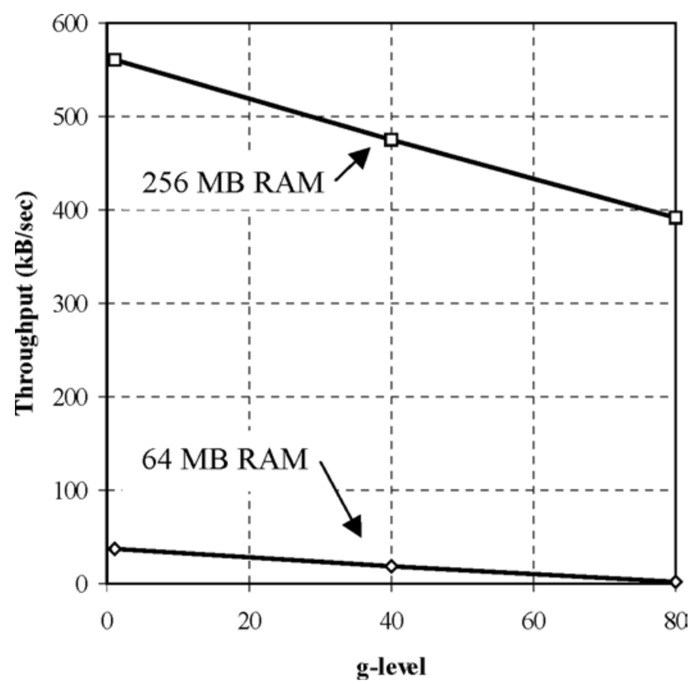

FIG. 9—*Effect of RAM on wireless throughput.*

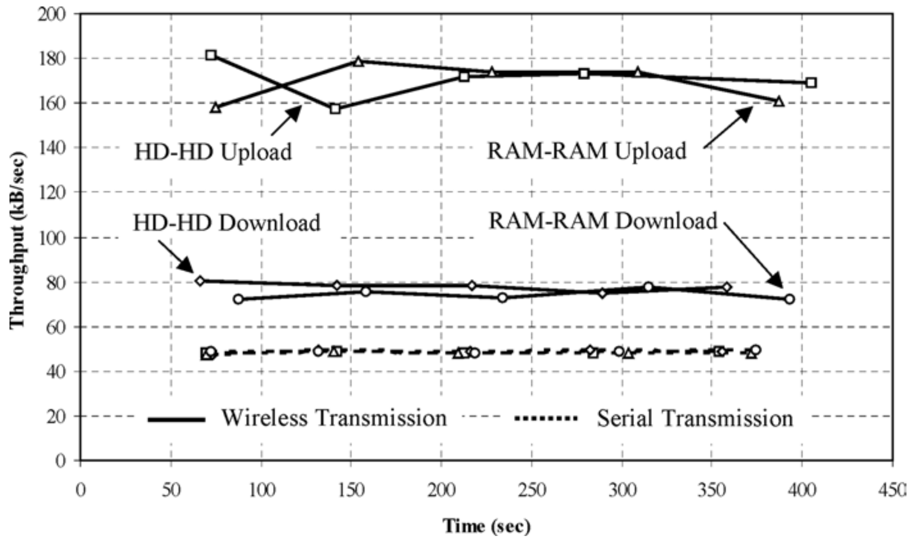

FIG. 10—*Data throughput under 80 g.*

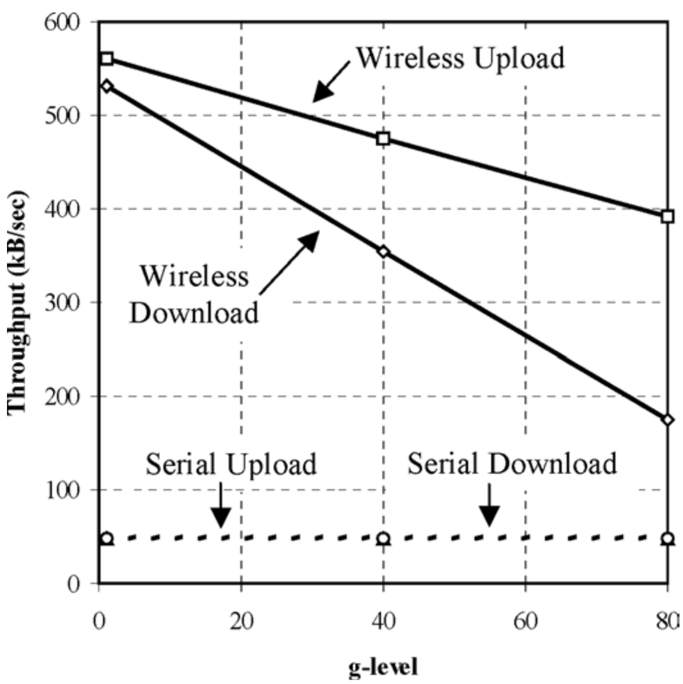

FIG. 11—*Effects of acceleration on wireless throughput.*

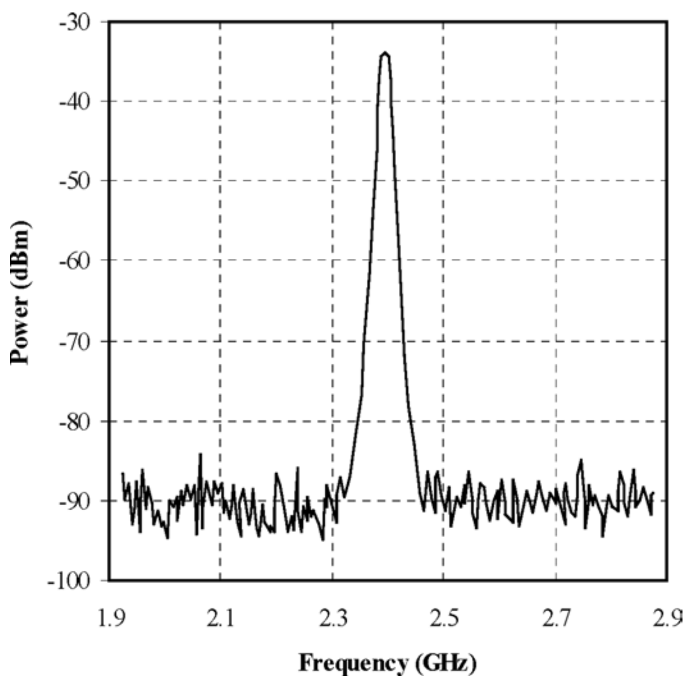

FIG. 12—*Typical EMI measurement for an antenna of the wireless hub.*

serial communication under 80 g (48 kB/s on average) is consistently slower than the wireless communication under 80 g. Similar throughput was obtained for the serial communication under 40 g and under normal gravity.

Figure 11 shows the effect of increasing g-level on the throughput for both the wireless and serial systems. The figure shows results for both upload and download transmissions. The wireless results are those obtained using Wireless Card B. As observed in the figure, the serial throughput is independent of the g-level, suggesting that the internal computer's hardware is not affected by the g-level. The wireless throughput is always greater than the serial throughput (48 kB/s). However, the wireless throughput decreases with increasing g-level. Specifically, the wireless download throughput is initially 11 times greater than the serial throughput under 1 g, but is 3.7 times greater than the serial throughput under 80 g. Similarly to Fig. 10, wireless uploads are faster than wireless downloads.

The reason for the overall decline in wireless throughput performance with increasing g-level was assessed in this study by evaluating the effect of electromagnetic interference (EMI), the location of the wireless hub antennas, the acceleration-induced forces on the PCMCIA card, and the type of wireless PCMCIA card. The effect of EMI was evaluated because, as the centrifuge spins, the slip rings may interfere with the wireless transmission if they generate noise with power in a frequency similar to that of the wireless system (2.4 GHz). To assess such potential interference, a spectrum analyzer was used under 1, 40, and 80 g to measure directly the power spectrum received by the antennas of the wireless hub. Figure 12 presents a typical noise measurement from the antenna under 1 g. Essentially the same results were obtained under 40 and

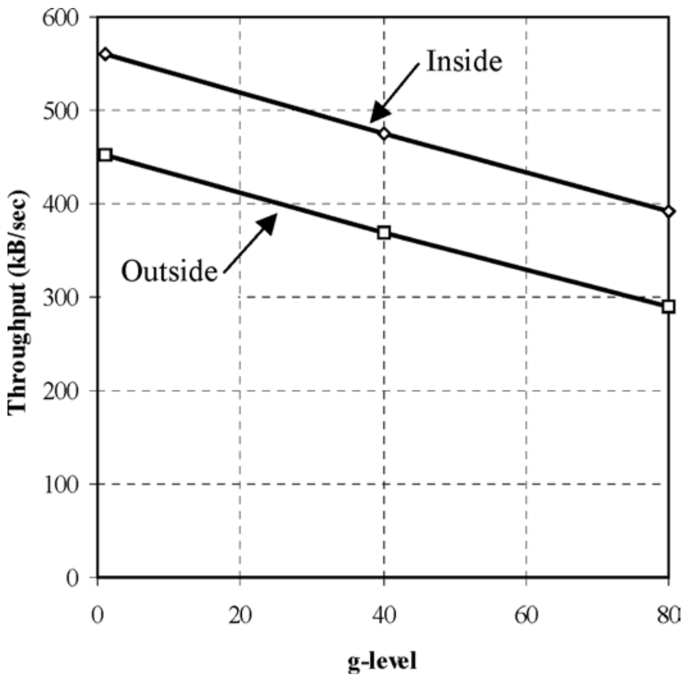

FIG. 13—*Effect of the location of the wireless hub antenna.*

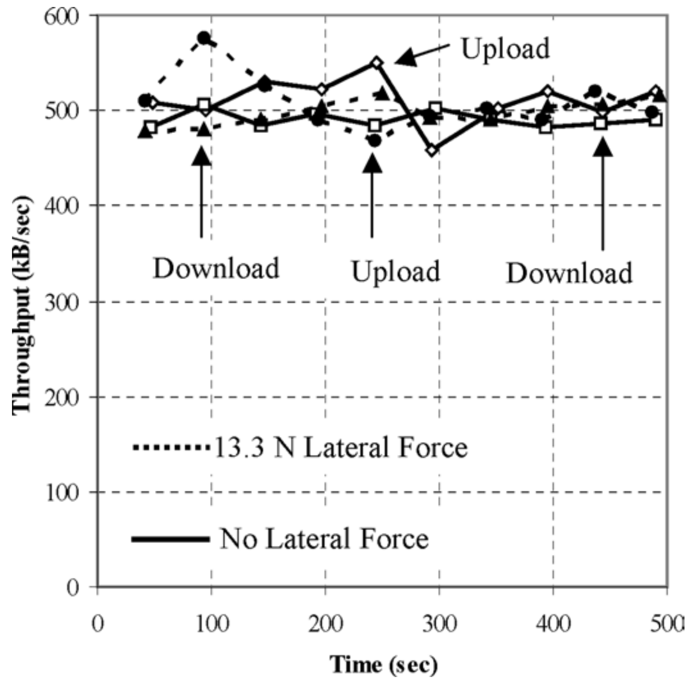

FIG. 14—*Effect of lateral force on the connection of the PCMCIA card.*

80 g. Had EMI been present under higher g-levels, the noise floor (approximately – 90 dBm in Fig. 12) would have increased in magnitude, thus making the data signal more difficult to recognize by the wireless system. However, the noise floor was always at least 50 dBm below the wireless signal (−33 dBm in Fig. 12). This indicates that the wireless link is well defined and the only signal present in the frequency band of interest. These measurements verify that the rotating slip rings (or any other source of EMI) do not interfere with the wireless transmission.

Another possible reason for the decreasing throughput with increasing g-level is the position of the wireless hub antennas. To quantify this variable, the average download throughput was measured for different locations of the wireless hub antennas. Figure 13 presents the results obtained using Wireless System B. The results show that the throughput is higher when the antennas point inside the centrifuge. However, both locations show a similar decreasing trend in data throughput with increasing g-level.

As previously mentioned, the constant throughput obtained using serial transmission under various g-levels suggests that the internal computer's hardware is not affected by increased g-levels. However, forces induced on the connection of the PCMCIA card could still be a possible cause for the decreasing wireless throughput. This is because the location of the wireless card in the centrifuge is such that the induced centripetal forces act not only by increasing its seat in the computer, but also laterally. These lateral forces may adversely affect the wireless throughput. To evaluate the effect of lateral forces on the PCMCIA card, a lateral force equivalent to that generated under 80 g (13.3 N) was radially applied to the PCMCIA card under 1 g using a calibrated spring. A 33-MB file was transferred between the two computers while applying the lateral force. As shown in Fig. 14, the wireless throughput remains approximately uniform and independent of the applied lateral force. Thus, body forces acting on the connection of the PCMCIA card are not responsible for the decreasing wireless throughput with increasing g-level.

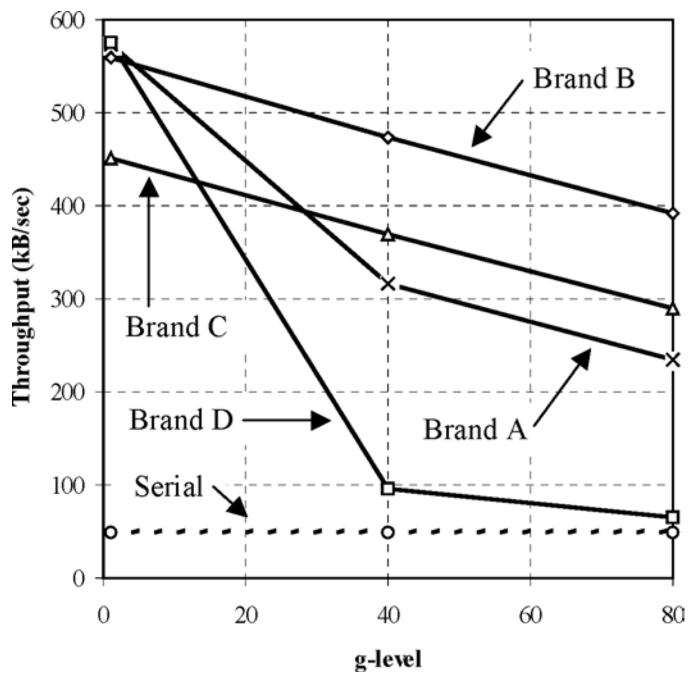

FIG. 15—*Wireless system performance for different cards.*

Figure 15 compares the average throughput performance of each wireless card type (from different vendors) for the case of upload transmission. As observed in the figure, increasing g-levels lead to a decrease in the communication throughput for all wireless cards. However, the magnitude of the decrease is highly sensitive to the card type. As shown in the figure, Wireless Cards B and C are less affected by the increasing g-level. In spite of the effect of the increasing g-level, the wireless throughput is always greater than the serial throughput. Specifically, the wireless throughput is 9.4–12 times greater than the serial throughput under 1 g and

1.3–8.2 times greater under 80 *g*. Since the external housing of the PCMCIA card does not become disconnected by body forces, internal components of the different PCMCIA cards are sensitive to *g*-level and responsible for the decreased performance. The different PCMCIA wireless cards include solid-state memory and controllers, which are circuits made of silicon crystal, as well as various discrete components such as resistors and capacitors. While the specific architecture of the wireless cards is proprietary information, all components are soldered to a circuit board, forming a rigid mechanical assembly. Consequently, these card components are not expected to be susceptible to increased *g*-levels. The wireless cards also include an antenna or electrical conductor. Unlike the circuit board components, the antenna is likely more sensitive to increased *g*-levels because it may change shape and bend under increased acceleration. Shape changes in the antenna leads to an alteration of its transmission and reception characteristics, since its beam width or "line of sight" becomes distorted (Lytel and Waters 1976). Consequently, among the different variables that may affect the transmission throughput, particular attention should be paid to the selection of the type of wireless card.

Conclusions

The performance of real-time wireless data transmission in a centrifuge DAS was evaluated and compared to that of traditional serial transmission. The following conclusions may be drawn from this study:

- Variables that affect the wireless transmission throughput include the computer RAM, antenna location, and type of wireless card.
- Electromagnetic interference and body forces on the wireless card were found not to affect the wireless throughput. Also, the wireless link quality and signal strength are independent of the *g*-level.
- The internal and external computers should have adequate RAM (at least 256 MB) to achieve reliable performance of data throughput over time. With sufficient RAM, the wireless throughput was observed not to decrease with time.
- The internal computer's hardware was found not to be affected by increased *g*-levels. RAM-RAM and HD-HD transfers showed similar rates.
- Serial communication was observed to be independent of the *g*-level and of the direction of data transmission (download and upload). However, wireless transmission was always faster than serial communication (at least 3.7 times greater than serial throughput for the cases investigated in this study).
- Wireless throughput was observed to decrease with increasing *g*-levels. The decrease is attributed to the effect of acceleration on the antenna of the wireless card.

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