PERFORMANCE, COST & RELIABILITY BENEFITS FOR TELEMETRY PROCESSING APPLICATIONS

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ABSTRACT

GSFC in keeping with the tenets of NASA has been aggressively investigating newer technologies for spacecraft and ground communications and processing. The application of these technologies, together with standardized telemetry formats, has made it possible to build systems that provide high-performance at low cost in a short development cycle. The High Rate Data (HRD) Broadcast System is one such effort that has validated NASA's push towards faster, better and cheaper telemetry processing systems. The HRD system architecture is based on the Peripheral Component Interconnect (PCI) bus and VLSI Application-Specific Integrated Circuits (ASICs). The telemetry processing system, which performed at rates of up to and greater than 100 Mbps per channel sustained through two cards developed in-house to demodulate and process the telemetry stream, was prototyped using a standard Personal Computer platform with a 900 MHz CPU with a standard NT 4.0 operating system.

The system can be configured as a two-channel system, one stream for weather data and the other for conventional CCSDS telemetry. The weather data stream "return link" data processing solution is capable of ingesting weather satellite telemetry and performing frame synchronization with CRC and/or Bit Transition Decoding. The conventional CCSDS data stream "return-link" channel ingests CCSDS satellite telemetry and performing Reed-Solomon error detection/correction and CCSDS AOS Service/Conventional Telemetry processing in Real-time. The advantage of moving towards the integrated processing element is low cost, higher reliability and most of all high performance. This paper identifies the cost drivers for such a system and demonstrates the performance, cost and reliability benefits of using this technology for processing direct broadcast telemetry.

1. INTRODUCTION

Consistent with the edicts of faster, smaller, and cheaper, GSFC's Microelectronics and Signal Processing Branch developed ground processing systems whose goal was to maintain performance while dramatically decreasing the manufacturing costs. To increase cost-effectiveness, new elements were added so that these ground-processing systems provided all telemetry acquisition and processing functions from receipt of raw telemetry at the antenna to generation of user data sets. Considerable effort was expended to develop a low-cost, integrated, and transportable ground system for the acquisition of data from low-earth orbiting satellites.

Currently, there are no processing elements available that ingest and process telemetry data at high rates in real time. To fill this vacuum, telemetry ASIC development by NASA GSFC Microelectronics and Signal Processing Branch has to date resulted in faster solutions than any other chips identified by research for this paper. The application of these technologies, together with standardized telemetry formats, has made it possible to build systems that provide high-performance at low cost in a short development cycle. The HRD validates NASA's push towards faster, better and cheaper.

2. HRD SYSTEM OVERVIEW

HRD combines the entire framework from data acquisition through to the level 0 data product generation into a single desktop box. This includes an infrastructure that allows for future performance and functional upgrades. The HRD is based on a commercially available platform and a standard PCI bus. Principal elements are the High Rate Digital Receiver (HRDR) Card and the Return Link Processor (RLP) Card, with the associated software for both cards.

The HRDR uses specialized processing techniques implemented in VLSI CMOS ASICs to provide receipt of modulated RF signals at rates up to 150 Mbps and beyond. Further enhancements could include modules for fast disk array storage, and level one image processing. The RLP includes functions for frame synchronization, Reed-Solomon error correction, and service processing at rates over 300 Mbps.
The service processing includes all CCSDS-defined services (VCDU, Insert, VCA, bit stream, path packet, and

encapsulation) at rates over 200,000 packets per second. These functions were implemented in high-density 'system-in-a-chip' ASIC components.

Figure 1. HRD Prototype

The software components of the system are made up of two elements. The first element, referred to as the Internal Control Software, is the control and monitoring system, which configures the two PCI cards prior to a data downlink session, enables the ingest and processing of telemetry, and monitors the progress of the processing. The second element, referred to as the Level Zero Processing System Software, is responsible for manipulating the stored frames and/or packets files output from the RLP, and producing data products that adhere to the format specified in the mission Interface control documents. For example, in the case of Terra, the data products are Production Data Sets (PDS) files. These data set files consist of separate files sorted for each Application Process Identifier (APID) in the case of Packet Data, or Virtual Channel Identifier (VCID) in the case of CCSDS Frames.

The weather data files produced for the end users will follow the format specified by the respective control documents.

3. SUBSYSTEM ANALYSES

The performance, cost and reliability benefits of the HRD system are demonstrated from the analyses carried out on its precursor, the High Rate Telemetry Acquisition System, a prototype to validate the new ASIC technologies; and the analyses comparing the Digital Receiver with traditional Analog Receivers. The first subsection analyzes the RLP Cost versus Performance, Reliability and Replication. The next subsection performs a similar type of analysis on the HRDR.

3.1 RLP – Cost & Performance

To evaluate the performance benefits relative to a cost basis, we first assign weightings to the performance factors. For example, the primary aim of a telemetry processing system is process all the telemetry down-linked from the spacecraft. This means that we should keep the losses to a minimum, and hence the 'Minimize Data Loss' criteria may be classed with a weight of 1, 0.1 being the least. Similarly the following table lists the performance criteria and the respective weights assigned to each of these criteria.

These requirements are assigned to a system using these technology options and an equivalent traditional system that does not use the plug-and-play paradigm. Using relative cost terms, the cost assignment for the traditional system assumes $100,000 per man-year, and the cost of a high-end computing environment to be $250,000 per workstation. Using the assigned weightings and the Cost Benefit ratios, the Cost-Performance Benefit for each task and the overall system may be calculated.

$$\text{Cost-Benefit Ratio} = CR = (\text{Cost})_{HRD} / (\text{Cost})_{Traditional}$$

$$\text{Cost-Performance Benefit} = CR \times HRD_{Weighting}$$

Performance Criteria	Factors	HRD Weighting
Minimize Data Loss	Accommodate Data Rate Ingest all telemetry Detect & Correct Errors at Rate Capable of Back-to-Back Processing	1
Maximize Data Processing	Accommodate all Services at Rate Detect & Account for all Telemetry	1
Minimize Availability Delays	Provide Source Data in Minimum Time Provide Real-time Data in Near Time	0.8
Maximize User Capability	Graphical User Interface for Operations, Configuration, and Control	0.5
Maximize Flexibility	Accommodate New Missions & Standards	0.4

Table 1. Performance Criteria

Task Assignment	HRD	Traditional System	Cost Benefit Ratio	Cost Performance Benefit
Ingest & Error Detection	230,000	500,000	2.17	2.17 x 1
Error Correction & Packet Extraction		350,000	1.52	1.52 x 1
Level-Zero Processing		450,000	1.95	1.95 x 0.8
Back-end Processing & Distribution				
Graphical User Interface	5,000	10,000	2.0	2.0 x 0.5
Build-in Capability for Future Needs	50,000	200,000	4.0	4.0 x 0.4
		Subsystem Cost-Performance Benefit :		7.85

Table 2. Cost Performance Benefit

3.2 RLP – Cost & Reliability

The functional reliability depends on whether the objectives are met and how well and whether they are repeatable. The performance aspect is the quality and timeliness of the functions being performed and the lifetime of the system. What this means in quantitative terms, is that the system is graded as to (1) how much of the functional requirements are met, and (2) how well have they been met. The functional task has to be repeatable 100% of the time over the lifetime of the system to achieve a true grading of '1' for functional reliability of 100%.

To complete the grading process, the task implementation is tempered with weighting that demonstrates how well the task has been implemented. For example, if the requirement calls for ingesting data at 150 Mbps with 'no' data loss, and this task has to be repeatable 100% over the life-time of the system, the weighting (Reliability) given to this task would be '1'. The overall task Reliability score would be '(1*1)*1' or '1'. Using this approach the Ingest task may be evaluated as follows:

$$\text{Reliability Score} = (SYS_{IMP} \times SYS_{PERF}) \times SYS_{REL}$$

The cost factor associated with this task implementation has two components, Cost-of-Implementation CR_i and Cost-of-Non-Implementation CR_n. CR_I is the cost of building in reliability into the system to implement the task, and CR_n is the estimated cost of re-engineering if the system task fails. To ensure that the comparison is not prejudiced, the 'best-case' scenario is assumed for the traditional system and the 'worst-case' scenario for the HRD. The Cost-Benefit ratio is evaluated as follows and is shown in Table 3 for each task and the overall system.

$$\text{Cost-Benefit Ratio} = CR$$
$$= (CR_I + CR_n)_{HRD} / (CR_I + CR_n)_{Traditional}$$

From the CR values and the Reliability Scores, the Cost-Reliability Benefit for each task and the overall system is evaluated, and also shown in Table 3.

Cost-Reliability Benefit = CR x Requirement Weighting x (Reliability Score $\text{Ratio}_{HRD/Traditional}$)

Task	Cost Benefit Ratio	Reliability Score Ratio	Cost Reliability Benefit
Ingest CRC Error Detection	2.0	2.078	2.078x1
RS Error Correction Packet Extraction	2.5	10.622	10.622x1
Level-Zero Processing	2.05	2.663	2.663x1
Back-end Processing Distribution	3.85	2.339	2.339x0.8
Graphical User Interface	1.34	1.025	1.025x0.5
Build-in Capability – Future	7.0	21.28	21.28x0.4
		Subsystem Cost-Reliability Benefit:	26.259

Table 3. Cost Reliability Benefit

3.3 RLP – Cost & Replication

The replication cost is a straightforward cost of reproducing the same system. The cost is based on the cost of parts, the evaluation. Table 4 shows the replication cost benefit evaluation based on relative market prices and information.

Task Assignment	HRD	Traditional System	Cost Replication Ratio
Ingest & Error Detection	230,000	500,000	2.17
Error Correction & Packet Extraction		350,000	1.52
Level-Zero Processing		450,000	1.95
Back-end Processing & Distribution			
Graphical User Interface	5,000	10,000	2.0
Build-in Capability -Future	50,000	200,000	4.0
Subsystem Cost-Replication Benefit	285,000	1,510,000	11.69

Table 4. Cost Replication Benefit

3.4 HRDR – Cost & Performance

In the case of the HRDR the Performance factors that are valid for evaluation are shown in Table 5. Once again, using relative cost terms. The cost issue and replacement value makes the traditional Analog option expensive. The analog or the hybrid systems for BPSK range from a two card set for the very low data rate receivers to the rack mounted boxes that are used for the higher data rates.

Performance Criteria	Factors	HRD Weighting
Minimize Data Loss	Accommodate Data Rate Ingest all telemetry Detect & Correct Doppler at Rate	1
Minimize Availability Delays	Provide Source Data in Minimum Time Provide Real-time Data in Near Time	0.8
Maximize User Capability	Graphical User Interface for Operations, Configuration, and Control	0.5
Maximize Flexibility	Accommodate New Missions & Standards	0.4

Table 5. Performance Criteria

The analog boxes have additional properties of set up and tune and are restricted to ranges in frequency. The Analog receivers cost from $20,000 for the 5 Mbps receivers to $150,000 for higher data rates. Using the assigned weightings and the Cost Benefit ratios, the Cost-Performance Benefit for each task and the overall system may be calculated.

Cost-Performance Benefit = CR x $HRD_{Weighting}$

Task Assignment	HRD	Traditional System	Cost Benefit Ratio	Cost Performance Benefit
Ingest Intermediate Frequency	10,000	150,000	15	15.0 x 1
Doppler Detect & Correct				
Demodulate & Bit-Sync Data				
Viterbi Decode	940	2000	2.13	2.13 x 0.8
Graphical User Interface	5,000	5,000	1.0	1.0 x 0.5
Build-in Capability for Future Needs	10,000	10,000	1.0	1.0 x 0.4
		Subsystem Cost-Performance Benefit		17.6

Table 6. Cost Performance Benefit

3.5 HRDR - Cost & Reliability

Any one of the two cards from an Analog or Hybrid system going awry would require a costly replacement as the tuning of the card is paramount. This increases the time factor to at least a factor of five over the digital option. Assume a MTBF of 75,000 per board, and a Mean Time To Replace on the system (consisting of four boards) of 5 hours, the availability of the system is given as:

Overall System Failure Rate = 4(1/75,000)
= 0.000053

Overall MTBF ≅ 18,750 hours

A_{AS} = MTBF/MTBF + MTTR
= (18,750)/(18,750 + 5) = 0.9997

The cost of the replacement/repair would be on the order of $5000. The Digital option has a great advantage in the cost of repair and replacement, and most importantly the ease and speed of replications and repair. The cost of the board level receiver replacement would be a plug and play in about a 100th of the time it takes the analog system to be replaced and tuned.

A_{DS} = MTBF/MTBF + MTTR
= (55,000)/(55,000 + 1)
= 0.99998

Thus using the expressions described in section 3.2, the Cost-Benefit Ratio and Reliability Score Ratios, the Cost-Reliability can be calculated as shown in Table 7.

Task Assignment	Cost Benefit Ratio	Reliability Score Ratio	Cost Reliability Benefit
Ingest Intermediate Frequency	4.6	4.59	4.59 x 1
Doppler Detect & Correct	8.67	9.59	9.59 x 1
Demodulate & Bit-Sync Data	4.59	5.95	5.95 x 1
Viterbi Decode	2.0	1.98	1.98 x 0.8
Graphical User Interface	2.0	1.53	1.53 x 0.5
Build-in Capability for Future Needs	3.5	10.64	10.64 x 0.4
		Subsystem Cost-Reliability Benefit :	24.74

Table 7. Cost Reliability Benefit

3.6 HRDR – Cost & Replication

The digital receiver compared to the traditional receivers takes one card to provide the functionality as opposed to two or more cards. This by itself gives the size and power advantage for the digital approach. But more importantly no specialized screening or shielding techniques are needed to enclose the functional elements. The power requirements of the digital receiver are in the 5 to 10 watts range as compared to the power requirements for the traditional receivers, which range from 25 watts upwards. The form factor of the analog system that was alluded to in the preceding paragraphs has a size enclosure for the receiver of approximately 5"x 3"x 11". The sizing of the digital receiver is the one card that will fit into the same chassis that the other ground processing subsystems are mounted. The replication cost of the Digital receiver is the actual cost of the parts and the printed circuit board on which they are mounted. The actual parts cost and assembly of the replication of the digital receiver is less than $10,000.

Task Assignment	HRDR	Traditional System	Cost Replication Ratio
Ingest Intermediate Frequency	10,000	150,000	15
Doppler Detect & Correct			
Demodulate & Bit-Sync Data			
Viterbi Decode	940	2,000	2.13
Graphical User Interface	5,000	5,000	1.0
Build-in Capability for Future Needs	10,000	10,000	1.0
Subsystem Cost-Performance Benefit	25,940	167,000	19.13

Table 8. Cost Replication Benefit

4. SYSTEM PERFORMANCE, COST & RELIABILITY BENEFITS

The custom elements of the HRD are the controllable elements for Replication, Performance and Reliability. If we were to take the simplest expression for Reliability the series expression for System level reliability shows that it is directly dependent on the HRDR, RLP, ICS and the LZDPS. The hardware platforms, i.e. the chassis for the cards and the personal computer of the software subsystems have the reliability assured to us by the vendors. The PCI bus extension is assigned the same reliability, performance and cost numbers given by the vendors. The throughput performance and cost per unit performance of the network, and the I/O to and from the storage device and the network are also fixed and beyond our control. The first assumption in developing a relative merit model for the HRD is to state that traditional ground processing system will use the same storage devices and networks. The assumption also extends to the fact that to achieve higher performance, the cost of the storage devices and the network has to increase. Thus the relative merit is to compare the cost, performance and reliability of the ingest and processing systems, i.e., the HRDR and RLP together with the software elements for control and data products. If we further assume that the software elements used for control and data product generations are comparable to the traditional model, the only elements to be compared are the hardware elements. Having made these assumptions, based on the analyses carried out the following results were obtained.

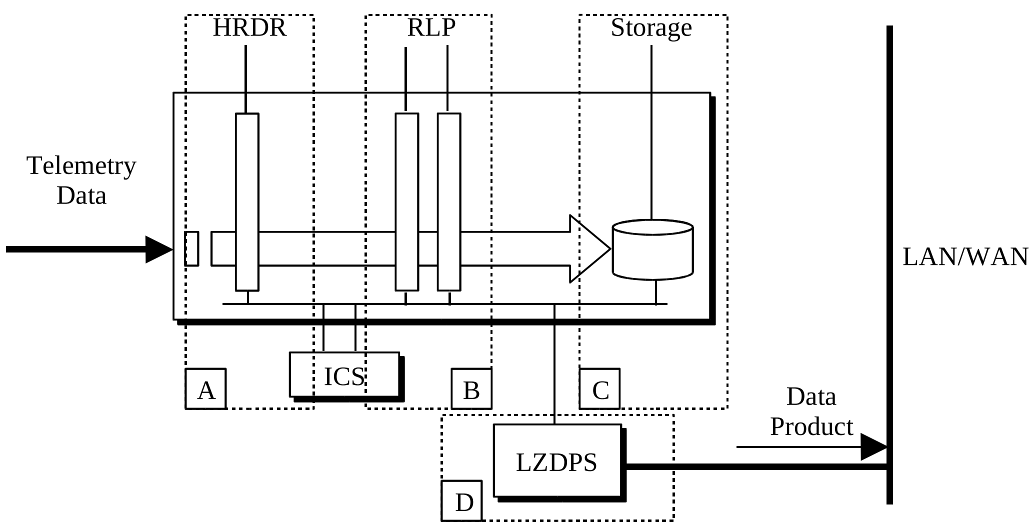

Figure 2. Block Diagram of HRD

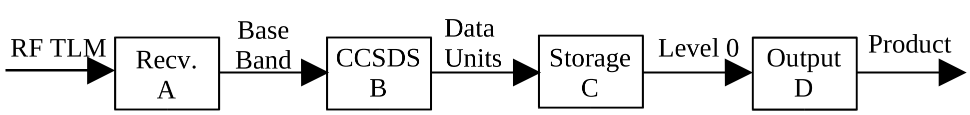

Figure 3. Comparable Elements

Overall System Cost-Performance Benefit is defined as the Cost per Performance Units of the system over the traditional Ground Processing System, based on certain performance criteria. Some of the factors are Minimize Data Loss, Maximize Data Processing, Minimize Availability Delays and so on. Since we have only certain elements that can be compared, it was assumed, conservatively, that the missing elements have the same Cost-Performance. Similarly, the Cost-Reliability and Replication for the missing elements was assumed to be equal. Thus if we consider only the comparable elements in the two systems, the subsystems that can be isolated and compared are the RF Ingest; RF Demodulation & Correction; CCSDS Base-band Ingest, Error Correction & Protocol Processing; Data Storage; Production & Delivery.

The Cost Benefit for each of these elements is evaluated and then the criteria for Performance, Reliability and Replication are compared. The results from these analyses [2], [3], showed that the Cost Benefit in each of these comparable elements and subsequently the Performance, Reliability and Replication Cost Benefit were higher by orders of magnitude for the HRD solution over the traditional ground processing option. Figure 2 shows the architectural block diagram of the HRD.

From Table 1, to evaluate the Cost Performance of the hardware component of the RLP, the back-end processing function can be excluded from the Subsystem Cost-Performance Benefit, since the LZPD has the capability of ingesting extracted data units and providing the Back-End Processing and Distribution Function.

Thus the RLP Cost-Performance Benefit is given by Table 9:

Task Assignment	Cost Performance Benefit
Ingest & Error Detection	2.17 x 1
Error Correction & Packet Extraction	1.52 x 1
Level-Zero Processing	
Graphical User Interface	2.0 x 0.5
Build-in Capability for Future Needs	4.0 x 0.4
RLP Cost-Performance Benefit	6.29

Table 9. RLP Cost Performance Benefit

Similarly, the LZDPS or the Back-end Processing and Distribution System has to implement a Graphical User Interface and Capabilities for future needs.

The LZDPS and HRDR Cost-Performance & Reliability Benefits are given by Tables 10 - 14.

Task Assignment	Cost Performance Benefit
Back-end Processing & Distribution	1.95 x 0.8
Graphical User Interface	2.0 x 0.5
Build-in Capability for Future Needs	4.0 x 0.4
LZPDS Cost-Performance Benefit	4.16

Table 10. LZDPS Cost Performance Benefit

Task Assignment	Cost Performance Benefit
Ingest Intermediate Frequency	15.0 x 1
Doppler Detect & Correct	
Demodulate & Bit-Sync Data	
Viterbi Decode	2.13 x 0.8
Graphical User Interface	1.0 x 0.5
Build-in Capability for Future Needs	1.0 x 0.4
HRDR Cost-Performance Benefit	17.6

Table 11. HRDR Cost Performance Benefit

Task	Cost Reliability Benefit
Ingest CRC Error Detection	2.078x1
RS Error Corr. & Pkt Extraction	10.622x1
Level-Zero Processing	2.663x1
Graphical User Interface	1.025x0.5
Build-in Capability – Future	21.28x0.4
RLP Cost-Reliability Benefit	24.38

Table 12. RLP Cost Reliability Benefit

Task	Cost Reliability Benefit
Back-end Processing Distribution	2.339x0.8
Graphical User Interface	1.025x0.5
Build-in Capability – Future	21.28x0.4
LZDPS Cost-Reliability Benefit	10.89

Table 13. LZDPS Cost Reliability Benefit

Task Assignment	Cost Reliability Benefit
Ingest Intermediate Frequency	4.59 x 1
Doppler Detect & Correct	9.59 x 1
Demodulate & Bit-Sync Data	5.95 x 1
Viterbi Decode	1.98 x 0.8
Graphical User Interface	1.53 x 0.5
Build-in Capability for Future Needs	10.64 x 0.4
HRDR Cost-Reliability Benefit	24.74

Table 14. HRDR Cost Reliability Benefit

Task Assignment	Cost Replication Benefit
Ingest & Error Detection	2.17
Error Correction & Packet Extraction	1.52
Level-Zero Processing	
Graphical User Interface	2.0
Build-in Capability -Future	4.0
RLP Cost-Replication Benefit	9.69

Table 15. RLP Cost Replication Benefit

The Cost Replication Benefits are evaluated and tabulated as follows.

Task Assignment	Cost Replication Benefit
Back-end Processing & Distribution	1.95
Graphical User Interface	2.0
Build-in Capability -Future	4.0
LZDPS Cost-Replication Benefit	7.95

Table 16. LZDPS Cost Replication Benefit

Consider the system, Figure 3, made up of Subsystems A, B, C and D. The overall System Performance Cost Benefit is given by the geometric mean of the Subsystem Performance Cost Benefit.

System Performance Cost Benefit =
$\sqrt[4]{17.6(A); 6.29(B); (C); 4.16(D)}$

Task Assignment	Cost Replication Benefit
Ingest Intermediate Frequency	15
Doppler Detect & Correct	
Demodulate & Bit-Sync Data	
Viterbi Decode	2.13
Graphical User Interface	1.0
Build-in Capability for Future Needs	1.0
HRDR Cost-Replication Benefit	19.13

Table 17. HRDR Cost Replication Benefit

Assuming that there is no Performance Cost Benefit in the Storage element, the overall System Performance Cost Benefit can be calculated without C, thus,

System Performance Cost Benefit =
$\sqrt[3]{17.6(A); 6.29(B); 4.16(D)}$ = 7.72

Similarly;

System Reliability Cost Benefit =
$\sqrt[3]{24.74(A); 24.38(B); 10.89(D)}$ = 18.72

System Replication Cost Benefit =
$\sqrt[3]{19.13(A); 9.69(B); 7.95(D)}$ = 11.38

5. CONCLUSION

The HRD is the basis for a low cost, high-speed solution to processing for high-rate telemetry downlinks. The previous paragraphs have shown that using conservative estimates for performance, replication costs, reliability measures and ratios thereof, that the PCI two card solution is orders of magnitude better than the traditional ultra high cost, low performance systems available today.

6. REFERENCES

[1] C. Mirchandani; D. Nguyen, "Low-Cost, High Rate Data Processing", *3rd International Symposium on Reducing the Cost of Spacecraft Ground Systems & Operations*, Tainan, Taiwan - Mar. 1999.

[2] C. Mirchandani; A. Gray, "Reliable, Low Cost All-Digital Receiver", *American Institute of Aeronautics and Astronautics, 17th International Communications Systems Conference*, Yokohama, Japan - Feb. 1998.

[3] C. Mirchandani; D. Fisher; P. Ghuman, "Cost Beneficial Solution for High Rate Data Processing", *International Telemetering Conference*, Las Vegas, NV - Oct. 1999.

[4] C. Mirchandani, "Cost & Performance Measures in Systems Design", *11th Annual International Council on Systems Engineering (INCOSE) 2001 Symposium*, Melbourne, Australia - July 2001.

[5] C. Mirchandani, "Evaluating Performance Factors In System Development", Military & Aerospace Applications of Programmable Logic Devices (MAPLD), Applied Physics Laboratory, John Hopkins University, Laurel, MD - Sep. 2001

[6] C. Mirchandani; P. Ghuman, "Performance Analyses for System Selection", *International Telemetering Conference*, Las Vegas, NV - Oct. 2001.