Cost Beneficial Solution for High Rate Data Processing

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ABSTRACT

GSFC in keeping with the tenets of NASA has been aggressively investigating new technologies for spacecraft and ground communications and processing. The application of these technologies, together with standardized telemetry formats, make it possible to build systems that provide high-performance at low cost in a short development cycle. The High Rate Telemetry Acquisition System (HRTAS) Prototype is one such effort that has validated Goddard's push towards faster, better and cheaper. The HRTAS system architecture is based on the Peripheral Component Interconnect (PCI) bus and VLSI Application-Specific Integrated Circuits (ASICs). These ASICs perform frame synchronization, bit-transition density decoding, cyclic redundancy code (CRC) error checking, Reed-Solomon error detection/correction, data unit sorting, packet extraction, annotation and other service processing. This processing in performed at rates of up to and greater than 150 Mbps sustained using a high-end performance workstation running standard UNIX O/S, (DEC 4100 with DEC UNIX or better). ASICs are also used for the digital reception of Intermediate Frequency (IF) telemetry as well as the spacecraft command interface for commands and data simulations.

To improve the efficiency of the back-end processing, the level zero processing sorting element is being developed. This will provide a complete hardware solution to extracting and sorting source data units and making these available in separate files on a remote disk system. Research is on going to extend this development to higher levels of the science data processing pipeline. The fact that level 1 and higher processing is instrument dependent; an acceleration approach utilizing ASICs is not feasible. The advent of field programmable gate array (FPGA) based computing, referred to as adaptive or reconfigurable computing, provides a processing performance close to ASIC levels while maintaining much of the programmability of traditional microprocessor based systems. This adaptive computing paradigm has been successfully demonstrated and its cost performance validated, to make it a viable technology for the level one and higher processing element for the HRTAS.

Higher levels of processing are defined as the extraction of useful information from source telemetry data. This information has to be made available to the science data user in a very short period of time. This paper will describe this low cost solution for high rate data processing at level one and higher processing levels. The paper will further discuss the cost-benefit of this technology in terms of cost, schedule, reliability and performance.

KEYWORDS

Telemetry, frame synchronization, Reed-Solomon error detection and correction, service processing, CCSDS, low cost platforms, Application Specific Integrated Circuits (ASICs), Field Programmable Gate Arrays (FPGAs)

INTRODUCTION

Traditional ground processing systems relied on un-bounded resources in cost and schedule. The satellite was launched when the system was ready. With shrinking budgets and the restrictive schedules, the need to have systems up and ready for a lower cost and quicker has become a norm at NASA. When one looks at the staggering cost of NRE and development costs to build customized ground systems for processing data from a single mission, the strides made by NASA are stupendous. The old Data Systems Technology Branch (DSTD) at NASA pursued the goal of faster cheaper and better by adopting the plug and play paradigm.

From 1985, the large mainframes with software applications that were very unwieldy and large, were being replaced by hardware, firmware and software modules that were smaller, cheaper to maintain and more efficient. Albeit, these systems were still custom built to meet the needs of the project. However these first generation ground systems soon gave way to the second generation whereby hardware, firmware and software modules could be reused to a large extent by the new missions. The percentage of new code and changes that had to be made was less than 20 %. However, there were drawbacks. Even though the costs of getting a new system were reduced, the flexibility of the system to meet the new challenges of even higher data rates and volumes was limited by the technology.

Consistent with the new edicts of faster, smaller and cheaper, DSTD has developed its Third Generation of ground processing systems. To further increase cost-effectiveness new elements are being developed and will be added so that these ground processing systems will provide all telemetry acquisition and processing functions from receipt of raw telemetry at the antenna to generation of user data sets.

Figure 1 shows how the paradigm reduced costs while increasing the performance of the processing systems. The basic elements of telemetry processing, namely ingest, error correction and packet extraction had been implemented in three custom ASICs. These three ASICs together with associated devices was the basis of the low cost, high rate telemetering system.

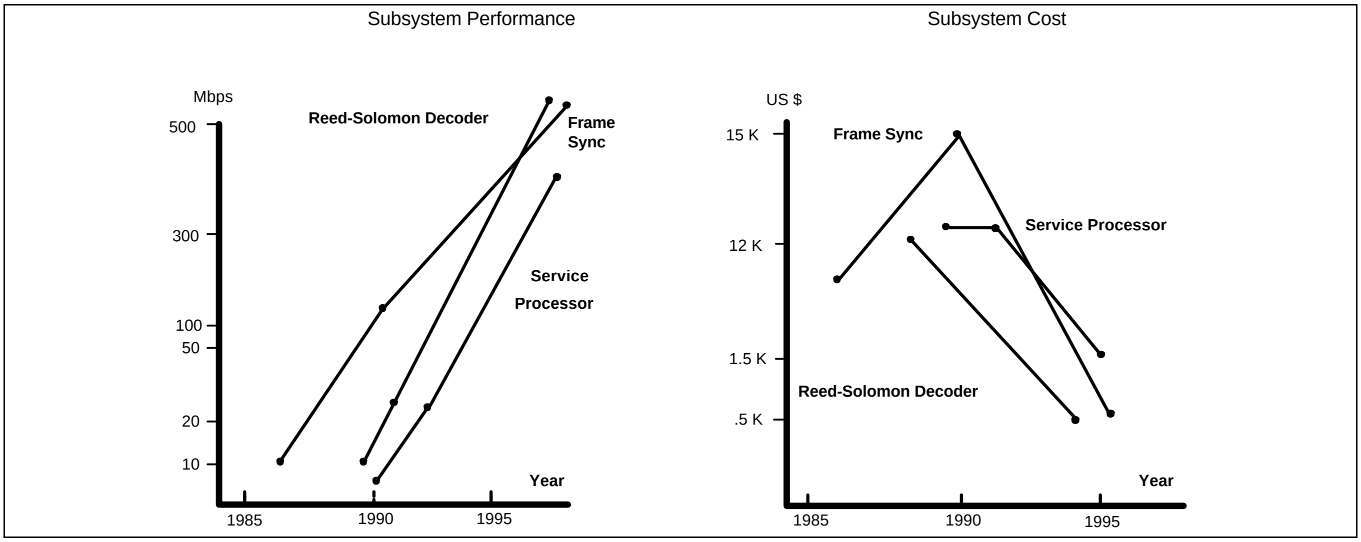

Figure 1 Process Cost and Performance versus Time

SYSTEM OVERVIEW

Conceptually, the HRTAS can serve as a standalone telemetry processing system to support a mission as shown in Figure 2. The HRTAS will receive and capture serial telemetry data streams from an antenna, perform IF reception, frame synchronization, and optionally perform Reed-Solomon decoding and service processing.

primary function of the HRTAS is to capture and process space telemetry and output frames and/or data packets out to an end user on a network interface. The front-end of the HRTAS System will process telemetry received in the Intermediate Frequency (IF) spectrum as well as the digital spectrum (RS-422). The performance of the HRTAS far exceeds the available telemetry processing and generating systems in cost and performance. It has been proven to process frames at rates up to and above 150 Mbps using desktop workstation (DEC Alpha 4100) class machine. The demonstration included the capability to process packets at telemetry rates of up to 150 Mbps. It is capable of achieving the following packet rates: 676,000/7-byte packets per second to 82/65542-byte packets per second. The uplink capability was simulated and demonstrated to

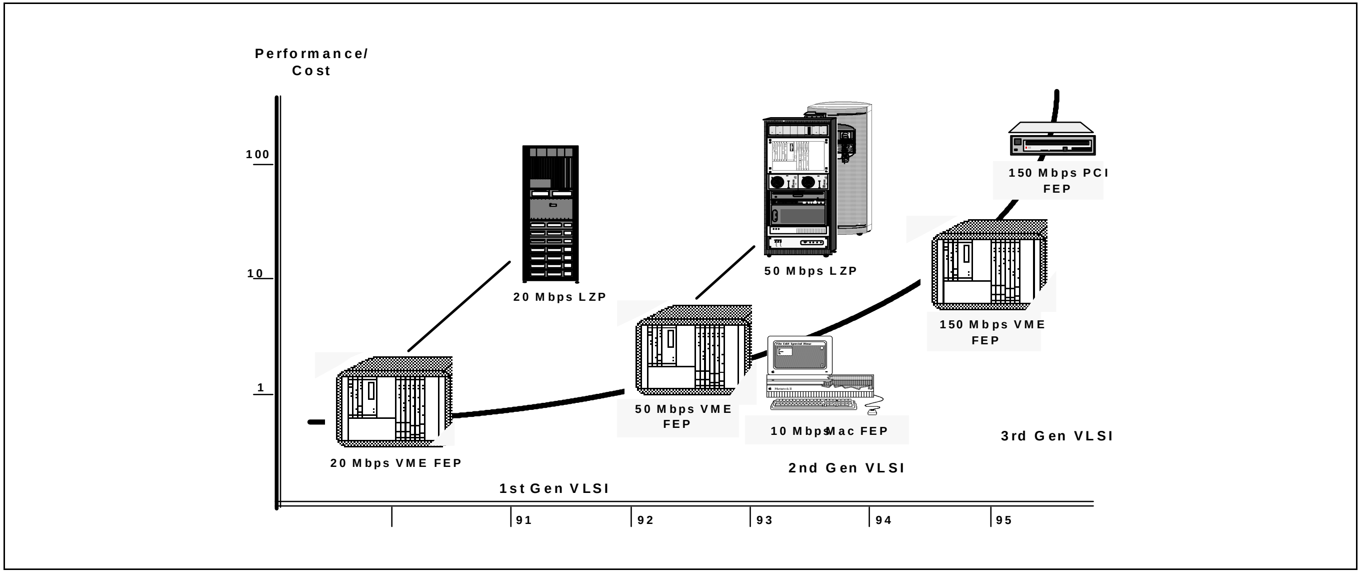

Figure 2 System Cost/Performance Curve

transfer commands at rates up to 2 MHz. In addition to the operational capability, the HRTAS can be used to self test the system. It has the capability to perform data simulation at rates in excess of 150 Mbps.

As opposed to the traditional ground processing system, the HRTAS can also deliver packets to external users and/or local disk storage from selected subsystem sources within 5 ms (at 150 Mbps ingest rate) of receipt. However, it must be pointed out that the external network must be capable of sustaining and ingesting the data output from the HRTAS. For example, a destination capable of ingesting the data products must have the capability to receive and ingest multiple data product sets at rates up to 5 Mbps over Ethernet, 25 Mbps over FDDI* and 50 Mbps over ATM* (* optional interface installed by user).

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 data downlinked 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. The HRTAS development followed these criteria for performance:

Performance Criteria	Factors	HRTAS 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	GUI for Operations, Configuration, and Control	0.5
Maximize Flexibility	Accommodate New Missions & Standards	0.4

Table 1 Performance Criteria

From the above table we can assign these requirements to the HRTAS and an equivalent traditional system that does not use the plug-and-play paradigm. 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.

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

Cost-Performance Benefit = CR x $\text{HRTAS}_{\text{Weighting}}$

Task Assignment	HRTAS	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				
Back-end Processing & Distribution		450,000	1.95	1.95 x 0.8
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
		System Cost-Performance Benefit :		7.85

Table 2 Cost Performance Benefit

COST-RELIABILITY

All the traditional aspects of reliability, modeling and prediction need to be considered. The most difficult problem to be faced being: the knowledge base. The <u>functional</u> reliability depends on whether the objectives are met and how well and whether they are repeatable. The <u>performance</u> 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. For example, if tasked to ingest a telemetry stream and maintain the qualitative and quantitative accounts for the same, the system obliges with no error in the ingest process. Thus it is 100% reliable and may be graded with a score of 1 (1 being the highest and 0 being the lowest). However, this logical acquiescence is not enough to achieve a reliable system. This 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:

Reliability Score = $(\mathrm{SYS}_{\mathrm{IMP}} \times \mathrm{SYS}_{\mathrm{PERF}}) \times \mathrm{SYS}_{\mathrm{REL}}$

HRTAS uses the PIFS chips for frame synchronization, CRC error detection and quality accounting t the ingest stage prior to pipelining the data stream to the RS chip. The functional integrity of the chip is far higher than the printed circuit board on which it is mounted. Since this is a ‘new’ product, no historical statistical data exists for true availability numbers, however, using the small sample of in-house boards over a period of two years, the prior estimate of the board availability may be obtained. Using the Bayesian approach, the degree of accuracy of this prior estimate is re-evaluated using newer data as it becomes available to provide a posterior estimate of board reliability. The traditional approach uses mini-computers or high-end workstations in a redundant configuration to achieve high reliability. To ensure that there is no data loss, the traditional systems have been known to use up to three high-rate storage media to capture the raw telemetry downlink.

To grade the ‘ingest’ task, the requirement has to be stated in two parts. The system (a) must capture all the data, and (b) must attain and maintain sync. The second part of this requirement is met by both systems. For the first part, the HRTAS does not process data with ‘bad sync’ patterns, since it is a pipeline processing system, and as a result discards this data. However, for a successful downlink, the actual loss of data due to ‘bad sync’ is less than 1%. The traditional approach uses the ‘store-and-process-later’ method, and hence captures all the data onto disk or tape media in the raw form. Hence the score of 0.99 for the HRTAS and 1.0 for the traditional system. In the same way, the values for the other tasks are evaluated using realistic, historical precedent for allowable errors, delays, and usability. Table 3 shows the grading, reliability and reliability scores for the two approaches.

Task	Implementation		Performance		Reliability		Reliability Score	
	HRTAS	Trad.	HRTAS	Trad.	HRTAS	Trad.	HRTAS	Trad.
Ingest	0.99	1.0	1.0	1.0	0.9987	0.9907	0.9887	0.9907
CRC Error Detection	1.0	1.0	1.0	1.0		0.9608		0.9608
RS Error Correction	1.0	1.0	1.0	0.5	0.9807	0.9608	0.9807	0.4804
Packet Extraction	1.0	1.0	1.0	0.5		0.9608		0.4804
Level-Zero Processing	1.0	1.0	1.0	0.8	0.9987	0.9608	0.9987	0.7686
Back-end Processing	0.9	1.0	0.95	1.0	0.9974	0.9974	0.7675	0.9974
Distribution	0.9	0.9	0.75	1.0	0.9945	0.9945	0.6713	0.8950
Graphical User Interface	0.9	1.0	0.85	1.0	0.9947	0.9947	0.7609	0.9947
Build-in Capability for Future Needs	0.8	0.5	0.8	0.5	0.95	0.8	0.608	0.2

Table 3 Reliability Scores

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. For example in the case of ‘ingest’, CR_I for HRTAS is in the order of the cost of the board. The CR_n value for not capturing all the data is to have a redundant system that is set to accept the complete stream of data ignoring the sync errors. The redundant system cost is $230,000. For the traditional system, these values are in the order of the ingest system i.e. $500,000. Similarly, the values for the other tasks may be calculated. For example, the CR_I and CR_n values for the level zero processing task may be estimated as follows; for HRTAS the values are CR_I is $90,000 {~ 1/3(cost of system $230,000) + $20,000} and CR_n is $20,000, cost of the board. Whilst for the traditional system, CR_I is approximately $175,000 and CR_n is $50,000. 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 HRTAS. The Cost-Benefit ratio is evaluated as follows and is shown in Table 4 for each task and the overall system.

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

From the CR values and the Reliability Scores from Table 3, the Cost-Reliability Benefit for each task and the overall system is evaluated, and shown in Table 4.

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

Task	HRTAS		Traditional		Cost Benefit Ratio	Reliability Score Ratio	Cost Reliability Benefit
	CR_I	CR_n	CR_I	CR_n			
Ingest CRC Error Detection	70K	230K	500K	100K	2.0	2.078	2.078x1
RS Error Correction Packet Extraction	70K	20K	175K	50K	2.5	10.622	10.622x1
Level-Zero Processing	90K	20K	175K	50K	2.05	2.663	2.663x1
Back-end Processing Distribution	40K 40K	25K 25K	450K	50K	3.85	2.339	2.339x0.8
Graphical User Interface	5K	10K	10K	10K	1.34	1.025	1.025x0.5
Build-in Capability – Future	50K	50K	200K	500K	7.0	21.28	21.28x0.4
					System Cost-Reliability Benefit:		26.259

Table 4 Cost Reliability Benefit

COST-SCHEDULE

Costs incurred in meeting schedules for operational systems are an order of magnitude higher than those incurred for a test system. Together with the tenet of 'faster, cheaper and better', NASA has also changed the way of doing business. The responsibility for spacecraft support has been transferred to the mission projects with fixed budgets. This calls for tighter schedules and lower budgets. With the advent of faster and higher volume data downlink, the project has to develop newer systems in half the time with the same or better levels of performance.

Given the Cost of Time, C_{time} and the Budget, the Cost-Schedule Benefit is evaluated for the HRTAS on a task by task basis. Using the same functional allocation the time to develop a ground system may be enumerated in one of two ways, (1) time to develop a new system from scratch T_{new}, or (2) time to enhance an existing system to support a new mission T_{enhance}. In the first approach, the NRE costs have to be included and this requires adding the manpower costs needed to meet the schedule. The total schedule cost will include the cost of time to re-engineer errors and re-test the same. For example, the ingest task for the HRTAS is implemented in hardware – an integrated circuit (PIFS chip), software – embedded in firmware to setup and enable the chip; and monitor and account for the processing statistics. The time to develop, fabricate and test this task is shown in Table 5, as follows:

HRTAS Ingest Task – PIFS Chip on RLP Card				
Function	Budgeted – Time (months)	Actual - Time (months)	Manpower (man-years)	Cost Schedule ($K)
Develop & Design	24	30	2	200
Fabricate	2	2	Contract	300
Test Chip	2	2	0.2	20
Develop Software	4	4	0.4	40
Develop Firmware	2	2	0.2	20
Integrate & Test	3	4	0.8	80
Correct Errors	6	2	0.4	40
System Test	2	2	0.4	40
			Cost-Schedule	740

Table 5 Ingest HRTAS Cost - Schedule

Similarly the schedule cost for the traditional system is tabulated and shown in Table 6. The best case scenario has been used so as not to prejudice the comparison.

Traditional Ingest Task – Hardware Front-End & Software Processing				
Function	Budgeted – Time (months)	Actual – Time (months)	Manpower (man-years)	Cost Schedule ($K)
Develop & Design Hardware	24	30	2	200
Develop Software	12	12	2	200
Develop Firmware	6	6	1	100
Integrate & Test	6	6	1	100
Correct Errors	6	6	1	100
System Test	6	6	1	100
			Cost–Schedule	800

Table 6 Ingest Traditional Cost - Schedule

It should be noted that the NRE costs keep the two systems within the same order of magnitude where the schedule is concerned. It must however be pointed out that the element that caused the greatest contribution to the cost for the HRTAS, is the fabrication task that is contracted to an outside source and hence the control is lost at that point. In keeping with the requirement that the system should be flexible enough to be enhanced at low cost to meet the new mission requirements, the following cost elements are tabulated in Table 7.

Enhance Ingest Task							
Function	HRTAS		Traditional		Cost Schedule($K)		Cost Schedule Ratio
	Time	Manpower	Time	Manpower	HRTAS	Trad.	
Enhance Design	6	0.5	18	1.5	50	150	3
Develop Software	1	0.2	24	3	20	300	15
Develop firmware	0.5	0.1	0.5	0.1	10	10	1
Correct Errors	2	0.3	6	0.9	30	90	3
Integrate & Test	2	0.2	6	1	20	100	5
Ingest Cost–Schedule Benefit					130	650	5

Table 7 Ingest Enhancement Cost Schedule Benefit

Thus in a similar manner the Cost-Schedule Benefit can be calculated for all the different elements in the two systems, and these are tabulated in Table 8. To evaluate the overall System Cost-Schedule Benefit, it is necessary to sum the manpower requirements and then calculate the ratio.

Task	HRTAS		Traditional		Schedule Benefit Ratio	Cost Schedule Ratio
	Time	Manpower	Time	Manpower		
Ingest CRC Error Detection	11.5	1.3	54.5	6.5	4.74	5.0
RS Error Correction Packet Extraction	0.1	0.02	1 2	0.2 0.4	30	30
Level-Zero Processing	0.2	0.04	6	0.5	30	12.5
Back-end Processing Distribution	1 2	0.2 0.4	12 12	1 1	8	3.34
Graphical User Interface	1	0.2	1	0.2	1	1
Build-in Capability – Future	2	0.4	2	0.4	1	1
System Cost–Schedule Benefit	17.8	2.56	90.5	10.2	5.08	3.98

Table 8 Cost Schedule Benefit

Cost-Schedule Benefit = □ (Traditional $\text{Manpower}_{\text{TASK}}$)/□ (HRTAS $\text{Manpower}_{\text{TASK}}$)

COST-REPLICATION

The replication cost is a straightforward cost of reproducing the same system. The cost is based on the cost of parts, integration and test and labor cost associated with the same. The NRE costs are up-front expenses, which are not included in the evaluation. Table 9 shows the replication cost benefit evaluation based on relative market prices and information.

Task Assignment	HRTAS	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			
Back-end Processing & Distribution		450,000	1.95
Graphical User Interface	5,000	10,000	2.0
Build-in Capability -Future	50,000	200,000	4.0
System Cost-Replication Benefit	285,000	1,510,000	5.29

Table 9 Cost Replication Benefit

FUTURE CAPABILITY

With the newer and better technologies in the pipeline, it is but inevitable that the systems are going to be more complex yet smaller and albeit orders of magnitude faster. The single-chip-solution for the basic tasks may be developed into a single chip solution for the whole LZP system. If this happens then the cost benefit increases an order of magnitude. The chip could be developed using commercially available Intellectual Property (IP) that is optimized for speed, size or functionality. These elements may be acquired in the VHDL media whereby the designer has the option to optimize these criteria.

CONCLUSIONS

From the paper it is obvious that the technological advances in systems and hardware have opened the door to hitherto unattainable data rates. The ability to include the whole solution on complex and yet easily replicated hardware has removed the responsibility from the platform and software-processing environment. The greatest cost benefit has been in system reliability, which is in keeping with the classical theories: namely smaller and easily renewable elements increase the reliability of a system.

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