Using Disk Throughput Data in Predictions of End-to-End Grid Data Transfers

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Abstract. Data Grids provide an environment for communities of researchers to share, replicate and manage access to copies of large datasets. In such environments, fetching data from one of the several replica locations requires accurate predictions of end-to-end transfer times. Predicting transfer time is significantly complicated due to the involvement of several shared components such as networks, disks, etc., in the end-to-end data path each of which experiences load variations that can significantly affect the throughput. Of these, disk accesses are rapidly growing in cost, and have not been previously considered, although on some machines they can be up to 30% of the transfer time.

In this paper, we present techniques to combine observations of end-to-end application behavior and disk I/O throughput load data. We develop a set of regression models to derive predictions that characterize the effect of disk load variations on file transfer times. We also include network component variations and apply these techniques to the logs of transfer data using the GridFTP server, part of the Globus Toolkit™. We observe up to 9% improvement in prediction accuracy when compared with approaches based on past system behavior in isolation.

1 Introduction

Increasingly, scientific discovery is driven by computationally intensive analyses of massive data collections. This promising recent trend has encouraged the research and development of sophisticated infrastructures for maintaining large data collections in a distributed, secure fashion, and improving the rapid access of large subsets of data files.

One example of this is in high-energy physics experiments, such as ATLAS [MMR+01] and CMS [HSS00], that have agreed upon a tiered architecture [HJS+00, Holtman00] for managing and replicating the petascale data generated by the LHC experiment at CERN beginning 2006. The current architecture proposes to manage these petabytes of data, generated at CERN (Tier0), by replicating subsets (approximately an order of magnitude reduction) across national (Tier1) and regional (Tier2) centers.

As data grid environments begin to be deployed and used, the amount of replication of data will likely grow rapidly as more users cache copies of datasets nearby for better performance. Thus, a particular copy of a dataset will reside at multiple locations, and a choice of site to retrieve it from must be made.

In previous work [VS02, VSF02], we addressed this replica selection problem by having replica locations expose transfer performance estimates. Estimates were derived from past history of transfers (using the GridFTP server, part of the Globus Toolkit™) between sources and sinks, and by also factoring in the network link load to account for the sporadic nature of data grid transfers using regressive techniques. Our results showed prediction accuracy to hover around 15-24% for predictors solely based on past transfer behavior, but improved 5-10% when network load variations were factored in. In this paper, we consider the effects of disk I/O as well.

The addition of disk I/O behavior in our predictions is motivated by three main factors. 1) Disk I/O currently plays a large role, up to 30% on our testbed, in large data transfer times (as detailed below). 2) This role will only become more important due to trends in disk size and network behavior. 3) Having access to additional data streams become more important as Grid environments grow, and not all resources will have the same information available about them.

In fact, we observe that disk I/O can account for up to 30% of the transfer time (Figure 1). In Figure 1, we show the percentage of I/O time spent on an average data transfer. We compare the cost of performing a local GridFTP read/write (source disk to device abstraction at source, essentially eliminating the network) to the wide-area transfer cost (source disk to device abstraction at sink). For these experiments, the disks on the source ends were all high-end RAID servers. On lower-end disk systems the effect would be even more significant.

In addition to current behavior, trends in disk storage and networking suggest that disk I/O will play an even larger role in the future. Disk capacity is increasing at the rate of about 100x per decade [GS00]. However, the ratio between disk capacity and disk throughput is increasing at only 10x per decade, indicating that storage capacity is far outpacing disk speeds. Further, Gilder's law predicts that network bandwidth will triple every year for the next 25 years [GS00], so both network throughput and storage capacity are outpacing advances in disk speeds. Therefore, as link speeds increase the network latency significantly drops and disk accesses are likely to become the bottleneck in large file transfers across the Grid.

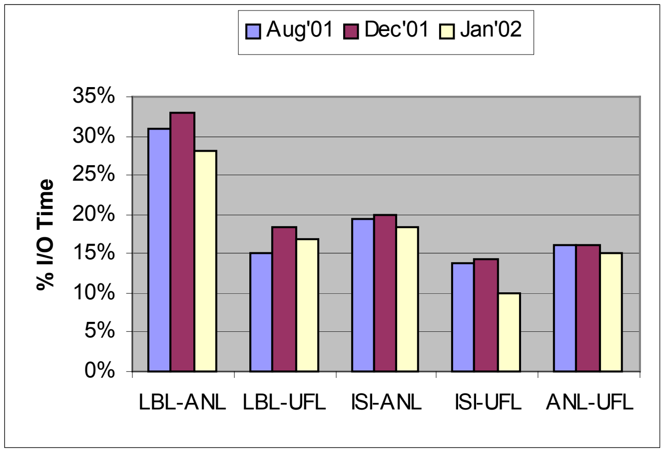


Figure.1. Disk I/O time as a percentage of the total data transfer time for our experiments. Sites include Argonne National Laboratory (ANL), Lawrence Berkeley National Laboratory (LBL), University of Southern California's Information Science Institute (ISI) and University of Florida at Gainesville (UFL). Transfers include several file sizes ranging from 10MB to 1GB. Transfers were conducted over three distinct two-week periods.

In addition to the proportionality of the disk I/O time to the full transfer time, we must consider that data grids are potentially highly dynamic with resources joining and leaving communities. The availability of data sources (required for obtaining forecasts) can also vary unpredictably due to failures in the various components, monitoring sensors, etc. Thus, we need to be able to derive forecasts from several combinations of "currently available" data sources. For example, we can build predictions using 1) just past GridFTP transfer logs, 2) transfer logs combined with current network load observations, 3) transfer logs with disk I/O load data, or 4) a combination of past transfer logs, network and disk load traces. In our previous work, we investigated (1) and (2), while this paper explores techniques to derive predictions for the two latter cases.

In this paper, we extend our previous work to combine transfer log data with disk throughput data using regressive techniques. We develop multiple regression models, deriving predictions from past transfer logs, disk and network load data combined. Our results denote an improvement in prediction accuracy of up to 4% when using regression techniques between GridFTP transfers and disk I/O throughput data when compared to predictions based on past GridFTP behavior in isolation; 9% when combining all three data sources.

In the remainder of the paper we present related and previous work (Section 2), prediction model (in Section 3), an evaluation of our techniques (in Section 4) and finally conclude (Section 5).

2 Related and Previous Work

Our goal is to obtain an accurate prediction of file transfer times between a storage system and a client. Achieving this can be challenging because numerous devices are involved in the end-to-end path between the source and the client, and the performance of each (shared) device along the end-to-end path may vary in unpredictable ways.

One approach to predicting this information is to construct performance models for each system component (CPUs at the level of cache hits and disk access, networks at the level of the individual routers, etc.) and then use these models to determine a schedule for all data transfers [SC00], similar to classical scheduling [Adve93, Cole89, CQ93, Crovella99, ML90, Schopf97, TB86, ZLP96]. In practice, however, it is often unclear how to combine this data to achieve accurate end-to-end measurements. Also, since system components are shared, their behavior can vary in unpredictable ways [SB98]. Further, modeling individual components in a system will not capture the significant effects these components have on each other, thereby leading to inaccuracies [GT99].

Alternatively, observations from past application performance of the entire system can be used to predict end-to-end behavior, which is typically what is of interest to the user. This technique is used by Downey [Downey97] and Smith et. al., [SFT98] to predict queue wait times and by numerous tools (Network Weather Service [Wolski98], NetLogger [NetLogger02], Web100 [Web100Project02], iperf [TF01], and Netperf [Jones02]) to predict the network behavior of small file transfers. We used this technique in [VSF02], but found that it had large errors due to the sporadic nature of GridFTP transfers, and that we needed to be able to include additional data about current system conditions in order to improve the predictions.

	GridFTP and NWS						GridFTP and Disk I/O					
	Aug'01		Dec'01		Jan'02		Aug'01		Dec'01		Jan'02	
	Upper	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*
LBL-ANL	0.8	0.5	0.5	0.3	0.6	0.2	0.6	0.1	0.5	0.2	0.5	0.1
LBL-UFL	0.7	0.5	0.7	0.4	0.6	0.1	0.5	0.2	0.5	0.3	0.5	0.3
ISI-ANL	0.8	0.5	0.6	0.4	0.7	0.3	0.5	0.2	0.6	0.4	0.6	0.3
ISI-UFL	0.9	0.4	0.6	0.2	0.5	0.1	0.5	0.1	0.6	0.3	0.5	0.2
ANL-UFL	0.5	0.2	0.6	0.2	0.6	0.1	0.5	0.2	0.4	0.1	0.4	0.2

Figure.2. 95% Confidence for the upper and lower limits of the rank-order correlation coefficient for the GridFTP, NWS and Disk I/O datasets between four sites in our testbed. Denotes coefficients for our three datasets.

In our previous work [VS02], we combined end-to-end throughput observations from past GridFTP data transfers and current network load variations using regression models to obtain better predictions. A similar effect was addressed by Faerman et.al., [FSW+99] using the NWS and adaptive linear regression models for the Storage Resource Broker [BMR+98] and SARA [SARA02]. That work compared transfer times obtained from a raw bandwidth model (*Transfer-Time=ApplicationDataSize/NWS-Probe-Bandwidth*, with 64 KB NWS probes) with predictions from regression models and observed accuracy improvements ranging from 20% to almost 100% for the sites examined. Swany and Wolski have also approached the problem by constructing cumulative distribution functions (CDF) of past history and deriving predictions from them as an alternative to regressive models. This has been demonstrated for 16MB HTTP transfers with improved prediction accuracy when compared with their univariate prediction approach [SW02].

3 Prediction Model

In this section, we examine the various data sources we used, their relations, regressive models and our prediction algorithm.

3.1 Data Transfer Logs and Component Data

In this section, we describe our three primary data sources. We use the GridFTP server to perform our data transfers and log its behavior every time a transfer is made, thereby recording the end-to-end transfer behavior. However, since these events are very sporadic in nature, we also need to capture data about the current environment to have accurate predictions. We use the Network Weather Service network probe data as an estimate of bandwidth for small data transfers and the iostat disk throughput data to measure disk behavior.

GridFTP [AFN+01] is part of the Globus Toolkit™ [FK98, Globus02] and is widely used as a secure, high-performance data transfer protocol [ACF+02, AFN+01, DataGrid02, GriPhyN02]. It extends standard FTP implementations with several features needed in Grid environments, such as security, parallel transfers, partial file transfers, and third party transfers, etc. We instrumented the GT 2.0 wuftp-based GridFTP server to log the source address, file name, file size, number of parallel streams, stripes, TCP buffer size for the transfer, start and end timestamps, nature of the operation (read/write), and logical volume to/from which file was transferred, etc. [VSF02].

Since the GridFTP logging data is very sporadic in nature, we also use two sets of data about the current environment. The iostat tool is part of the sysstat [SYSSTAT02], system-monitoring suite. It collects disk I/O throughput data. Iostat can be configured to periodically monitor disk transfer rates, block read/write rates, etc., of all physically connected disks. We are particularly interested in the disk transfer rate that represents the throughput of a disk.

The Network Weather Service [Wolski98] monitors the behavior of various resource components by sending out light-weight probes or querying system files at regular intervals. NWS sensors exist for components such as CPU, disk, and network. We used the network bandwidth sensor with 64KB probes to estimate the current network throughput.

In subsequent sections, we see how forecasts can be derived from these correlated data streams using regressive techniques.

3.2 Correlation

Correlation gives a measure of the linear strength of the relationship between two variables and is often used as a test of significance before linear regression analysis is performed [Edwards84]. For our data sources, namely GridFTP logs, iostat load and NWS traces we computed rank order correlation (a distribution free test). Figure 2 shows 95% confidence interval for the correlation and indicates a moderate correlation between the variables.

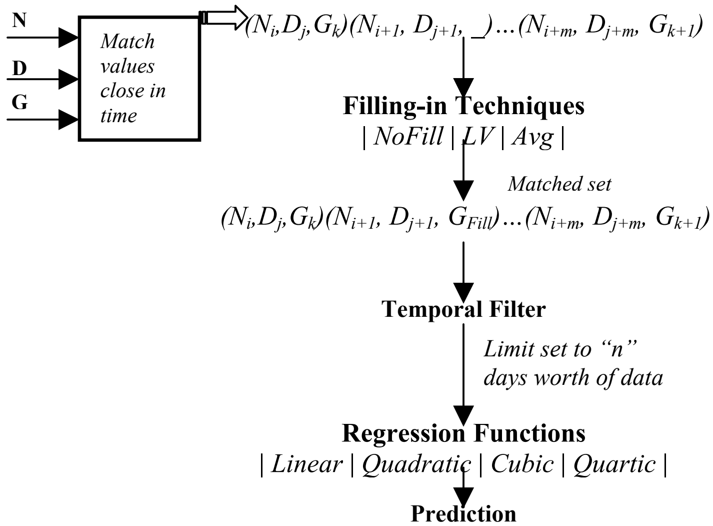


Figure.3. Algorithm for deriving predictions from GridFTP (G), Disk load (D) and NWS (N) data streams by using regression techniques.

3.3 Algorithm

Our three data sources (GridFTP, disk I/O and NWS network data) are collected exclusive of each other and rarely had same timestamps. However, in order to use common statistical techniques on the data streams, we need to line up the values to be considered. Because of this, we are required to match values from these three sets such that for each GridFTP value, we find disk I/O and network observations that were made around the same time.

For each GridFTP data point (T_G, G), we match a corresponding disk load (T_D, D) and NWS data point (T_N, N) such that T_N and T_D are the closest to T_G, are established. By doing this, the triplet (N_i, D_j, G_k) represents an observed end-to-end GridFTP throughput (G_k) resulting from a data transfer that occurred with the disk load (D_j) and network probe value (N_i). At the end of the matching process the sequence looks like the following:

$$(N_i,D_j,G_k)(N_{i+1}, D_{j+1}, \_)\ldots(N_{i+m}, D_{j+m}, G_{k+1})$$

where G_k, and G_{k+1} are two successive GridFTP file transfers, N_i and N_{i+m} are NWS measurements, and D_j and D_{j+m} are disk load values that occurred in the same timeframe as the two GridFTP transfers. The sequence also consists of a number of disk load and NWS measurements between the two transfers for which there are no equivalent GridFTP values, such as $(N_{i+1}, D_{j+1}, \_)$. Note that these interspersed network and disk load values also need to be time-aligned as they seldom have same timestamps.

After matching the data streams we need to address the tuples that do not have G values. This is caused by the sporadic nature of data grid transfers – we will have more disk I/O and network data than GridFTP data. Regression models expect a one-to-one mapping between the data values, so we can either discard unaccounted network and I/O data (for which there are no equivalent GridFTP data) or fill in synthetic transfer values for the unaccounted data. We use three strategies to fill in missing values both in this work and in previous work [VS02]. These filling in techniques are: discard unaccounted disk I/O and network data (NoFill), use last GridFTP transfer values as a filling (LV) for unaccounted data, and use average of previous transfers as a filling (Avg) for unaccounted data. After filling in G values, these datasets are fed to the regression models (Figure 3).

3.4 Regressive Techniques

In order to predict the end-to-end GridFTP throughput and study the effect of the disk I/O component, we use standard regressive techniques. Regression provides the necessary mechanisms to analyze the impact of several independent variables (in our case, I/O traces or NWS bandwidth data) on the dependent variable (GridFTP throughput).

3.4.1 Simple Regression

In our previous work, we developed simple regression techniques between GridFTP (G) and NWS network data (N). We built a set of linear as well as nonlinear regression models between the two variables and derived forecasts from it. In this paper, we employ similar techniques to analyze the effect of disk I/O variations (D) on end-to-end GridFTP bandwidth. We constructed a linear model between two variables D and G as follows: $G^{|}=a+bD$, where $G^{|}$ is the prediction of the observed value of G for the corresponding value of D. The coefficients, a and b are calculated based on a regression function that accounts for previous Ds and Gs, using the method of least squares:

$$a = \text{Mean}(G) - b * \text{Mean}(D)$$

while the coefficient b is calculated by using the formula:

$$b = \frac{\sum DG - (\sum D \sum G/\text{size})}{\sum G^2 - (\sum G)^2/\text{size}}$$

where "size" is the total number of values in the dataset [Edwards84].

3.4.2 A Case for Multiple Regression

In addition to simple regression, we study the effect of deriving predictions from all three data sources. For this purpose, we construct multiple regression strategies. Multiple regression techniques allow us to study the effect of several independent variables on a dependent variable.

We constructed multiple regression models by adding terms corresponding to various components to the simple regression equation. Similar to the disk component discussed earlier, to include network variations into the equation, we add a network load term. Thus, the multiple regression model is as follows: $G^{|}=a+b_1D+b_2N$, where $G^{|}$ is the prediction of the observed value of G for the corresponding values of N and D. The regression coefficients are calculated [Edwards84] as follows:

$$a = \text{Mean}(G) - (b_1 * \text{Mean}(D)) - (b_2 * \text{Mean}(N))$$

$$b_1 = \frac{(\sum DG \sum N^2) - (\sum NG \sum DN)}{(\sum D^2 \sum N^2) - (\sum DN)^2}$$

$$b_2 = \frac{(\sum NG \sum D^2) - (\sum DG \sum DN)}{(\sum D^2 \sum N^2) - (\sum DN)^2}$$

Including further components (that which contribute to the end-to-end data path) would mean adding terms to the multiple regression equation, whose coefficients can then be computed using the method of least squares [Edwards84]. To summarize, we are interested in predicting the performance of the dependent variable, GridFTP, by studying the impact of adding independent components such as disk and network link loads to the regression model.

4 Evaluation

In order to analyze the performance of our predictors, we conducted several wide-area experiments between our testbed sites comprising of resources from Argonne National Laboratory (ANL), Lawrence Berkeley National Laboratory (LBL), University of Southern California's Information Sciences Institute (ISI) and University of Florida at Gainesville.

First, we setup GridFTP experiments between these sites transferring files ranging from 10M-1G at random intervals in twelve-hour durations for a two-week period (during August 2001, December 2001 and January 2002). All transfers were made with tuned TCP buffers size of 1MB and eight parallel streams. Disk I/O throughput data was collected using the iostat tool logging transfer rates every five minutes. NWS was setup to monitor network bandwidth between these sites at five-minute intervals using 64KB probes. All logs were maintained at the respective sites.

We analyze the performance of our regressive techniques in the following cases: (1) regression between GridFTP transfer data and disk I/O trace data, (2) regression between GridFTP, disk I/O and NWS network data. We compare the results from these approaches against prediction based on GridFTP data in isolation [VSF02] and prediction based on regressing GridFTP and NWS data [VS02]. In all of the above, we compare several of our filling strategies.

4.1 Metrics

We calculate the prediction accuracy using the normalized percentage error calculation

$$\% \text{ Error} = \frac{\sum |\text{Measured}_{BW} - \text{Predicted}_{BW}|}{(\text{size} * \text{Mean}_{BW})} * 100$$

where "size" is the total number of predictions and the Mean is the average measured GridFTP throughput. We show our results based on the August 2001 dataset. Elaborate results for all our datasets can be found at [Traces02].

In addition to just evaluating the error of our predictions, we evaluate information about the variance. Depending on the use case, a user may be more interested in selecting a site that has reasonable performance bandwidth estimates with a relatively low prediction error instead of a resource with higher performance estimates and a possibly much higher error in prediction. In such cases, it can be useful if the forecasting error can be stated with some confidence and with a maximum/minimum variation range. These limits can also, in theory, be used as catalysts for corrective measures in case of performance degradation.

In our case, we can also use these limits to verify the inherent cost of accuracy of the predictors. Comparing the confidence intervals of these prediction error rates, we can determine if the accuracy achieved is at the cost of greater variability, in which case, there is little gain in increasing the component complexity of our prediction approach.

Thus, for any predictor (for any site pair), the information denoted by the following triplet can be used as a metric to gauge its accuracy:

Accuracy-Metric = [Throughput, % Error-Rate, Confidence]

where *Throughput* is the predicted GridFTP value (higher the better), with a certain percentage error (lower the better) and a percentage confidence interval (smaller the better). Interested parties can use a function of this accuracy metric to choose one site from the other.

	Only GidFTP Logs [VSF02]	**Linear Regression between GridFTP logs and network load [VS02]**			**Linear Regression between GridFTP logs and disk load**			**Linear Regression using all three data sources**		
	Moving Avg	**G+N NoFill**	**G+N LV**	**G+N Avg**	**G+D NoFill**	**G+D LV**	**G+D Avg**	**G+N+D NoFill**	**G+N+D LV**	**G+N+D Avg**
LBL-ANL	24.4%	22.4%	20.6%	20%	25.2%	21.7%	21.4%	22.3%	17.7%	17.5%
LBL-UFL	15%	18.8%	11.1%	11%	20.1%	11.6%	11.9%	11.1%	8.7%	8%
ISI-ANL	15%	12%	9.5%	9%	13.1%	13%	11.4%	11%	8.9%	8.3%
ISI-UFL	21%	21.9%	16%	14.5%	22.7%	19.7%	18.8%	14.7%	13%	12%
ANL-UFL	20%	21%	20%	16%	21.8%	19.9%	19.3%	15.3%	16.7%	15.5%

Figure.4. Normalized percent prediction error rates for the various site pairs for the August 2001 dataset. Figure denotes four categories: (1) Prediction based on GridFTP data in isolation (Moving Avg), (2) Regression between GridFTP and NWS network data with the three filling in techniques (G+N), (3) Regression between GridFTP and disk I/O data with the three filling in techniques (G+D), (4) Regression based on all three data sources (G+N+D). Shaded portions indicate a comparison between our approaches.

4.2 Results

Figure 4 presents the average normalized percent error based on all transfers for the site pairs we examined. They are classified as follows: MovingAvg corresponds to prediction based on GridFTP in isolation [VSF02]; G+N corresponds to regression between GridFTP and NWS network data [VS02]; G+D corresponds to regression between GridFTP and disk I/O with all three filling strategies; G+N+D corresponds to regressing all three datasets. We have shown all results in the interest of continuity.

From Figure 4, we can observe that including disk I/O component load variations in the regression model provides us with gains of up to 4% (G+D Avg) when compared with MovingAvg (first and third shaded columns in Figure 4). Different filling techniques (G+D Avg and G+D LV) perform similarly.

Further, from Figure 4, we see that all variations of G+N perform better than G+D in general – i.e., regression using network data performs better than regression using disk I/O data. This observation is in sync with our initial measurements that only 15-30% of the total transfer time is spent in I/O, while majority of the transfer time (in our experiments) is spent in network transport.

When we include both disk I/O and NWS network data in the regression model (G+N+D) along with GridFTP transfer data, we see that prediction error drops up to 3% when compared with G+N (second and fourth shaded columns in Figure 4). Overall, we see up to 9% improvement when we compare G+N+D against our original prediction based on Moving Avg. As disk sizes grow and speeds continue to stay the same we believe this will be even more significant.

Figure 5a compares the forecasting error in Moving Avg, G+D Avg, G+N Avg, and G+N+D Avg for all of our site pairs (represents the shaded columns in Figure 4 graphically) and also presents 95% confidence limits for our prediction error rates. The forecasting accuracy trend is as follows:

Moving Avg < (G+D Avg) < (G+N Avg) < (G+N+D Avg)

From Figure 5b we can observe that the interval does in fact reduce with more accurate predictors, but the reduction is not significant for our datasets.

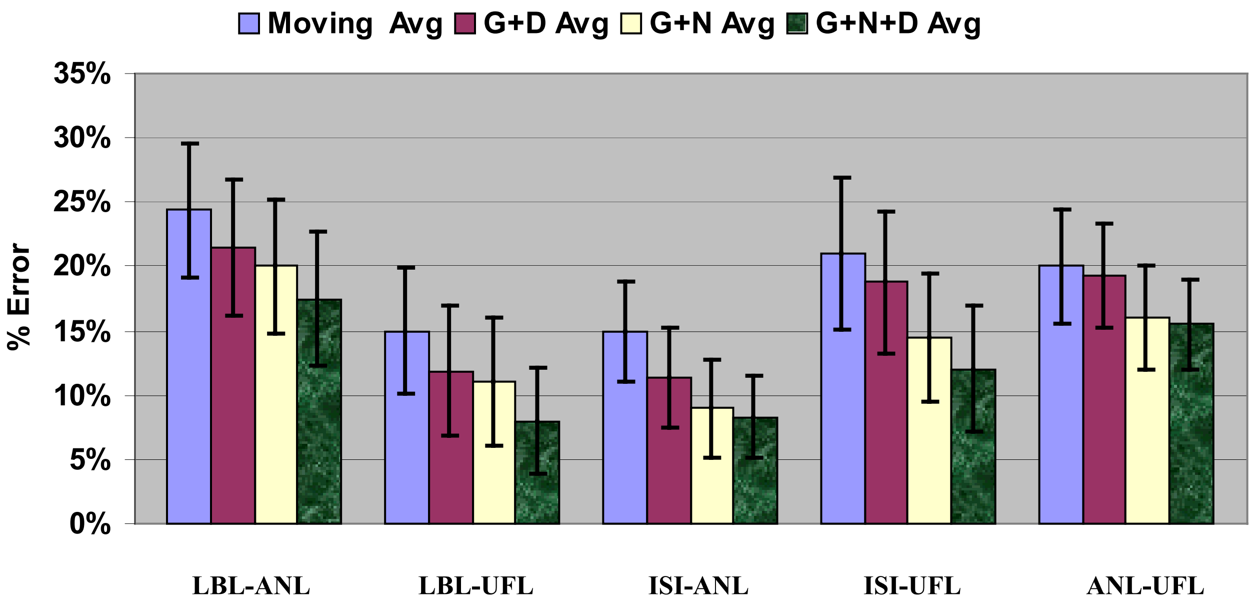
Figure 6 depicts the performance of predictors G+D Avg and G+N+D Avg. Graphs show the relevant data sources and the associated predictions. We can see how predictors closely track the measured GridFTP values. Predictions were obtained using regression equations that were computed for each observed network or disk throughput value. Sample regression equations with computed coefficients (based on discussion from Section 3.4) for the last observed N and D values in 6a and 6b are as follows:

$$G' = 6.9 - 0.18*D$$

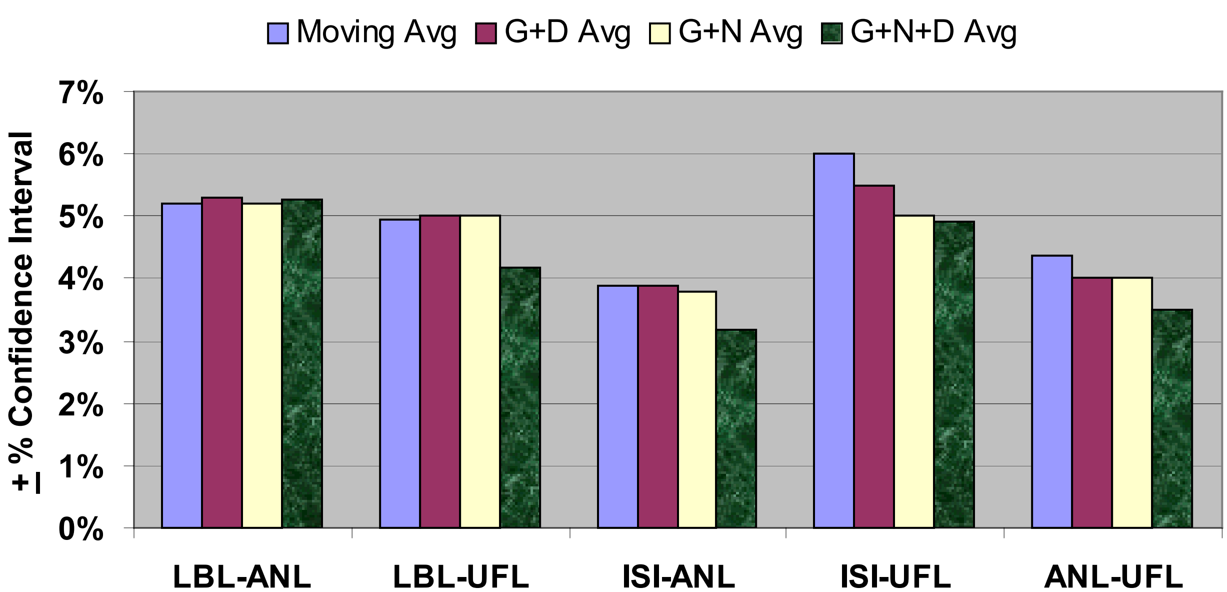
for the simple regression case and

$$G' = 7 - 0.38*N - 0.18*D$$

for the multiple regression.

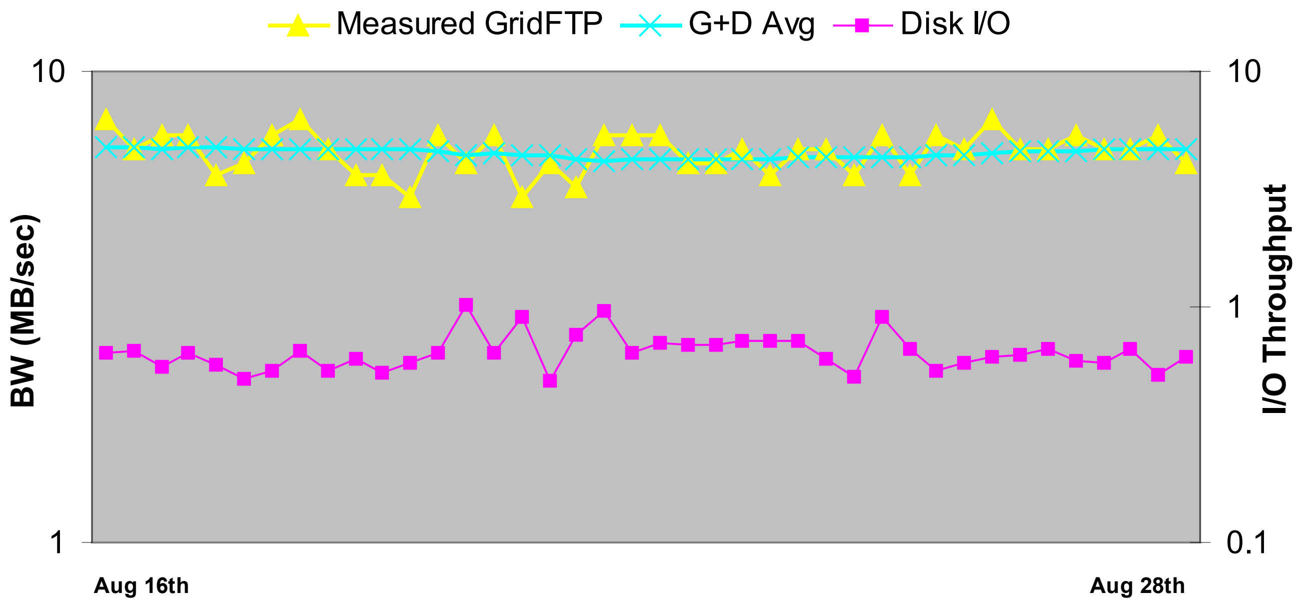


(a) Comparison of normalized percent errors for the predictors with 95% confidence limits

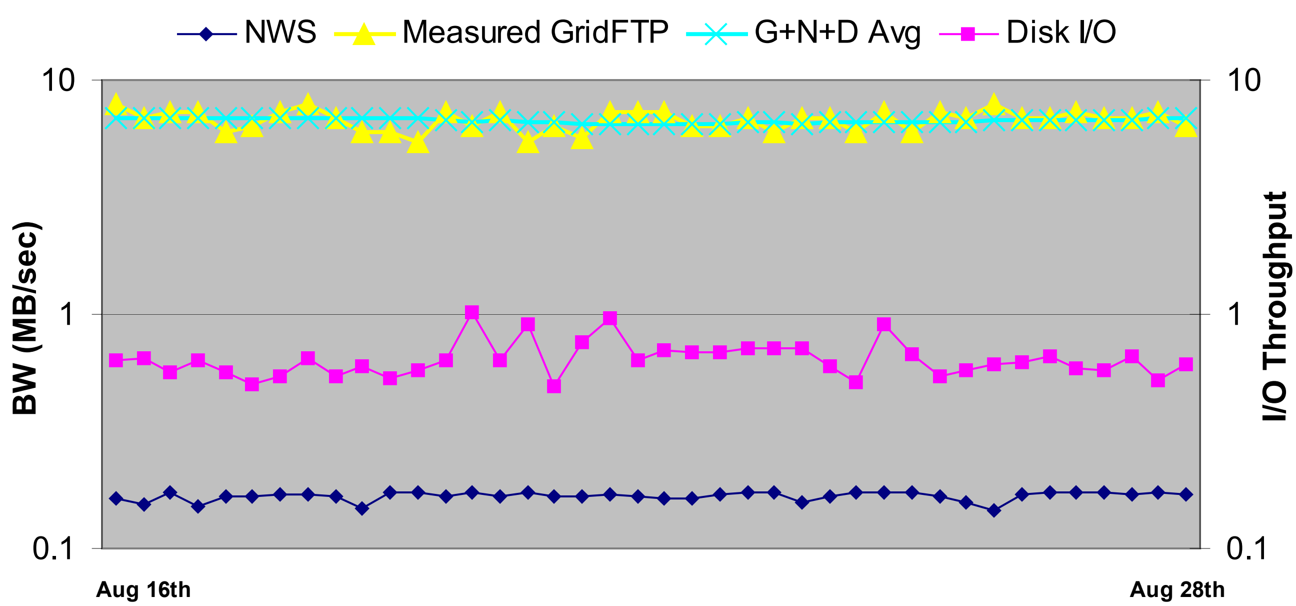


(b) Comparison of intervals for the predictors

Figure.5. (a) Normalized percent prediction error and 95% confidence limits for August 2001 dataset due to (1) prediction based on GridFTP in isolation (MovingAvg), (2) regression between GridFTP and disk I/O with Avg filling strategy (G+D Avg); (3) regression between GridFTP and NWS network data with Avg filling strategy (G+N Avg), and (4) regressing all three datasets (G+N+D Avg). Confidence Limits denote the upper and lower bounds of prediction error. For instance, the LBL-ANL pair had a prediction range of [17.3% ± 5.2%]. (b) Comparison of the percentage of variability among the predictors.



(a) Regression between GridFTP and Disk I/O



(b) Regression between GridFTP, NWS and Disk I/O

Figure.6. Predictors for 100M transfers between ISI and ANL for August 2001 dataset. In both graphs, GridFTP, G+D Avg, G+N+D Avg and NWS are plotted on the primary Y-axis; while Disk I/O is plotted on the secondary Y-axis. I/O throughput denotes transfers per second.

5 Conclusion

In this paper, we present techniques to combine observations of end-to-end application behavior and disk I/O throughput load data. We develop a set of regression models to derive predictions that characterize the effect of disk load variations on file transfer times. Our methodology for deriving predictions used simple statistical tools that are reasonably straightforward and easy to implement and therefore easy to apply to other datasets.

Using disk I/O data improved prediction accuracy by up to 4% when compared to predicting with just past GridFTP behavior; Similarly predicting based on I/O, NWS and GridFTP data improved accuracy further, by up to 9%. By adding additional data streams, each of which describing a piece of the end-to-end GridFTP transfer path, we saw improvements in the accuracy of the predictions generated. For our datasets, we observed no improvements in using polynomial regression.

Future work includes exploring rank functions to evaluate the accuracy of predictors, using the variance information of predictors to perform scheduling decisions, etc.

Acknowledgments

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