The Measured Network Traffic of Compiler–Parallelized Programs

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Abstract

Using workstations on a LAN as a parallel computer is becoming increasingly common. At the same time, parallelizing compilers are making such systems easier to program. Understanding the traffic of compiler–parallelized programs running on networks is vital for network planning and designing quality of service systems. To provide a basis for such understanding, we measured the traffic of six dense-matrix applications written in a dialect of High Performance Fortran, compiled with the Fx parallelizing compiler, and run on an Ethernet LAN. The traffic of these programs is profoundly different from typical network traffic. In particular, the programs exhibit global collective communication patterns, correlated traffic along many connections, constant burst sizes, and periodic burstiness with bandwidth dependent periodicity. The traffic of these programs can be characterized by the power spectra of their instantaneous average bandwidth.

1. Introduction

As the performance of local area networks grows, it is increasingly tempting to use a cluster of workstations as a parallel computer. At the same time, presentation layer APIs such as PVM [12] and MPI [19], and parallel languages such as High Performance Fortran [10] (HPF) have been, greatly enhancing the portability of parallel programs to workstation clusters. Further, the parallel computing community has developed extremely efficient implementations of these APIs and languages [17, 1, 4].

As implementations continue to become more efficient, the performance of the network will be increasingly important. In addition to significantly increased connection and aggregate bandwidths, next generation networks will supply quality of service (QoS) guarantees for connections [2, 3]. Parallel programs may be able to benefit from such guarantees. However, to extract a QoS guarantee from a network, an application must supply a characterization of its traffic [8]. Much of the work in traffic characterization has concentrated on media streams [9, 11], although some work on ATM call admission for parallel applications has assumed correlated bursty traffic [7]. In this paper, we detail measurements of the traffic of dense matrix parallel programs written in a dialect of HPF and compiled with Carnegie Mellon University's Fx parallelizing compiler [13].

In all, we measured the network behavior of six Fx parallel programs on a shared 10 mbps Ethernet. Five of these programs are kernels which exhibit global communication patterns common to Fx programs. Fx parallelizes dense matrix codes written in a dialect of HPF. Fx targets the SPMD machine model, as do many other parallelizing compilers. We also look at a large scale example of an Fx application, an air quality modeling application which is being parallelized at CMU in a project related to Fx [14].

The outgrowth of these measurements is the observation that the traffic of Fx parallel programs is fundamentally different from those of media streams. Specifically, parallel programs exhibit

- Global collective communication patterns
- Correlated traffic along many connections
- Constant burst sizes
- Periodic burstiness
- Bandwidth dependent periodicity

We characterize the programs' bandwidth demands by the power spectra of their instantaneous average bandwidths. These spectra directly correspond to the Fourier series coefficients needed to reconstruct the instantaneous average bandwidth at any point in time. Interestingly, these spectra are rather sparse and "spiky", which means the Fourier expansion can be limited to important spikes, forming a simple analytic model that approximates the instantaneous average bandwidth.

2. Communication patterns

The Fx compiler parallelizes dense matrix codes based on parallel array assignment statements and targets distributed memory parallel computers using the Single Program, Multiple Data (SPMD) model. This model is the ultimate target of many parallel and parallelizing compilers. In the SPMD model, each processor executes the same program, which works on processor-local data. Frequently, the

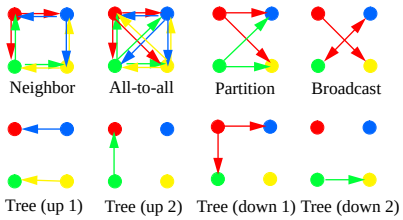


Figure 1. Fx Communication patterns

processors exchange data by message passing, which also synchronizes the processors. This message exchange is referred to as a *communication phase*. The parallel program executes as interleaved communication and local *computation phases*.

A communication phase can be classified according to the pattern of message exchange among the processors. In general, this pattern can be *many-to-many*, where each processor sends to any arbitrary group of the remaining processors. However, certain patterns are much more common than others, especially in dense matrix computations such as those typically coded in HPF and Fx. For example, the *neighbor* pattern, where each processor p_i sends to processors p_{i-1} and p_{i+1} is common. Another common pattern is *all-to-all*, where each processor sends to every other processor. A third pattern is *partition*, where the processors are partitioned into two or more sets and each member of a set sends to every member of another set. Fourth, a single processor may *broadcast* a message to every other processor. Finally, the pattern can be a *tree*, where every second processor sends to its left neighbor and then drops out. This is repeated until one processor remains. Sometimes this is followed with a "down-sweep", reversing the process. These communication patterns are summarized in Figure 1.

3. Program descriptions

The six Fx programs chosen for investigation fall into two classes. Five of the programs, SOR, 2DFFT, TDFFT, SEQ, and HIST, are kernels that exhibit the communication patterns discussed in section 2. These kernels are part of the Fx test suite. AIRSHED [16, 14], an air quality modeling application, represents a "real" scientific application.

3.1. Fx kernels

Five of the Fx programs, SOR, 2DFFT, T2DFFT, SEQ, and HIST, were chosen to exhibit communication patterns common to SPMD parallel programs discussed in section 2. These kernels are summarized in figure 2. For each program, we discuss the distribution of its data (an $N \times N$ matrix) over its P processors, the local computation on each processor, and the global communication it exhibits.

Pattern	Kernel	Description
Neighbor	SOR	2D Successive overrelaxation
All-to-all	2DFFT	2D Data parallel FFT
Partition	T2DFFT	2D Task parallel FFT
Broadcast	SEQ	Sequential I/O
Tree	HIST	2D Image histogram

Figure 2. Fx kernels

SOR is a successive overrelaxation kernel. In each step, each element of an $N \times N$ matrix computes its next value as a function of its neighboring elements. In the Fx implementation, the rows of the matrix are distributed across P processors by blocks: processor 0 owns the first $\frac{N}{P}$ rows, processor 1 the next $\frac{N}{P}$ rows, etc. Because of this distribution, at each step, every processor p except for processors 0 and $P-1$ must exchange a row of data with processor $p-1$ and processor $p+1$ before computing the next value of each of the elements it owns. In every step, each processor performs $O(\frac{N^2}{P})$ local work and sends an $O(N)$ size message to processors $p-1$ and $p+1$. SOR is our example of such a *neighbor* communication pattern.

2DFFT is a two-dimensional Fast Fourier Transform. Like in SOR, the $N \times N$ input matrix has its rows block-distributed over the processors. In the first step, local one-dimensional FFTs are run over each row a processor owns. Next, the matrix is redistributed so that its columns are block-distributed over the processors. Finally, local one-dimensional FFTs are run over each column a processor owns. Each processor performs $O(\frac{N^2 \log N}{P})$ work and generates a $O((\frac{N}{P})^2)$ size message for every other processor. 2DFFT is our example of a *all-to-all* communication pattern.

T2DFFT is a pipelined, task parallel 2DFFT. Half of the processors perform the local row FFTs and send the resulting matrix to the other half, which perform the local column FFTs. A side effect of the communication is the distribution transpose, so each sending processor sends an $O((\frac{N}{P})^2)$ size message to each of the receiving processors. Notice that each message is twice as large as for 2DFFT for the same number of processors. Each processor performs $O(\frac{N^2 log N}{P})$ work. This is our example of a *partition* communication pattern.

SEQ is an example of the kind of *broadcast* communication pattern that results from sequential I/O in Fx programs. An $N \times N$ matrix distributed over the processors is initialized element-wise by data produced on processor 0. This is implemented by having processor 0 broadcast each element to each of the other processors, which collect the elements they need. This program performs no computation, but processor 0 sends N^2 $O(1)$ size messages to every other processor. This is our example of a *broadcast* communication pattern.

HIST computes the histogram of elements of a $N \times N$ input matrix. The input matrix has its rows distributed over the processors. Each processor computes a local histogram vector for the rows it owns. After this, there are $\log P$ steps, where at step i, processors whose numbers are odd multiples of 2^i send their histogram vector to the processors that are even multiples of 2^i. These processors merge the incoming histogram vector with their local histogram vector. Ultimately, processor 0 has the complete histogram, which it broadcasts to all the other processors. This is an example of a *tree* communication pattern.

3.2. AIRSHED Simulation

The multiscale AIRSHED model captures the formation, reaction, and transport of atmospheric pollutants and related chemical species [15]. The goal of a related research project was to convert this massive application into a portable and scalable parallel program [14]. As a part of this work, AIRSHED was ported to Fx. However, at the time of our research, this port had not been completed. Instead, we measured an Fx skeleton of the application which was prepared by the porting group. The skeleton models both the computation and communication of the actual application.

AIRSHED simulates the movement and reaction of s chemical species, distributed over domains containing p grid points in each of l atmospheric layers [16]. Input is an $l \times s \times p$ concentration array C, which is transformed into an output concentration array C' via a pre-processing step followed by a sequence of k simulation steps, each consisting of a horizontal transport phase, and a chemistry/vertical transport phase. Each horizontal transport phase performs $l \times s$ independent computations, one for each layer and species. The chemistry/vertical transport phase performs an independent computation for each of the p grid points. The $C \rightarrow C'$ transformation forms a simulation-hour and is repeated h times.

In the implementation, to compute the horizontal transport phase, the array is block-distributed across P processors by layer: processor 0 owns the first $\frac{l}{P}$ layers, processor 1 owns the next $\frac{l}{P}$ layers, and so on. The chemistry/vertical transport phase is computed with the array block-distributed by the grid dimension. Thus, after the horizontal transport phase, a distribution transpose is performed, requiring that each processor send a message of size $O(\frac{p \times s \times l}{P^2})$ to every other processor. Once the chemistry/vertical transport computation is finished, another distribution transpose is performed in which each processor sends a message of size $O(\frac{p \times s \times l}{P^2})$ to each of the other processors.

4. Methodology

Nine DEC 3000/400 Alpha (21064 at 133 MHz with 64 MB RAM) workstations [6] running OSF/1 2.0 were used as our testbed. The built-in Ethernet adaptors were married to a multi-segment bridged Ethernet LAN, so all machines shared a common collision domain and an aggregate 1.25 MB/s of bandwidth. Since these machines are office workstations and other machines share the LAN, all measurements were performed in the early morning hours (4-5 am) to avoid other traffic, and were repeated several times.

We used PVM [12] for communication, configuring it use direct TCP connections for all intermachine communication instead of routing messages through the PVM daemons. While data is "packed" into a PVM message using a variety of API calls, the data is not necessarily appended into a contiguous memory buffer. Instead, it is stored as a list of fragments which are sent independently. This means that programs that make multiple pack calls per message will have different network characteristics than those that make a single pack call.

Each of the six Fx programs can be compiled for an arbitrary number of processors. Due to the stress these programs place on machines and networks, it was decided to compile them for four processors. The programs were compiled with version 2.2 of Fx compiler and version 3.3 of the DEC Fortran compiler. The basic level of optimization (-O) was used with the latter compiler. The object files were linked with version 3.3.3 of PVM and with version 2.2 of the Fx/PVM run-time.

To measure the network traffic, one of the workstations was configured with the DEC packet filter software, which allows privileged users to use the network adaptor in promiscuous mode. The measurement workstation was not used to run any Fx program. Instead, it ran the TCPDUMP program included with OSF/1 and collected a trace of all the packets on the LAN generated by each test program. For the Fx programs, including AIRSHED, each outer loop as iterated 100 times, except for SEQ, which was iterated five times.

Each of our traces captured all the packets on the network, providing a time stamp, size, protocol, source and destination for each packet. We considered the size of the packet to include the data portion, TCP or UDP header, IP header, and Ethernet header and trailer. Where sensible, we produced a trace for a single connection by extracting all packets sent from one host to another.

5. Results

In this section, we describe the traffic characteristics for each of the six Fx programs using a common format.

5.1. Fx kernels

For each of the kernels, we examined its aggregate traffic and the traffic of a representative connection, if there was one. We define a connection to be a kernel-specific simplex channel between a source machine in a destination machine. Thus for $P = 4$, each of the kernels exhibits 12 connections. Notice that by considering a connection between *machines* as opposed to between machine-port pairs, we capture all kernel-specific traffic between a source and destination machine. This includes TCP traffic for message passing, UDP traffic between the PVM daemons, and TCP ACKs for the symmetric channel. The communication pattern of HIST and SEQ are not symmetric, so we only examine the aggregate traffic of these kernels. T2DFFT's pattern is symmetric about the partition, so we consider a connection from a machine in the sending half to a machine in the receiving half. The other kernels have symmetric communication patterns, so we choose the connection between two arbitrary machines.

The traffic of each of the kernels is characterized by its packet sizes, interarrival times for packets, and bandwidth, both for the aggregate traffic and the traffic over the representative connection. We concentrate on characterizing the bandwidth, since this appears the most interesting.

Figure 3 shows the minimum, maximum, average and standard deviation of packet sizes for each of the five applications. Although we do not present histograms here, it is important to remark that for several of the kernels (2DFFT, HIST, SOR), the distribution of packet sizes is *trimodal*. This is because these programs send messages large messages which are split over several maximal size packets and a single smaller packet for the remainder. Further, because TCP is used for the data transfer, there are a significant number of ACK packets. One would expect T2DFFT to also send large messages and therefore exhibit a trimodal distribution of packet sizes. However, with T2DFFT, multiple PVM pack calls are made per message. As described earlier, many fragments result, explaining the variety of packet sizes.

Figure 4 shows the minimum, maximum, average, and standard deviation of the packet interarrival times for each of the five programs. Notice that ratio of maximum to average interarrival time for each program is quite high. This is due to the aggregate bursty nature of the traffic, as we discuss below.

Figure 5 shows the average bandwidth used over the lifetime of each of the five programs. It is somewhat counterintuitive (and quite promising!) that even the most communication intensive Fx programs such as 2DFFT do not consume all the available bandwidth. However, recall that Fx programs synchronize via their global communication phases, so there are stretches of time where every processor is computing. Each of these periods is followed by an intense burst of traffic, as every processor tries to communicate.

Program	Packet Size (Bytes)			
	Min	Max	Avg	SD
SOR	58	1518	473	568
2DFFT	58	1518	969	678
T2DFFT	58	1518	912	663
SEQ	58	90	75	14
HIST	58	1518	499	575

(aggregate)

Program	Packet Size (Bytes)			
	Min	Max	Avg	SD
SOR	58	1518	577	591
2DFFT	58	1518	977	667
T2DFFT	134	1518	1442	158
SEQ	-	-	-	-
HIST	-	-	-	-

(connection)

Figure 3. Packet size statistics: Fx kernels

Program	Interarrival Time (ms)			
	Min	Max	Avg	SD
SOR	0.0	1728.7	82.1	234.9
2DFFT	0.0	1395.8	1.3	10.8
T2DFFT	0.0	1301.6	1.5	14.3
SEQ	0.0	218.6	1.3	8.6
HIST	0.0	449.9	16.5	45.5

(aggregate)

Program	Interarrival Time (ms)			
	Min	Max	Avg	SD
SOR	0.0	1797.0	614.2	590.8
2DFFT	0.0	2732.6	15.1	120.5
T2DFFT	0.0	4216.7	9.5	127.3
SEQ	-	-	-	-
HIST	-	-	-	-

(connection)

Figure 4. Interarrival time statistics: Fx kernels

It is important to note that this synchronization is inherent in the Fx model and is not merely a result of serialization due to the Ethernet MAC protocol. In fact, in several new communication strategies optimized for compiler-generated SPMD programs the global synchronization is *enforced* by a separate barrier synchronization before each communication phase [18].

The effect of this inherent synchronization is made clear by examining figure 6, which plots the instantaneous bandwidth averaged over a 10 ms window for the each of the kernel. This was computed using a sliding 10 ms averaging

Program	KB/s
SOR	5.6
2DFFT	754.8
T2DFFT	607.1
SEQ	58.3
HIST	29.6

(aggregate)

Program	KB/s
SOR	0.9
2DFFT	63.2
T2DFFT	148.6
SEQ	-
HIST	-

(connection)

Figure 5. Average bandwidth: Fx kernels

window which moves a single packet at a time. Since HIST and SEQ have no representative connection, only their aggregate bandwidths are plotted. In each case, we show a ten second span of time, enough to include several iterations of the kernel.

The most remarkable attribute of each of the kernels is that the bandwidth demand is highly periodic. Consider the 2DFFT. Both plots show about five iterations of the kernel. Notice that there are substantial portions of time where virtually no bandwidth is used (all the processors are in a compute phase). The reason the third and fourth burst are short is because they are, in fact, a single communication phase where some processor descheduled the program. Because the all-to-all communication schedule is fixed and synchronous, the communication phase stalled until that processor was able to send again.

Figure 7 shows the corresponding power spectra (periodograms) of the instantaneous average bandwidth. The power spectra show the frequency-domain behavior of the bandwidth, and are very useful for characterizing it, as we will explore in Section 6. It is important to note that the power spectra capture the periodicity of the bandwidth demands these applications place on the network.

For these calculations, the entire trace of each kernel was used, not just the first 10 seconds displayed in figure 6. Because a power spectrum computation requires evenly spaced input data, the input bandwidth was a computed along static 10 ms intervals by including all packets that arrived during the interval. This is a close approximation to the sliding window bandwidth, and more feasible than correctly sampling the sliding window bandwidth data, which would require a curve fit over a massive amount of data.

Not surprisingly, SEQ, in which processor 0 repeatedly broadcasts a single word, is extremely periodic, with the four Hz harmonic being the most important. HIST has a 5 Hz fundamental with linearly declining harmonics at 10, 15, etc. Hz.

SOR and 2DFFT display opposite relationships between the connection and aggregate power spectra. For SOR, the connection power spectrum shows great periodicity, with a fundamental of about 5 Hz and interestingly modulated harmonics, but the aggregate power spectrum shows far less clear periodicity. For 2DFFT, the relationship is the reverse,

Program	Packet Size (Bytes)			
	Min	Max	Avg	SD
AIRSHED	58	1518	899	693

(aggregate)

Program	Packet Size (Bytes)			
	Min	Max	Avg	SD
AIRSHED	58	1518	889	688

(connection)

Figure 8. Packet size statistics: AIRSHED

although less strong, with a clear fundamental of $1/2$ Hz and exponentially declining harmonics. There are two explanations for this. First, 2DFFT transfers more data per message than SOR ($O(\left(\frac{N}{P}\right)^2)$ versus $O(N)$, $N = 512$, $P = 4$), so has a better chance of being descheduled (as discussed above). Second, 2DFFT's communication pattern more closely synchronizes all the processors than SOR's. Thus a single SOR connection has a better chance of being periodic because the sending processor is less likely to be descheduled. On the other hand, SOR's aggregate traffic will be less periodic because the processors are less tightly synchronized. Notice, however, that in both cases, the representative connection's power spectrum *does* show considerable periodicity.

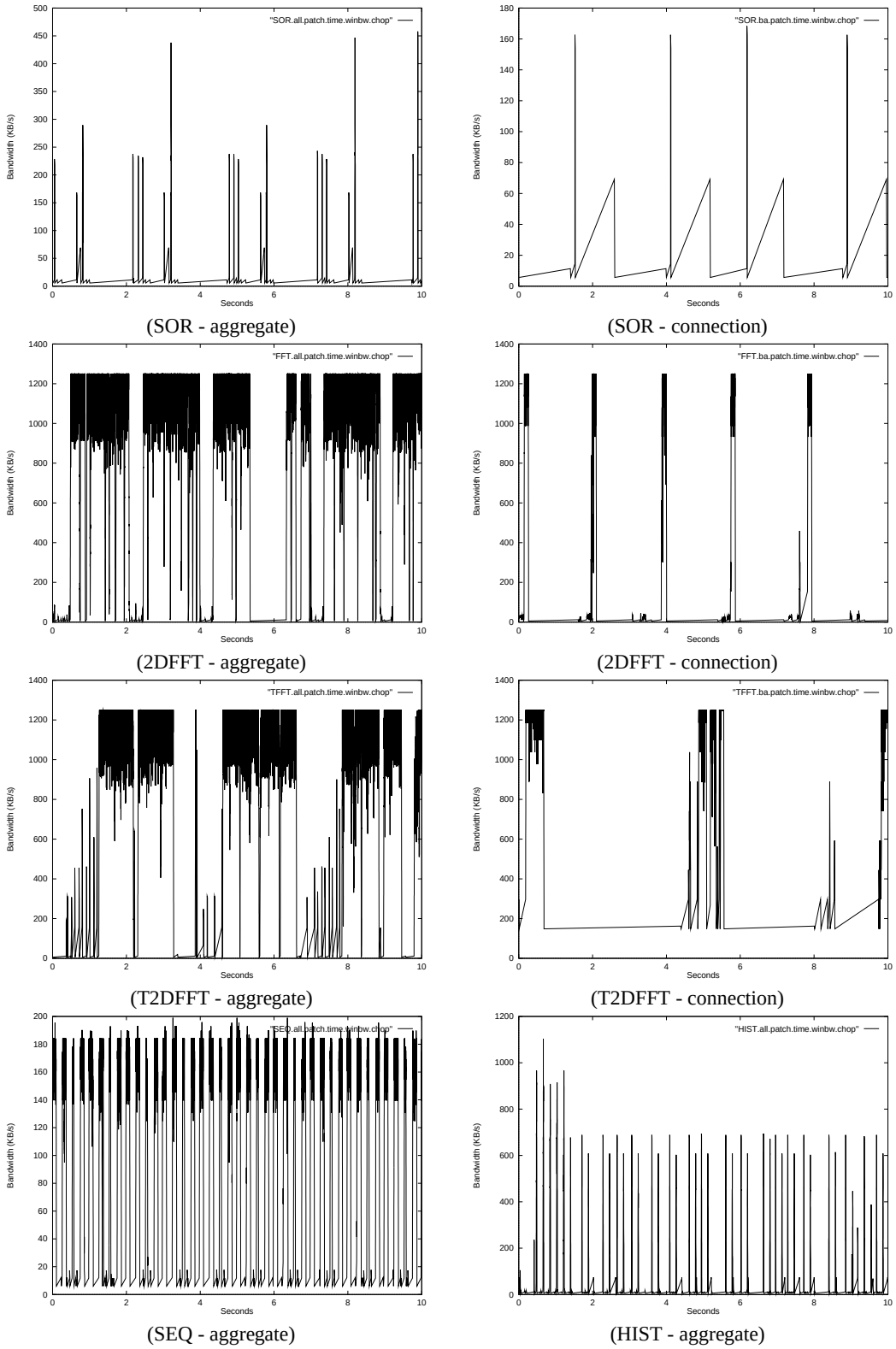
T2DFFT's power spectra have the least clear periodicity of all the Fx kernels. However, the aggregate spectrum seems slightly cleaner than the spectrum of the representative connection. The fact that neither spectrum is very clean is surprising given the synchronizing nature of this pattern, the balanced message sizes, and the communication schedule (shift) used for it. We believe the problem arises from fragmentation.

5.2. AIRSHED Simulation

Figure 8 shows the minimum, maximum, average, and standard deviation of packet sizes for the AIRSHED application. We observe that the packet size distribution for the single connection is very similar to the aggregate packet distribution, which supports the argument that the traffic from the single connection is representative of the aggregate traffic.

Figure 9 shows the minimum, maximum, average, and the standard deviation of packet interarrival times. Note that both the maximum and average interarrival times are of an order of magnitude greater than that of the kernel applications. As in the case of the kernel applications, the ratio of maximum to average interarrival time is quite high, which is characteristic of bursty traffic.

The average aggregate and per-connection bandwidths for the AIRSHED application are 32.7 KB/s and 2.7 KB/s,



(SOR - aggregate) (SOR - connection)

(2DFFT - aggregate) (2DFFT - connection)

(T2DFFT - aggregate) (T2DFFT - connection)

(SEQ - aggregate) (HIST - aggregate)

Figure 6. Instantaneous bandwidth of Fx kernels (10ms averaging interval)

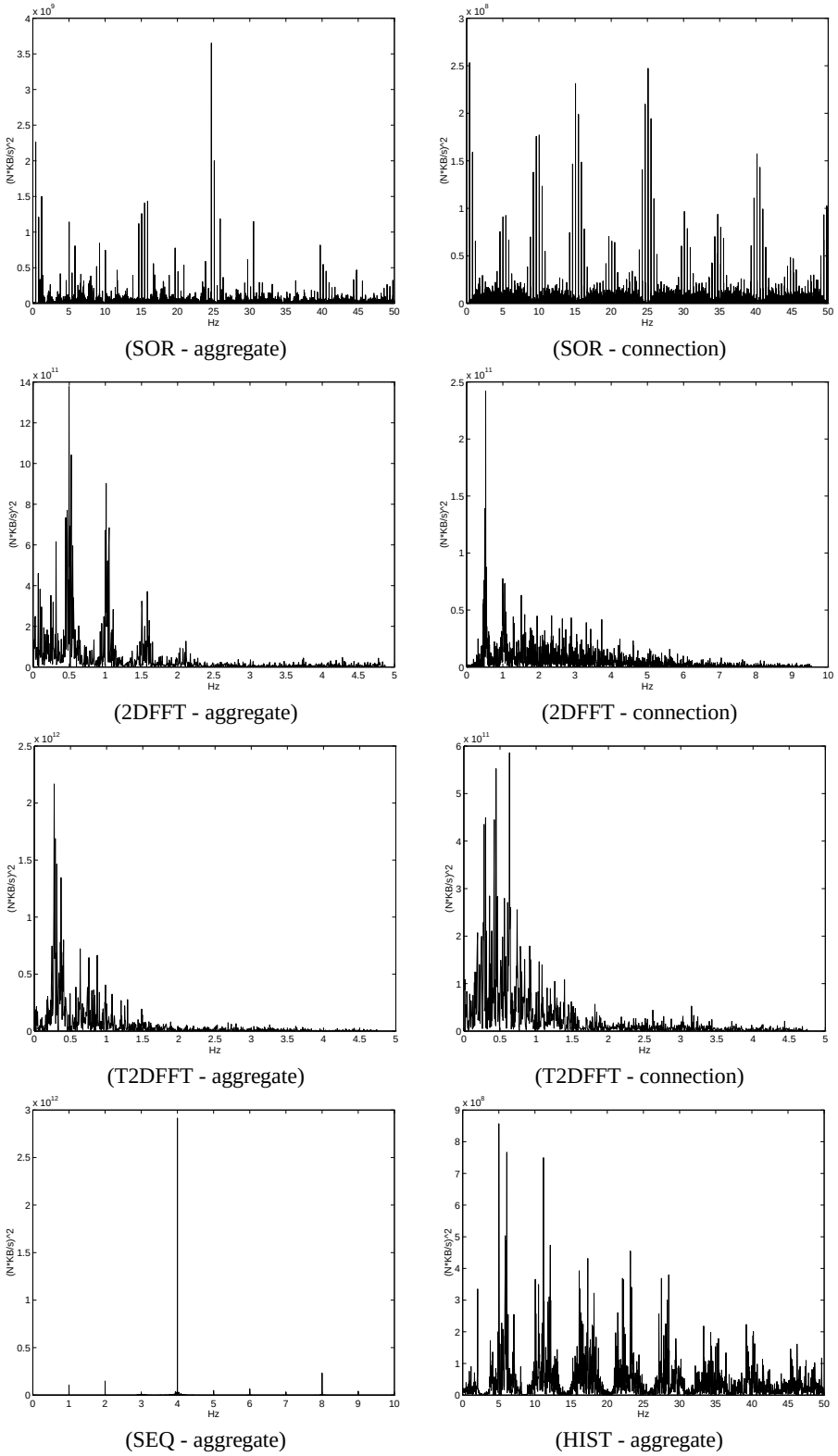


Figure 7. Power spectrum of bandwidth of Fx kernels (10ms averaging interval)

Program	Interarrival Time (ms)			
	Min	Max	Avg	SD
AIRSHED	0.0	23448.6	26.8	513.3

(aggregate)

Program	Interarrival Time (ms)			
	Min	Max	Avg	SD
AIRSHED	0.0	37018.5	317.4	2353.6

(connection)

Figure 9. Interarrival time statistics: AIRSHED

respectively. Figure 10 shows the instantaneous bandwidth averaged over a 10 ms window (over a 500 sec interval, and a 60 sec interval). It is clear that the bandwidth demand is highly periodic, and is periodic over *three* different time scales, corresponding to the $h = 100$ simulation-hours, the $k = 5$ simulation steps in an hour, and the two phases and distribution transposes within a simulation step.

Such periodicity becomes very clear when we observe the power spectra (figure 11). There are three peaks (plus their harmonics) in the power spectrum at approximately 0.015 Hz (66 sec, corresponding to a simulation hour), 0.2 Hz (5 sec, corresponding to the length of the chemical/vertical transport phase), and 5 Hz (200 ms, corresponding to that of the horizontal transport phase), respectively.

6. Discussion

The measurement and analysis of the Fx kernels and the AIRSHED program point to several important characteristics of the network traffic of Fx parallel programs. The most important of these is that their periodicity is well characterized by their power spectra, and can be emulated by simplifying the Fourier series implied by the spectra. Finally, we suggest a negotiation model for QoS which would allow both the network and the program to co-optimize for performance.

Elementary characteristics: Fx programs exhibit some global, collective communication patterns which may not necessarily be characterized by the behavior of single connection. For example, the SEQ (broadcast pattern) and HIST (tree pattern) kernels are not symmetric — in SEQ only the connection from processor 0 to the every other processor (and the symmetric connections back to processor 0) see traffic. Furthermore, characterizing the symmetric patterns such as neighbor, all-to-all, and partition by a single connection ignores the fact that these patterns are very different in the number of connections that are used. For example, each of the patterns may communicate the same size message along a connection, but while all-to-all sends such a message along *all* $P(P-1)$ connections, neighbor sends a message along only at most $2P$ connections.

Another important characteristic of Fx programs is that their communication phases are synchronized, either explicitly or implicitly. This means that the traffic along the active connection is *correlated* and any traffic model must capture this. Further, the stronger the synchronization, the more likely it is that the connections are *in phase.*

Characterizing periodicity: As stated above, the synchronized communication phases of a Fx program imply that its connections act in phase. Thus, the power spectra of Figures 7 and 11 fully characterize the bandwidth demands of the applications discussed in this paper. Furthermore, it should be realized that the power spectrum is the square of the Fourier transform of the time-domain instantaneous average bandwidth. Since this underlying signal is periodic, the transform is a Fourier series. We can approximate the signal by choosing some number of the most significant coefficients (the "spikes"). As the number of spikes chosen increases, the approximation will converge to the actual signal.

QoS negotiation model: From the perspective of a QoS system, the communication pattern of an Fx program is vital information, as is the number of processors. The pattern shows how traffic will be correlated, and the number of processors determines the pacing of the traffic. The Fx program, on the other hand, wants to choose the number of processors that will let it minimize its running time, or, equivalently, it's inter-burst interval, t_{bi}. We suggest therefore that the program should characterize its traffic with three parameters, $[l(), b(), c]$, where c is the communication pattern, l is a function from the number of processors P to the local computation time t_{local} on each processor, and b is a function from P to the burst size N, along each connection. To meet the "guarantee" of minimizing t_{bi}, the network would return the number of processors P the program should run on.

7. Conclusions and future work

We measured the traffic characteristics of six parallel programs on a shared 10 mbps Ethernet. The conclusion to be drawn from the measurements is that the traffic of parallel programs is fundamentally different from the media traffic that is the current focus of QoS research. Unlike media traffic, there is no intrinsic periodicity due to a frame rate. Instead, the periodicity is determined by application parameters and the network itself. We suggested a traffic characterization and service negotiation model that allows

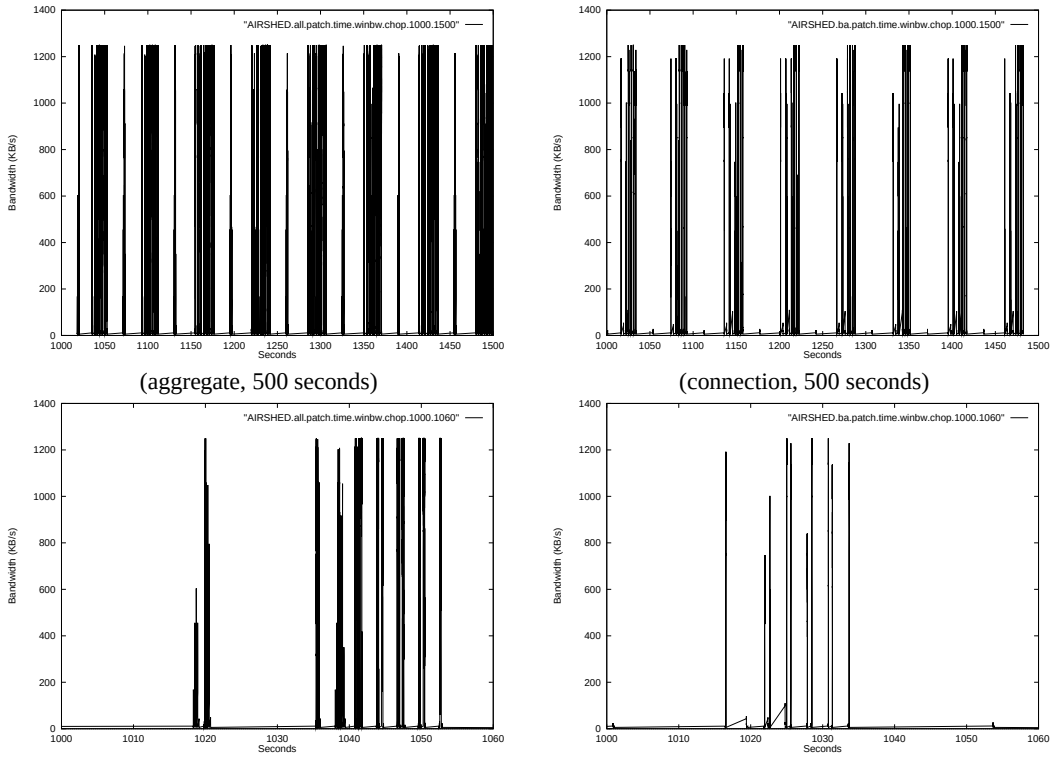


Figure 10. Instantaneous bandwidth of AIRSHED (10ms averaging interval)

the network to modulate application parameters in an effort to achieve the best performance possible given the current network state.

Repeating this study on a more modern switched network would be enlightening, although even on our slow network the programs were for the most part compute-bound. However, in our study the injected traffic could become serialized through the shared media. We don't believe that happened often, but the chances would be even lower in a modern switched network. We are also considering what meaning our results have for current efforts to predict resource availability in networks [5, 20].

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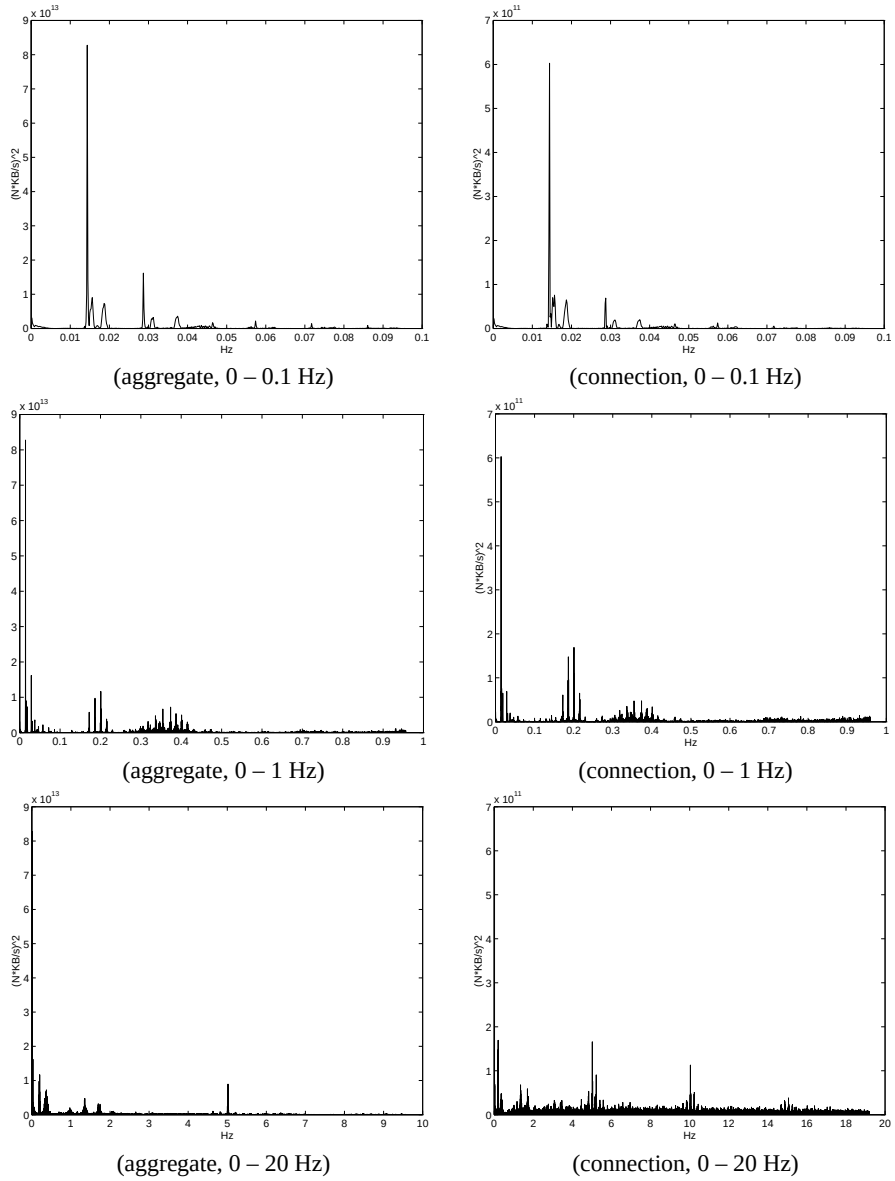

Figure 11. Power spectrum of bandwidth of AIRSHED (10ms averaging interval)

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