Scalability of Linux Event-Dispatch Mechanisms

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Abstract

Many Internet servers these days have to handle not just heavy request loads, but also increasingly face large numbers of concurrent connections. In this paper, we discuss some of the event-dispatch mechanisms used by Internet servers to handle the network I/O generated by these request loads. We focus on the mechanisms supported by the Linux kernel, and measure their performance in terms of their dispatch overhead and dispatch throughput. Our comparative studies show that POSIX.4 Real Time signals (RT signals) are a highly efficient mechanism in terms of the overhead and also provide good throughput compared to mechanisms like `select()` *and* `/dev/poll`. *We also look at some limitations of RT signals and propose an enhancement to the default RT signal implementation which we call* signal-per-fd. *This enhancement has the advantage of significantly reducing the complexity of a server implementation, increasing its robustness under high load, and also potentially increasing its throughput. In addition, our results also show that, contrary to conventional wisdom, even a* `select()` *based server can provide high throughput, even though it has high overhead, if its overhead is amortized by performing more useful work per* `select()` *call.*

1 Introduction

The fast growth of the Web and e-commerce has led to a large increase in Internet traffic. Most network applications such as Web servers and proxies have to handle heavy loads from clients spread all across the globe. In addition to high request rates, servers also have to handle a large number of concurrent connections, many of which are idle most of the time. This is because the connection times are large due to (i) the “last-mile problem” [3], which has the effect that most clients connect to the Internet through slow modems, and (ii) due to the geographically distributed nature of the Internet, which causes much of the traffic to travel across many hops, increasing both latency and the probability of packet drops due to congestion. For Web servers, the problem of long connections is exacerbated by the HTTP/1.1 protocol [5], which provides for persistent TCP connections that can be reused to handle multiple interactions with the server. These persistent connections further add to the length of the connection times. The bottom line is that servers need to service the high incoming request load, while simultaneously handling a large number of concurrent connections efficiently.

To handle these demands, many high-performance Web servers are structured as event-handling applications [9, 16, 18]. These servers employ event-dispatch mechanisms provided by the underlying operating system to handle the network I/O on multiple concurrent connections. Some studies have looked at the scalability issues of such mechanisms and found that traditional dispatch mechanisms are not very scalable [1]. While the performance of Web servers clearly is important, we should not forget that there are many other Internet services, such as ftp servers, proxy caches, and mail servers, that have to deal with similar scalability concerns. For example, poor scalability is one of the primary reasons the number of concurrent connections on many ftp servers is limited to a small number (around 30-50) [1].

Another approach to building Internet servers that can handle high request loads and large number of concurrent connections is to move the entire application into kernel space. Recent efforts in this direction have produced dramatic results for Web servers (e.g., TUX [17]). However, this does not obviate the need for efficient event-dispatch mechanisms. In fact, it is our contention that due to security and robustness concerns, many server sites are likely to prefer running Internet servers in user space, provided that they can achieve performance that is comparable to a kernel space solution. Efficient event dispatch mechanisms are also essential

[1] The scalability problems of the most popular ftp servers is partially due to the fact that they are using a process-per-connection model. This could be fixed by using an event-oriented model, though security considerations may not always permit adopting such a model.

for those applications that may be important for some sites (e.g., ftp), but perhaps not quite important enough to warrant the effort of developing an OS-specific kernel solution.

In this paper, we look at the different Linux event-dispatch mechanisms used by servers for doing network I/O. We try to identify the potential bottlenecks in each case, with an emphasis on the scalability of each mechanism and its performance under high load. We use two metrics to determine the efficiency of each mechanism, namely, the event-dispatch overhead and the dispatch throughput. The mechanisms we study in particular are the `select()` system call, `/dev/poll` interface and POSIX.4 Real Time signals (RT signals), each of which is described in more detail in the following sections. Our studies show that RT signals are an efficient and scalable mechanism for handling high loads, but have some potential limitations. We propose an enhancement to the kernel implementation of RT signals that overcomes some of these drawbacks, and allows for robust performance even under high load. We also measure the performance of a variant of the `select()` based server which amortizes the cost of each `select()` call, and show that it is more scalable in terms of the server throughput.

The rest of the paper is organized as follows. In Section 2, we describe the primary event-dispatch mechanisms supported by the Linux kernel, and discuss some of the previous work in this regard. In Section 3, we compare some of these mechanisms for their dispatch overhead. We discuss RT signals in more detail, identifying their limitations and propose an enhancement to the default implementation of RT signals in the Linux kernel. In Section 4, we present a comparative study of some of the mechanisms from the perspective of throughput achieved under high loads. Finally, we present our conclusions in Section 5.

2 Event-Dispatch Mechanisms

In this section, we first discuss the two main schemes employed by servers for handling multiple connections. Next, we look at the various event-dispatch mechanisms supported by the Linux kernel that can be employed by Web servers for doing network I/O. We follow this up with a discussion of previous work that has focussed on the scalability of some of these mechanisms, including other mechanisms that have been proposed to overcome some of their drawbacks.

2.1 Handling Multiple Connections

There are two main methodologies that could be adopted by servers for performing network I/O on multiple concurrent connections.

- *Thread-based:* One way to handle multiple connections is to have a master thread accepting new connections, that hands off the work for each connection to a separate service thread. Each of these service threads is then responsible for performing the network I/O on its connection. These service threads can be spawned in two ways:
  - *On-demand:* Each service thread is forked whenever a new connection is accepted, and it then handles the requests for the connection. This can lead to large forking overhead under high load when there are large number of new connections being established.
  - *Pre-forked:* The server could have a pool of pre-forked service threads. Whenever the master thread receives a new connection, it can hand over the connection to one of the threads from the pool. This method prevents the forking overhead, but may require high memory usage even under low loads.
- *Event-based:* In an event-based application, a single thread of execution uses non-blocking I/O to multiplex its service across multiple connections. The OS uses some form of event notification to inform the application when one or more connections require service. For this to work, the application has to specify to the OS the set of connections (or, more accurately, the set of file-descriptors) in which it is interested (*interest set*). The OS then watches over the interest set and whenever there's activity on any of these connections, it notifies the application by dispatching an event to it. Depending on the exact event-dispatch mechanism in use, the OS could group multiple notifications together or send individual notifications. On receiving the events, the server thread can then handle the I/O on the relevant connections.

In general, thread-per-connection servers have the drawback of large forking and context-switching overhead. In addition, the memory usage due to threads' individual stack space can become huge for handling large number of concurrent connections. The problem is even more pronounced if the operating system does not support kernel-level threads, and the application has to use processes or user-level threads. It has been shown that thread-based servers do not scale well at high loads [7].

Hence, many servers are structured as event-based applications, whose performance is determined by the efficiency of event notification mechanisms they employ. Pure event-based servers do not scale to multiprocessor machines, and hence, on SMP machines, hybrid schemes need to be employed, where we have a multi-threaded server with each thread using event-handling as a mechanism for servicing concurrent connections. Even with a hybrid server, the performance of event-based mechanisms is an important issue. Since efficient event dispatching is at the core of both event-based and hybrid servers, we will focus on the former here.

2.2 Linux Kernel Mechanisms

As described above, event-based servers employ event-dispatch mechanisms provided by the underlying operating system to perform network I/O. In this section, we describe the mechanisms supported by the Linux kernel for event notification to such applications. Following are the mechanisms supported by the Linux kernel.

- `select()` *system call:* `select()` [15] allows a single thread or process to multiplex its time between a number of concurrently open connections. The server provides a set of file-descriptors to the `select()` call in the form of an `fdset`, that describes the interest set of the server. The call returns the set of file-descriptors that are ready to be serviced (for read/write, etc.). This ready set is also returned by the kernel in the form of an `fdset`.

  The main attributes of the `select()` based approach are:

  - The application has to specify the interest set repeatedly to the kernel.
  - The interest set specification could be sparse depending on the descriptors in the set, and could lead to excess user-kernel space copying. The same applies when returning the ready set.
  - The kernel has to do a potentially expensive scan of the interest set to identify the ready file descriptors.
  - If the kernel wakes up multiple threads interested in the same file descriptor, there could be a *thundering herd* problem, as multiple threads could vie for I/O on the same descriptor. This, however, is not a problem with Linux 2.4.0 kernel, as it supports single thread wake-up.

- `poll()` *system call:* `poll()` [15] is a system call identical to `select()` in its functionality, but uses a slightly different interface. Instead of using an `fdset` to describe the interest set, the server uses a list of `pollfd` structures. The kernel then returns the set of ready descriptors also as a list of `pollfd` structures. In general, `poll()` has a smaller overhead than `select()` if the interest set or ready set is sparse. But if these sets are dense, then the overhead is usually higher because `pollfd` structures are bigger than a bit (they are a few bytes typically). Other than that, `poll()` has the same problems as `select()`.

```
// Accept a new connection
int sd = accept(...);

// Associate an RT signal
// with the new socket
fcntl(sd, F_SETOWN, getpid());
fcntl(sd, F_SETSIG, SIGRTMIN);

// Make the socket non-
// blocking and asynchronous
fcntl(sd, F_SETFL, O_NONBLOCK|O_ASYNC);
```

Figure 1: Associating a new connection with an RT signal

- `POSIX.4` *Real Time Signals*: POSIX.4 Real Time signals (RT signals) [6] are a class of signals supported by the Linux kernel which overcome some of the limitations of traditional UNIX signals. First of all, RT signals can be queued to a process by the kernel, instead of setting bits in a signal mask as is done for the traditional UNIX signals. This allows multiple signals of the same type to be delivered to a process. In addition, each signal carries a *siginfo* payload which provides the process with the context in which the signal was raised.

  A server application can employ RT signals as an event notification mechanism in the following manner. As shown in figure 1, the server application can associate an RT signal with the socket descriptors corresponding to client connections using a series of `fcntl()` system calls. This enables the kernel to enqueue signals for events like connections becoming readable/writable, new connection arrivals, connection closures, etc. Figure 2 illustrates how the application can use these signal notifications from the kernel to perform network I/O. The application can block the RT signal associated with these events (`SIGRTMIN` in figure 2) and use `sigwaitinfo()` system call to synchronously dequeue the signals at its convenience. Using `sigwaitinfo()` obviates the need for asynchronous

```
sigset_t signals;
siginfo_t siginfo;
int signum, sd;

// Block the RT signal
sigemptyset(&signals);
sigaddset(&signals, SIGRTMIN);
sigprocmask(SIG_BLOCK, &signals, 0);

while (1) {
    // Dequeue a signal from the signal queue
    signum = sigwaitinfo(&signals, &siginfo);

    // Check if the signal is an RT signal
    if (signum == SIGRTMIN) {
        // Identify the socket associated with the signal
        sd = siginfo.si_fd;
        handle(sd);
    }
}
```

Figure 2: Using RT signals for doing network I/O

signal delivery and saves the overhead of invoking a signal handler. Once it fetches a signal, the *siginfo* signal payload enables the application to identify the socket descriptor for which the signal was queued. The application can then perform the appropriate action on the socket.

One problem with RT signals is that the signal queue is finite, and hence, once the signal queue overflows, a server using RT signals has to fall back on a different dispatch mechanism (such as `select()` or `poll()`). Also, `sigwaitinfo()` allows the application to dequeue only one signal at a time. We'll talk more about these problems in section 3.3.

Event-dispatching mechanisms also exist in operating systems other than Linux. For instance, Windows NT provides *I/O completion ports* [12], which are primarily used for thread-based servers. With I/O completion ports, there is a single event queue and a fixed number of pre-forked threads which are used to process the events. There is a throttling mechanism to ensure that at most N threads are running at any given time. This makes it possible to pre-fork a relatively large number of threads while avoiding excessive context switching during busy periods. Even though primarily intended for thread-based servers, it should be possible to use I/O ports in conjunction with asynchronous I/O to implement hybrid servers.

2.3 Previous Work

Banga et al. [1] have studied the limitations of a `select()` based server on DEC UNIX, and shown the problems with its scalability, some of which we have discussed above. They have proposed a new API in [2], which allows an application to specify its interest set incrementally to the kernel and supports event notifications on descriptors instead of state notifications (as in the case of `select()` and `poll()`). The system calls proposed as part of this API are `declare_interest()`, which allows an application to declare its interest in a particular descriptor, and `get_next_event()`, which is used to get the next pending event(s) from the kernel.

Another event-dispatch mechanism is the `/dev/poll` interface, which is supported by the Solaris 8 kernel [14]. This interface is an optimization for the `poll()` system call. Recently, Provos et al. [10] have implemented the `/dev/poll` interface in the Linux kernel. This interface works as follows. The application first does an `open()` on the `/dev/poll` device, which creates a new interest set for the application. From this point onwards, the application can add a new socket to this interest set incrementally by creating a `pollfd` struct and writing it to the `/dev/poll` device. Finally, the polling is done by using an `ioctl()` call, which returns a list of `pollfd` structs corresponding to the set of ready descriptors. Further, the overhead of user-kernel copies can be reduced by using `mmap()` to map the array of `pollfd` structs onto the `/dev/poll` device. In [10], the

/dev/poll interface is shown to be an improvement on the traditional poll() implementation, especially as it reduces the cost of specifying the interest set to the kernel. Hence, in our experiments, we have used /dev/poll instead of poll() for comparison to other dispatch mechanisms.

RT signals have been used for network I/O in the *phhttpd* [4] Web server. Provos et al. have discussed its implementation and some of its shortcomings, such as the potential of signal queue overflow and the ability of sigwaitinfo() system call to fetch only one signal at a time. They have proposed a new system call sigtimedwait4() which allows the server to dequeue multiple signals from the signal queue [11].

3 Dispatch Overhead

In this section, we look at the first scalability parameter for event-dispatch mechanisms, namely the overhead involved in handling requests as a function of the number of concurrent connections. This parameter becomes important in the context of large number of idle or slow connections, irrespective of the actual active load on the server. In what follows, we first present an experimental study of some of the Linux dispatch mechanisms, and then discuss some of the insights from this study. We follow this up with a detailed discussion of RT signal behavior, including their limitations. We then propose an enhancement to the implementation of RT signals in the Linux kernel to overcome some of these limitations.

3.1 Comparative Study

In this section, we present the results of our comparative study of some of the kernel mechanisms discussed above. The main goal of this study is to look at the behavior of Web servers under high load in terms of their CPU usage as the number of concurrent connections (most of them idle) increases.

3.1.1 Experimental Testbed

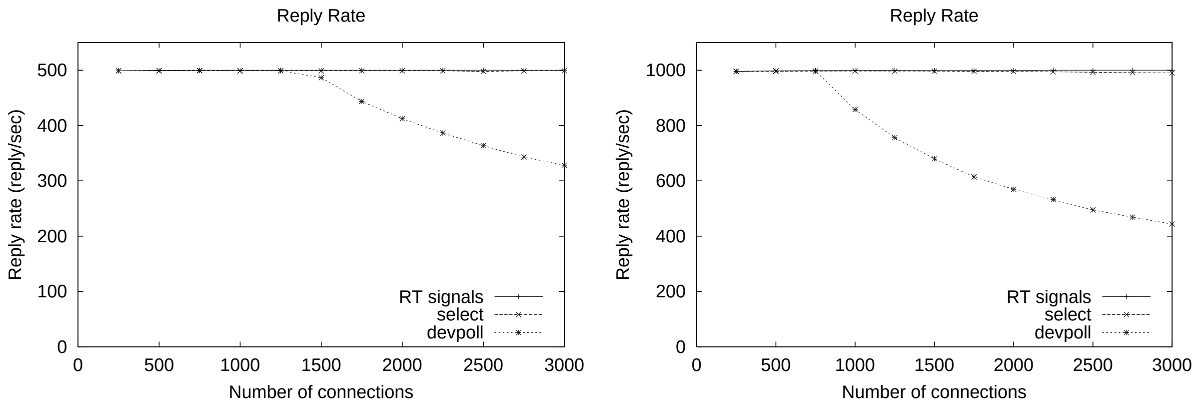
To conduct the experimental study, we implemented a set of *micro Web servers (μservers)*, each employing a different event-dispatch mechanism. Most of the request handling and administrative code in these μservers is identical to avoid differences in performance arising due to other factors. This ensures that the different versions are as similar as possible. Also, using the μservers instead of widely-used, full-fledged Web servers allows us to focus on the performance impact of the dispatch mechanisms by reducing all other overheads to the absolute minimum. Moreover, existing Web servers have an underlying event-handling architecture (such as process-per-connection for Apache), which may not be suitable for the purpose of our study. Thus, the μservers do very simple HTTP protocol processing, and the various μservers differ only in their use of the event-dispatch mechanism. Specifically, we compared μservers employing select(), /dev/poll and RT signals as their event-dispatch mechanisms. While this approach of using the μservers does not answer the question of how important the event-dispatch costs are as part of the overall server overhead for commercial Web servers, it does help in determining the limit on the scalability of such servers. This is because, even if the dispatch overhead is tiny with a small number of connections, non-linear scaling behavior could magnify this overhead with increasing number of connections until it eventually becomes the first order bottleneck.

Each of these μservers was run on a 400 MHz Pentium-III based dual-processor HP NetServer LPr machine running Linux 2.4.0-test7 in uniprocessor mode. The client load was generated by running *httperf* [8] on ten B180 PA-RISC machines running HP-UX 11.0. The clients and the server were connected via a 100 Mbps Fast Ethernet switch. To simulate large number of concurrent and idle connections, each httperf was used to establish a set of persistent connections, each of which generated periodic requests to the μserver. The effect was that at all times, some of the connections were active while the rest were idle, and these active and idle connection sets kept changing with time. Thus, in these experiments, the connection rate was different from the request rate (with each connection generating multiple requests). The server's reply size was 92 bytes. In each experiment, the total request rate was kept constant, while the number of concurrent connections was varied to see the effect of large number of idle connections on server performance.

To measure the CPU usage of the μserver, we inserted an idle_counter in the kernel running the μserver. This idle_counter counted the idle cycles on the CPU. We computed the CPU load imposed by the μserver by comparing the idle cycles for the system with and without the μserver running on it. The server reply rate and response times were measured by the httperf clients.

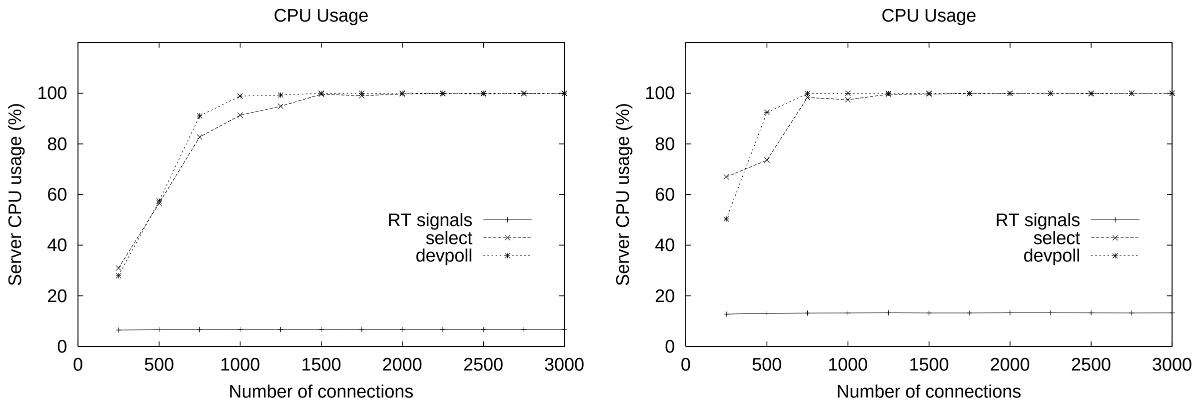
3.1.2 Experimental Results

As part of our comparative study, we ran experiments to measure the performance of three μservers based on select(), /dev/poll and RT signals respectively. In each experiment, the clients were used to generate a fixed request rate, and the number of concurrent connections was increased from 250 to 3000. Figure 3 shows



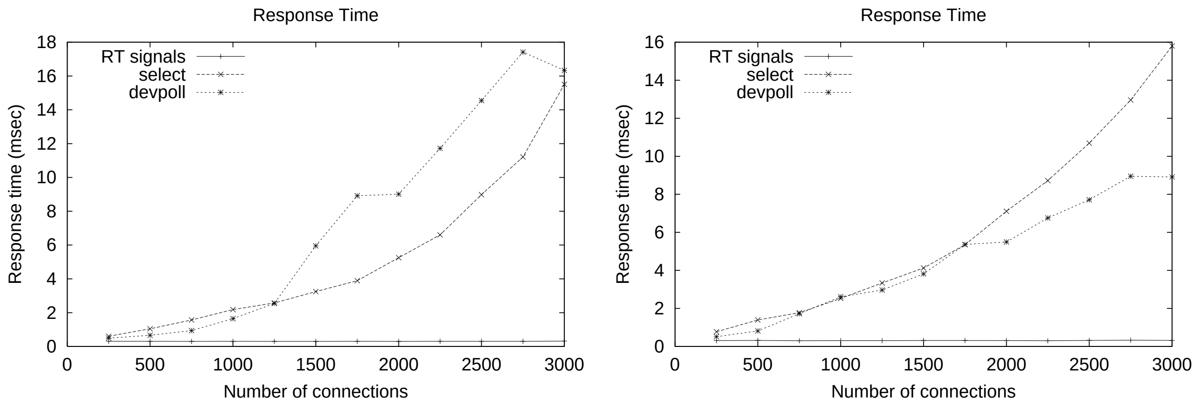
(a) 500 req/s (b) 1000 req/s

Figure 3: Reply rate with varying number of concurrent connections



(a) 500 req/s (b) 1000 req/s

Figure 4: CPU usage with varying number of concurrent connections



(a) 500 req/s (b) 1000 req/s

Figure 5: Response time with varying number of concurrent connections

the reply rates achieved by the servers for request rates of 500 req/s and 1000 req/s respectively. As can be seen from the figure, the reply rate matches the request rate for the RT signal and `select()` based servers at all points. On the other hand, the reply rate starts dropping off for the `/dev/poll` based server after a point. This is because the server becomes overloaded and starts dropping connections beyond a certain load. We cannot explain why the overload behavior of `/dev/poll` is so bad.

The more interesting figures are figures 4 and 5, which show the CPU usage and the average response time respectively for each of the μservers, as the number of concurrent connections is increased. As can be seen from figure 4, the CPU usage for both `select()` and `/dev/poll` increases with the number of concurrent connections and they become saturated after a certain point. On the other hand, the CPU usage for RT signals is insensitive to the number of idle connections. The RT signal based server's CPU usage is about 6.67% on average for the 500 req/s case, while it is about 13.25% for the 1000 req/s case. Thus, the CPU overhead of RT signals seems to be dependent only on the request rate. Also, the RT signal CPU usage is dramatically lower than either `select()` or `/dev/poll` based servers. A similar behavior is seen for the response time in figure 5. Once again, the response time increases for both the `select()` and `/dev/poll` based servers with the number of connections. On the other hand, the RT signal based server shows a very small response time for each of the request rates (about 0.3 ms in each case). Further, this response time is independent of the number of concurrent connections. Note that, even though the absolute value of the response times in the graphs may not seem significant from the perspective of an end user, it is the shape of these graphs which is significant, as these curves reflect the scalability of the dispatch mechanisms.

Thus, the results in this section show that RT signals have very small dispatch overhead and also that this overhead does not depend on the number of concurrent or idle connections being handled by the server. Rather, it is determined only by the active work being done by the server.

3.2 RT Signals: Reasons for Efficiency

From our comparative study, we observe that RT signals have a relatively low overhead compared to `select()` and `/dev/poll` event-dispatch mechanisms. Further, this overhead seems to be independent of the number of idle connections, and depends only on the active request rate. In other words, RT signals show essentially ideal behavior. In this section, we discuss the reasons for the better performance of RT signals in more detail.

RT signals are more efficient due to the following reasons:

- First, the server only needs to specify its interest set to the kernel incrementally. This is because the server application associates an RT signal with each socket file descriptor at the time of its creation (just after the `accept()` system call). From this point onwards, the kernel automatically generates signals corresponding to events on the descriptor, and thus obviates the need for the application to specify its interest in the descriptor again and again (as is the case with `select()` system call). This functionality is similar to the `declare_interest()` API proposed in [2].

- Unlike `select()`, `poll()` and `/dev/poll`, in the case of RT signals, the kernel does not know about the interest set explicitly. Rather, whenever there's an event on one of the descriptors, the kernel enqueues a signal corresponding to the event without having to worry about the interest set. Thus, the interest set is totally transparent to the kernel and this gets rid of the overhead of scanning each descriptor in the interest set for activity on every polling request from the application.

- Based on the `fd` field in the signal payload, the application can identify the active descriptor immediately without having to potentially check each descriptor in the interest set (as in the case of `select()`).

- By blocking the relevant RT signal and using `sigwaitinfo()` for dequeuing signals from the signal queue, the overhead of calling a signal handler is avoided.

3.3 Limitations of RT signals

In spite of their efficiency, RT signals, as currently implemented in Linux, have some potential limitations. These limitations arise from the fact that the signal queue is a limited resource. Since each event results in a signal being appended to the signal queue, a few active connections could dominate the signal queue usage or even trigger an overflow. The former could result in unfair service and the latter could cause a deadlock-like situation in which the server can no longer make any progress, and appears to be suspended or hung.

To understand how a signal queue overflow can lead to a "hung" server, note that once the queue is full, no further signals can be enqueued and hence all future events are dropped. Of course, eventually the server would drain the queue and new events would start to come in again. However, those events that got dropped are lost forever. Further, notice that the signal queue is delinked from the TCP buffers and there is no feedback mechanism between the two. Thus, even after the signal queue fills up and starts losing signals, there is nothing to throttle the TCP traffic. Thus, even though events are occurring on the open connections and the listening socket, the server loses notifications corresponding to these events. In other words, there is a "notification leak" at the server. If one of the lost events happened to indicate, for example, that the listen queue has pending connections, the server may never realize that it ought to call `accept()` to service those connections. Similarly, if an event got dropped that indicated that a particular connection is now readable, the server may never realize that it should call `read()` on that connection. Over time, the more events are dropped, the more likely it becomes that either some connections end up in a suspended state or that the listening socket is no longer serviced. In either case, throughput will suffer and eventually drop to zero.

To avoid this kind of suspended state, the Linux kernel sends a `SIGIO` signal to the application when the signal queue overflows. At this point, the application can recover from the overflow by falling back onto some other event dispatch mechanism. For example, the application could use `select()` or `poll()` to detect any events that may have been dropped from the signal queue. Unfortunately, using a fallback mechanism comes with its own set of problems. Specifically, there are two issues:

- First, having to handle signal queue overflows by switching onto another mechanism makes the application complex. It may require translating the interest set from the (implicit) form used by the RT signal mechanism into the explicit form used by the other mechanism (e.g.: setting up the `fdsets` for `select()` or `pollfd` lists for `poll()`, etc.). Furthermore, the application has to receive and service the kernel notifications in a different manner. Also, this transition needs to be done very carefully, as losing even a single event could potentially create the suspended state situation mentioned above.

- Second, switching over to a non-scalable mechanism also has the potential to make the application sluggish. Since the application is already under overload (which led to the signal queue overflow in the first place), using a high-overhead mechanism for recovery could overload the server even further, potentially sending it into a tailspin.

Another drawback with RT signals is that each call to `sigwaitinfo()` dequeues exactly one signal from the queue. It cannot return multiple events simultaneously, leading to high number of system calls to retrieve multiple events, which might be a problem under high load.

Thus, using RT signals as implemented in the kernel has some potential drawbacks even if they are used in conjunction with another mechanism.

3.4 Signal-per-fd: RT Signal Enhancement

As discussed above, having to handle a signal queue overflow could be potentially costly as well as complex for an application. It would be desirable, therefore, if signal queue overflows could be avoided altogether. To understand why signal queue overflows are happening in the first place, note that there's a potential of multiple events being generated for each connection, and hence multiple signals being enqueued for each descriptor. But, most of the time, the application does not need to receive multiple events for the same descriptor. This is because even when an application picks up a signal corresponding to an event, it still needs to check the status of the descriptor for its current state, as the signal might have been enqueued much before the application picks it up. In the meantime, it is possible that there might have been other events and the status of the descriptor might have changed. For instance, the application might pick up a signal corresponding to a read event on a descriptor *after* the descriptor was closed, so that the application would have to decide what to do with the event in this case. Thus, it might be more efficient and useful if the kernel could coalesce multiple events and present them as a single notification to the application. The application could then check the status of the descriptor and figure out what needs to be done accordingly.

To understand what kind of events can be coalesced together, we have to understand what kind of information the events are supplying to the application. In general, events are coalescable under two scenarios:

- If information from multiple events can be combined to provide consistent information to the application, then such events can be coalesced. This scenario occurs in many GUI systems, such as the X window system [13]. In such systems, typical implementations try to compact motion events in order to minimize system overhead and memory usage in device drivers. For instance, if we receive an event indicating that the mouse moved by (x_1, y_1), followed by an event that it moved by (x_2, y_2), then the two events can be merged into a single one indicating that the mouse moved by $(x_1 + x_2, y_1 + y_2)$.

- If events are used only as hints which the application might pick up at its leisure (or ignore) and are used only as feedback to guide it in its actions, then such events may be coalesced. This is the scenario in our RT signal-based server, where the signals are being used as hints to notify the server of connection-related events, but the onus is still on the server to verify the connection status and act accordingly.

We propose an enhancement to achieve this coalescing, which we call *signal-per-fd.* The basic idea here is to enqueue a single signal for each descriptor. Thus, whenever there's a new event on a connection, the kernel first checks if there's already a signal enqueued for the corresponding file descriptor, and if so, it does not add a new signal to the queue. A new signal is added for a descriptor only if it does not already have an enqueued signal.

To efficiently check for the existence of a signal corresponding to a descriptor, we maintain a bitmap per process. In this bitmap, each bit corresponds to a file-descriptor and the bit is set whenever there is an enqueued signal for the corresponding descriptor. Note that checking the bit corresponding to a descriptor obviates the need to scan the signal queue for a signal corresponding to the descriptor, and hence, this check can be done in constant time. This bit is set whenever the kernel enqueues a new signal for the descriptor and it is cleared whenever the application dequeues the signal.

By ensuring that one signal is delivered to the application for each descriptor, the kernel coalesces multiple events for a connection into a single notification, and the application then checks the status of the corresponding descriptor for the action to be taken. Thus, if the size of the signal queue (and hence the bitmap) is as large as the file descriptor set size, we can ensure that there would never be a signal queue overflow.

This enhancement has the following advantages:

- Signal-per-fd reduces the complexity of the application by obviating the need to fall back on an alternative mechanism to recover from signal queue overflows. This means that the application does not have to re-initialize the state information for the interest set, etc. that may be required by the second mechanism. In addition, the application does not have to deal with the complexity associated with ensuring that no event is lost on signal queue overflow. Finally, the server would not have to pay the penalty of potentially costly dispatch mechanisms.

- Signal-per-fd also ensures fair allocation of the signal queue resource. It prevents overloaded and misbehaving connections from monopolizing the signal queue, and thus achieves a solution for the proper resource management of the signal queue.

- By coalescing multiple events into a single notification, this mechanism prevents the kernel from providing too fine-grained event notifications to the application, especially as the application might not pick up the notifications immediately after the events. This enhancement thus notifies the application that there *were* events on a descriptor, instead of *how many* events there were. The latter information is often useless to the application as it has to anyway figure out *what* the events were and what the status of the descriptor is.

There are some similarities between the signal-per-fd mechanism and the API proposed in [2] in terms of their functionality. In particular, signal-per-fd allows the kernel to coalesce multiple events corresponding to a descriptor just like the implementation described there. But, signal-per-fd differs from this API in some important ways. First of all, signal-per-fd does not require any change in the system call interface or the kernel API, and is totally transparent to the application. Secondly, the goal of the signal-per-fd mechanism is not only to potentially improve the performance of an RT signal-based server, but also to reduce its complexity, by obviating the need for employing fallback mechanisms.

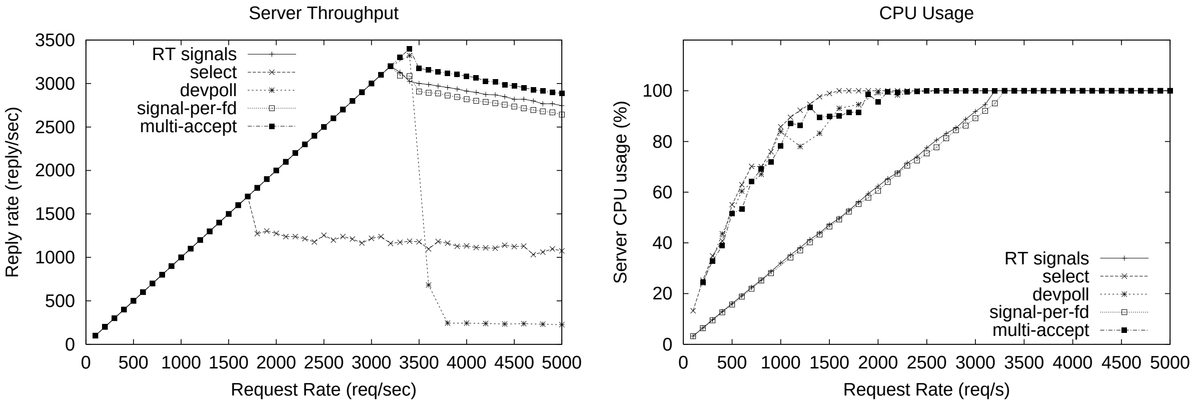
On the whole, signal-per-fd is a simple enhancement to the implementation of RT signals that can overcome some of their limitations in the context of using them as an event-dispatch mechanism for doing network I/O.

4 Dispatch Throughput

In this section, we look at another parameter associated with the efficiency of event-dispatch mechanisms, namely, the throughput that can be achieved as a function of the active load on the server. This metric is orthogonal to the overhead discussed in the previous section, as this refers to the actual amount of useful work being performed by the server. In what follows, we first provide a comparative experimental study of some of the Linux dispatch mechanisms, including the *signal-per-fd* optimization proposed in the previous section. In addition, we also look at the throughput achieved by a `select()` based server with a minor modification which allows the server to do multiple `accept()`s each time the listening socket becomes ready. Then, we discuss the results of this study and provide some insights into the behavior of the various mechanisms.

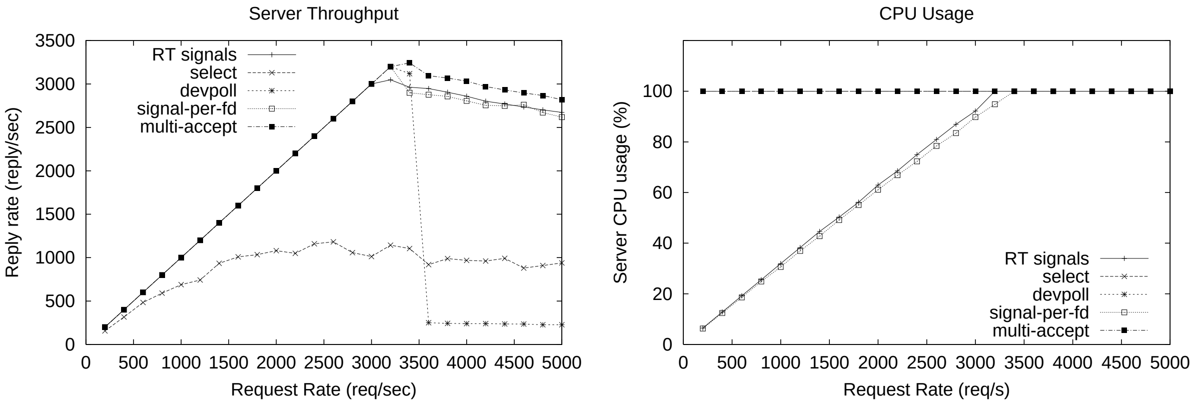
4.1 Experimental Study

Here, we experimentally evaluate the throughput achieved by various event-dispatch mechanisms under high load. Our experimental setup is the same as



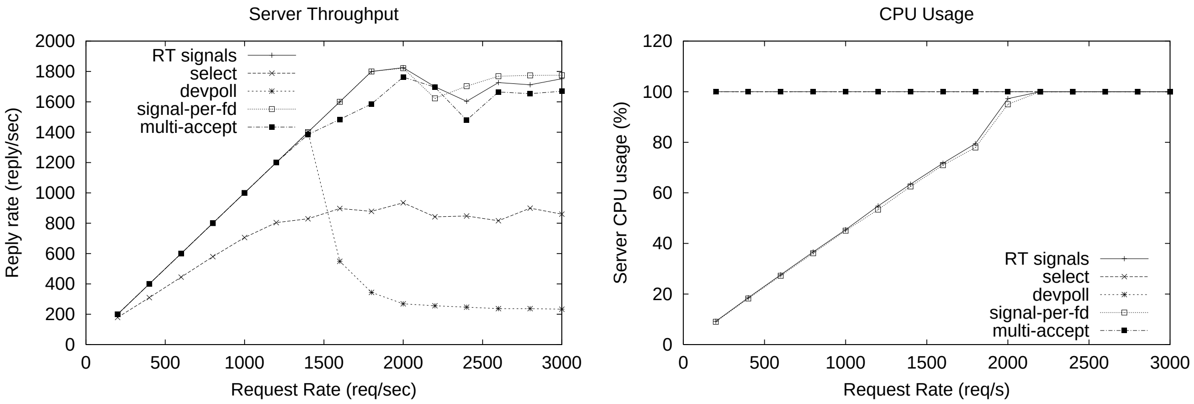
(a) Reply rate (b) CPU usage

Figure 6: Server performance with 252 idle connections (1B reply size)



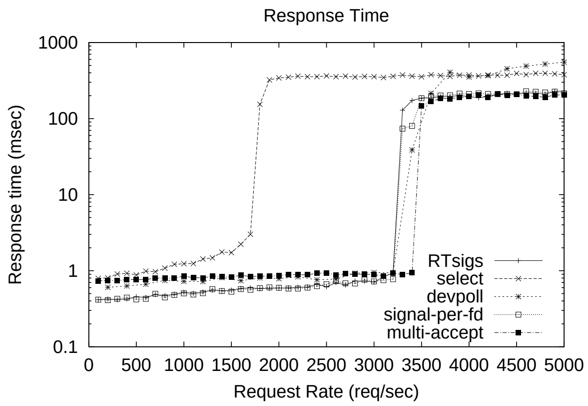
(a) Reply rate (b) CPU usage

Figure 7: Server performance with 6000 idle connections (1B reply size)

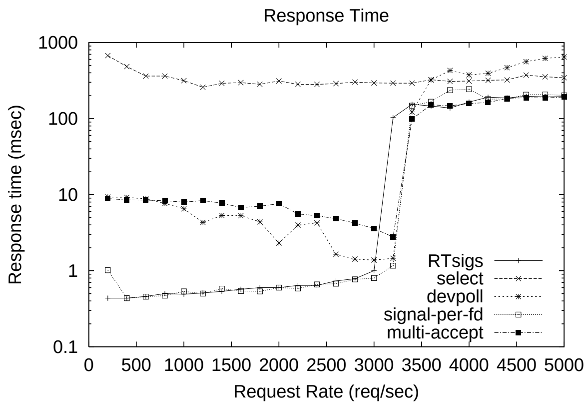


(a) Reply rate (b) CPU usage

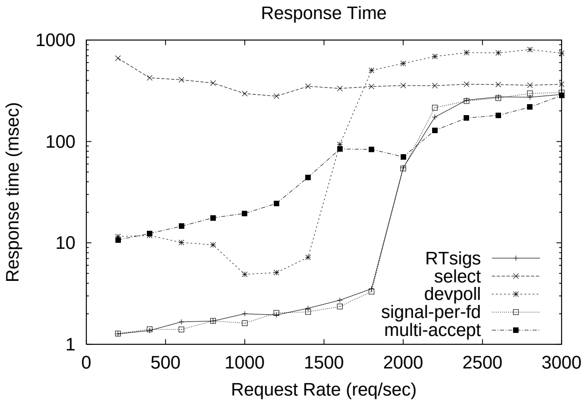
Figure 8: Server performance with 6000 idle connections (6K reply size)



(a) 252 idle connections (1B reply size)



(b) 6000 idle connections (1B reply size)



(c) 6000 idle connections (6K reply size)

Figure 9: Response time with increasing load

that used in Section 3.1 for comparative study of `select()`, `/dev/poll` and RT signals. In this study, we evaluate two new mechanisms/enhancements as well:

(i) The signal-per-fd enhancement to RT signals. We have implemented this enhancement in the Linux 2.4.0-test7 kernel, and we ran the RT signal based μserver on the modified kernel for measuring the effect of signal-per-fd.

(ii) A `select()` based μserver which does multiple `accept()`s each time the listening socket becomes ready, as opposed to the standard `select()` based μserver which does only one `accept()` for such a case. We'll refer to this modification as *multi-accept* `select`. The idea here is to enable the server to identify more connections and perform more useful work per `select()` call.

In order to measure the throughput of these various mechanisms under varying loads, we used a set of idle connections along with a set of *httperf* clients generating requests at high rates. In these experiments, we kept the number of idle connections fixed for each experiment and varied the request rate.

Figure 6 shows the performance of the servers with 252 idle connections and 1 byte server reply sizes, while figures 7 and 8 plot the same information for 6000 idle connections with server reply sizes of 1 byte and 6KB respectively. As can be seen from figures 6(a), 7(a) and 8(a), the throughput with `select()` plateaus out much before it does for the RT signals (both the default and the signal-per-fd implementations). The fall in reply rate of `/dev/poll` is much more dramatic and again, it seems to perform very poorly under overload. The interesting observation is that multi-accept `select` is able to sustain a high throughput, similar to the RT signals, and even manages to achieve a slightly higher peak throughput in the first two cases. Figures 6(b), 7(b) and 8(b) show the CPU usage for the μservers. Again, as can be seen from these figures, the CPU usage for RT signals is much less than that for `select()`, multi-accept `select` and `/dev/poll` in all cases, and RT signals reach saturation at a much higher load. In fact, for 6000 idle connections (figures 7(b) and 8(b)), CPU usage is 100% for the `select()`, multi-accept `select` and `/dev/poll` based μservers right from the beginning, which can be attributed to their high overhead in handling large number of concurrent connections. On the other hand, the CPU overhead for the RT signals based server (for both the default and signal-per-fd cases) increases linearly with the load in either case. An interesting point to be noted from these figures is that, for the 1 byte reply sizes, the server with the default RT signal implementation reaches saturation at a slightly smaller load than signal-per-fd, and this is more pronounced for the 6000 idle connections. We will discuss this point in more detail below.

Figures 9(a), (b) and (c) plot the average response times of the various servers with increasing load for 252 and 6000 idle connections (1B and 6KB reply sizes) respectively. Figure 9(a) shows that `select()` reaches overload at a relatively low load, while the other mechanisms get overloaded at much higher loads. In figures 9(b) and (c), `select()` shows high response times for all loads and is thus overloaded for all the points in the graph. These plots complement figures 6(a), 7(a) and 8(a), which show the throughput for these cases. The figures further show that the `/dev/poll` server achieves small response times at low loads, but under overload, it offers much higher response times compared to the other mechanisms. Thus, its overload behavior is again seen to be very poor. The interesting point in figure 9(a) is that multi-accept `select` is able to provide a low response time upto very high loads. Figure 9(b) shows an even more interesting behavior of multi-accept `select` — its response time actually *decreases* with increasing load until it hits overload. This behavior clearly shows the load amortization occurring for multi-accept `select`, so that more useful work being extracted for the same `select()` call overhead translates to lower *average* response times. In figure 9(c), multi-accept `select` shows higher response times, but these increase only gradually with load, which again shows that the `select()` cost is being amortized. Finally, the two RT signal implementations have the lowest response times until they get overloaded, which is expected as they have the lowest overhead. Once again, these graphs show that the default RT signal based server reaches overload slightly earlier than the signal-per-fd server for the 1 byte reply size cases.

Next, we will try to understand these results, and in particular, we will focus on the behavior of multi-accept `select` and the two implementations of RT signals.

4.2 Discussion

From the results of our comparative study, we get the following insights into the behavior of the various mechanisms:

- Using multi-accept `select` increases the throughput of the `select()` based server substantially. This is because `select()` is basically a state notification mechanism. Thus, when it returns the listening socket as ready, it means there are new connections queued up on the listen queue. Using multiple `accept()` calls at this point drains the listen queue without having to call `select()` multiple times. This helps prevent the high cost of using multiple `select()` calls for identifying new connections. Once new connections are efficiently identified and added to the interest set, under high load, `select()` would have large number of active connections to report each time it is called. Thus, its cost would be amortized as the server could perform more useful work per `select()` call. This has to do with the fact that the ready set returned by `select()` would be denser and hence, the scanning cost of `select()` is utilized better. Also, the more useful work the server does on each call to `select()`, the less often it needs to be called. Hence, the server is able to identify more connections and extract more useful work, and thus achieves a higher throughput. Note that the overhead is still high — only the overhead is being *better utilized* now. This amortization is especially visible from figure 8 and figure 9(c), where the reply sizes are large, and hence, there is more work per connection.

  The high throughput achieved by the multi-accept `select` server is contrary to conventional wisdom, according to which `select()` based servers should perform poorly under high loads in terms of their throughput as well. While this is true for a simple `select()` based server, our results show that implementing the server more carefully can help us achieve better performance.

- The behavior of the servers running on the default RT signal implementation and the signal-per-fd implementation are very similar until saturation. This is understandable as there are very few signal queue overflows under low loads, and hence, the two schemes work essentially the same. To verify that this is indeed the case, in table 1, we have tabulated the number of `SIGIO`s and the number of `sigwaitinfo()` calls for the default RT signal based server. These numbers correspond to some

Request Rate (req/s)	252 idle connections		6000 idle connections	
	No. of `sigwaitinfos`	No. of `SIGIOs`	No. of `sigwaitinfos`	No. of `SIGIOs`
2800	504728	0	504474	0
3000	540576	0	540792	0
3200	10538	1526	19	19
3400	40	40	16	16
3600	40	40	14	14
3800	39	39	13	13
4000	39	39	13	13

Table 1: Signal queue overflows under high loads

of the loads for 252 and 6000 idle connections respectively, with reply size of 1 byte. The number of `sigwaitinfo()`s denotes the number of times the server dequeued a signal from the signal queue, and the number of `SIGIOs` represents the number of signal queue overflows. As can be seen from the table, under low loads, there are no `SIGIOs` and hence, no signal queue overflows. On the other hand, at high loads, all the `sigwaitinfo()` calls result in `SIGIOs`. This indicates that the signal queue is overflowing all the time, and hence, the server has to fall back on an alternative mechanism to perform its network I/O under high loads. The fallback mechanism used in our server was multi-accept `select`[2]. Hence, under high loads, the default RT signal server behavior is identical to that of the multi-accept `select` server, as was seen from the throughput and the response time plots.

- As noted earlier, for the 1 byte reply sizes, the signal-per-fd server reached overload at slightly higher load compared to the default RT signal server. In particular, the default RT signal based server saturated at about 3200 req/s, which corresponds to the high number of `sigwaitinfo()`s resulting in `SIGIOs` at this load, as can be seen from table 1. Thus, preventing signal queue overflows seems to make the server sustain slightly higher loads before getting saturated. Once the signal-per-fd server becomes saturated, its throughput is bounded by the amount of useful work it can amortize over each signal notification, even though it does not suffer from signal queue overflows. Recall that similar to `select()`, signal-per-fd is also a state-notification mechanism — hence the server can extract more work per signal compared to the default event-notification mechanism. Thus, its throughput is comparable to that of multi-accept `select` under overload, even though its peak throughput is slightly smaller, as `sigwaitinfo()` still returns only one signal per call.

[2]We cannot simply use `select()` with single `accept()` in this situation because, to prevent any potential deadlocks, we have to ensure that no event is lost, and hence, we need to clear the listen queue completely.

To summarize, we find that RT signals are an efficient mechanism in terms of overhead, and under saturation, their throughput is determined by the fallback mechanism being used to handle signal queue overflows. We find that `select()` system call can give high throughput if we use multiple `accept()`s to identify more new connections per `select()` call. This is in spite of the fact that `select()` based servers have high CPU overhead. Finally, signal-per-fd has a behavior almost identical to that of the default RT signal implementation in terms of overhead and throughput, but it is able to sustain slightly higher load before becoming overloaded. Further, it helps reduce the complexity of the server to a large extent. This is because we do not have to worry about using alternative event-dispatch mechanisms, and state maintenance also becomes much easier.

5 Conclusion

In this paper, we first discussed some of the common event-dispatch mechanisms employed by Internet servers. We focussed on the mechanisms available in the Linux kernel, and measured their performance in terms of the overhead and throughput of a minimal Web server. Our comparative studies showed that RT signals are a highly efficient mechanism in terms of their dispatch overhead and also provide good throughput compared to mechanisms like `select()` and `/dev/poll`. In particular, the overhead of RT signals is independent of the number of connections being handled by the server, and depends only on the active I/O being performed by it. But, an RT signal based server can suffer from signal queue overflows. Handling such overflows leads to complexity in the server implementation and also potential performance penalties under high loads. To overcome these drawbacks, we proposed a scheme called *signal-per-fd*, which is an enhancement to the default RT signal implementation in the Linux kernel. This enhancement was shown to significantly reduce the complexity of a server implementation, increasing its robustness under high load, and also potentially increasing its throughput. Overall, we conclude that RT signals are a highly scalable event-dispatch mechanism and servers based on these signals can also be substantially simplified when coupled with the signal-per-fd enhancement.

Another interesting result of our study was the performance of `select()` based servers under high loads. According to conventional wisdom, `select()` based servers have high overhead and thus, perform very poorly under high loads in terms of the server throughput as well. Our experiments with the *multi-accept* variant of a `select()` based server show that though `select()` does have high dispatch overhead, this overhead can be amortized better by performing more useful work per `select()` call, resulting in a high throughput even under heavy load conditions. Thus, we conclude that even a `select()` based server can be made to scale substantially if its overhead is better utilized to perform more useful work.

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