COPS: A coroutine-based priority scheduling framework perceived by the operating system

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***Abstract*—The multi-threading model in the general operating systems is becoming insufficient in applications with increasing amounts of concurrency, due to the context-switching costs in the kernel multi-threading. In this paper, a new concurrency model named COPS is proposed. COPS uses a priority-based coroutine model as the smallest task unit to replace the multi-threading model in large concurrency scenarios, and provides a cohesive priority-based scheduling framework for kernel space and user space coroutines. COPS introduces coroutines as first-class objects in the OS to provide asynchronous I/O mechanism, which takes kernel coroutines as a bridge between I/O operations and devices and takes user coroutines as a bridge between applications and the OS's services respectively.**

We design a prototype of web server based on COPS and conduct extensive experiments in an FPGA-based system to evaluate COPS. Results show that the proposed model achieves one to four times higher throughput while remains relatively lower overhead than that using the multi-threading model in the large concurrency applications.

***Index Terms*—Multi-threading, Concurrency, Coroutine.**

I. Introduction

In today's era of data explosion, the ability of the general Operating Systems (OS) to process large amounts of data is receiving more attention. For example, Google's servers handle 883 billion requests per day in 2022 [1], with an average of 8 million requests per second. The increasing scale of the concurrency in the system poses severe challenges to the traditional multi-threading model, which has two main shortcomings in our point of view. First, the multi-threading model is nondeterministic [2]. The execution order of threads is uncertain, resulting in the access order of shared resources being uncertain. When used inappropriately in fixed workflows, multi-threading can lead to greater overhead. In order to improve the performance of the multi-threading model in large concurrency scenarios such as the web server, some research has tried to optimize it, but has not solved the problem mechanically [3], [4].

Second, the multi-threading model is incompatible with the asynchronous I/O mechanism in OS. For instance, Linux uses an event-driven model, such as *select* and *epoll* to handle multiple I/O operations on a single thread, which involves producer-consumer interaction and raises the cost of synchronous mutual exclusion, adding to the kernel's complexity [5]. Similarly, Windows' I/O Completion Ports(IOCP) [6] offers I/O multiplexing but can be challenging to program correctly due to callback functions [7]. The io_uring model, introduced in [8], enhances efficiency and throughput by using shared memory to avoid data copying. However, it adds kernel complexity and makes interface utilization more difficult [9]. Furthermore, because the OS is unaware of userland asynchronous tasks, userland-implemented asynchronous interfaces like POSIX AIO increase overhead due to thread handling, I/O buffer replication, and context switching across privilege levels [10].

Asynchronous I/O mechanisms are effective in high concurrency web server environments but challenging to design and implement. The challenge comes not only from providing asynchronous I/O for applications in kernel, but also from building runtime for kernel's asynchronous tasks. LXDs [11] created an in-kernel asynchronous runtime for efficient cross-domain processing. Memif [12] offered a low-latency, low-overhead interface using asynchronous and hardware-accelerated techniques. Lee *et al.* [13] introduced the asynchronous I/O stack (AIOS) to the kernel to reduce the I/O latency. Despite these advancements, most methods operate independently of the kernel's thread scheduler, limiting their adaptability and scalability and complicating the kernel's design.

As an alternative concurrency model, the concept of coroutines has not been widely adopted in modern programming languages in many decades. Currently, there is some renewal of interest in coroutines to explore the advantages of coroutines as an alternative to multi-threading. In this paper, we rethink the concurrency model and asynchronous framework to find solutions that could meet the larger-scale and higher performance requirements. We propose COPS[1], a coroutine-based priority scheduling framework in OS. COPS improves the high context-switching overhead and solve the problem

[1]The **CO** in COPS represents the coroutine, **P** represents the priority, and **S** represents scheduling. All tasks must be carried out under COPS's management.

of uncertain sequence of accessing shared resources by using coroutines as the basic task unit. In addition, COPS draws on the existing research on asynchronous I/O mechanism, introduces coroutines into the kernel, provides coroutines as first-class objects and combines it with the asynchronous I/O mechanism to provide a coordinated and cohesive scheduling framework for all tasks in OS.

The rest of the paper is organized as follows: In Section II, we explain the fall and resurgence of coroutines and the coroutine facilities in Rust language. Section III details the design of COPS, while Section IV explores common patterns in asynchronous and concurrent programming. Performance results for COPS are presented in Section V. We review related work in Section VI and conclude in Section VII.

II. Background

A. Coroutine

Coroutines, introduced in the 1960s, offer a lightweight way to improve concurrency with lower resource and overhead compared to processes or threads. The core characteristics of coroutines, shown as follows, are summarized in [14]:

1) The values of data local to a coroutine persist between successive calls;
2) The execution of a coroutine is suspended as control leaves it, only to carry on where it left off when control re-enters the coroutine at some later stage.

However, such a general definition leaves open relevant issues with respect to a coroutine construct which makes the support of coroutine facilities in programming languages different. Some implementation even contributed to the misconception of the expressive power of coroutines. Additionally, the introduction of first-class continuation and the adoption of multi-threading as a ”de facto standard” concurrent construct have contributed to the discard of the coroutine concept.

The revival of coroutines comes from the fact that Moura et al. [15] demonstrated that full coroutines have an expressive power equivalent to one-shot continuations and one-shot delimited continuations. Nowdays, modern programming languages, c++ 20 [16], Go [17], Rust [18], Python [19], Kotlin [20], etc., all provide varying degrees of support for coroutines.

B. The Coroutine facilities in Rust

Rust, a modern language, excels in performance, security, and concurrency. It features a robust trait system that offers similar capabilities as object-oriented languages, including abstraction, inheritance, and polymorphism.

In Rust, the coroutine facilities is based on its trait system. Rust provides a special trait named **Future** in its core library. Any object that implements **Future** exhibits asynchronous, which is called as coroutines. The poll method defined by the Future trait advances the coroutine's execution. If poll returns Poll::Ready, it indicates the coroutine has completed. Returning Poll::Pending signifies the coroutine is awaiting an event before resuming. The Future trait is detailed in listing 1.

```
pub trait Future {
  type Output;
  fn poll(self: Pin<&mut Self>, cx:
 ↪  &mut Context<'_>) ->
 ↪  Poll<Self::Output>;
}
enum Poll<T> {
  Ready(T),
  Pending,
}
```

Listing 1: Future trait.

Besides implementing Future trait manually, Rust also provides async/await keywords to create coroutines and drive the execution of coroutines. The async keyword transforms functions, blocks, or closures into futures without explicitly implementing the Future trait. The await keyword not only can be used to execute the Future object, but also can be used to relinquish CPU when the operation cannot continue, enabling other futures to run concurrently.

Through the Future trait and async/await keywords in Rust, the coroutines are provided as first-class objects to developers in the level of language. Moreover, Rust separates the coroutine runtime from coroutine's definition, allowing for customizable runtimes. This separation and definition flexibility could pave the way for introducing coroutines into the kernel, not just user space, and even making coroutines as first-class citizens at the OS level.

III. Design of COPS

COPS is designed to enhance the system's concurrency by treating coroutines as the fundamental task unit and integrating them as first-class objects within the OS. Both kernel and application developers can freely utilize coroutines. COPS offers a cohesive priority-based scheduling system for coroutines in both kernel and user spaces. Fig.1 illustrates COPS's overall structure. Both applications and the OS maintain their own Executor data structures and share COPS's scheduling framework via vDSO [21]. They represent tasks as coroutines and manage tasks by using the COPS's services through function calls. Applications access other system services via system calls. Additionally, the OS maintains a global bitmap for advanced priority-based cooperative scheduling.

In this section, we detail the design of COPS. We start by explaining the data structures behind COPS's coroutine runtime and how they enable coroutine scheduling (III-A). We then discuss the coroutine state transition model (III-B). Following that, we outline the COPS API (III-C). Lastly, we describe COPS's global cooperative scheduling mechanism (III-D).

A. Coroutine Runtime

Rust offers the **Future** and **Wake** traits to facilitate coroutines without tying them to a specific runtime. This flexibility

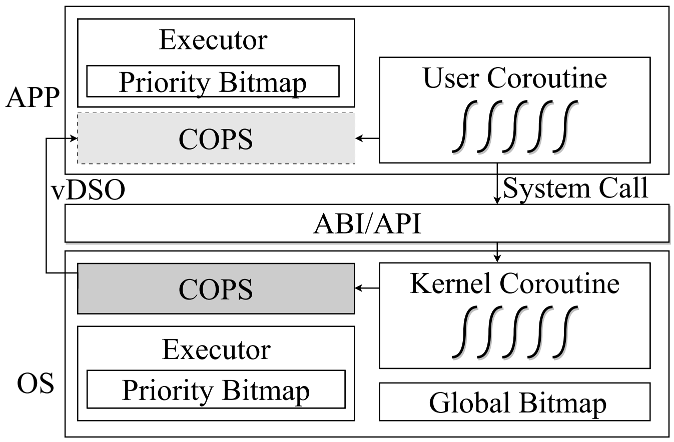


Fig. 1: The architecture of COPS.

```
pub struct Coroutine{
  pub cid: CoroutineId,
  pub kind: CoroutineKind,
  pub priority: usize,
  pub future: Pin<Box<dyn
↪   Future<Output=()> + 'static + Send
↪   + Sync>>,
  pub waker: Arc<Waker>,
}
```

Listing 2: Coroutine control block.

allows us to create a coroutine runtime suitable for both kernel and userland. The runtime consists of two main components:

1) Coroutine Control Block: As detailed in II-B, the polling method in Future trait is partially transparent, limiting precise coroutine control. To address this, we extends Rust's future and waker abstractions to create coroutine control blocks (CCBs) for more accurate management. The CCB structure is displayed in listing 2. The Wake trait is responsible for saving and switching context of coroutine. Both the execution and the context-switching of the coroutine are done by the compiler and are transparent. Therefore, the future and wake must be described in the CCB. However, relying solely on the future and wake traits results in a basic polling mechanism that cannot allow for precise control or integration with asynchronous I/O. To enable precise control, we have enhanced the CCB with three additional fields: 1) The Cid is used to identify CCB, and plays a key role in asynchronous I/O mechanism; 2) The Kind denotes the type of the coroutine, guilding the subsequent processing after the coroutine reaches a certain stage; 3) The Priority reflects the coroutine's priority level, which is fundamental to COPS's scheduling framework. We did not include a state field in CCB because Rust coroutines only exist in pending or ready states, with their state implicitly determined by the queue they reside in.

2) Executor: The core of the coroutine runtime is the Executor, which manages all coroutines in a process based on the

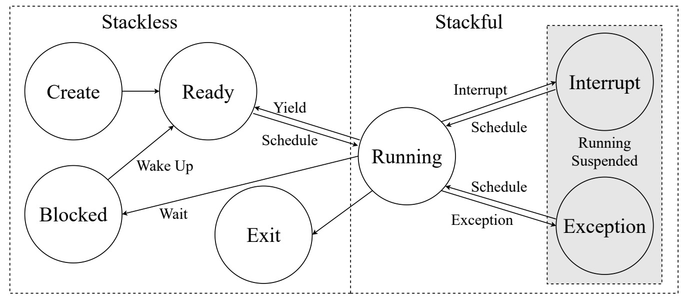


Fig. 2: Coroutine state transition model.

coroutine control block. The Executor's primary components consist of the following:

1) Ready Queues and Priority Bitmaps: The Executor manages queues of coroutines sorted by priority, ensuring that the highest priority coroutine is always executed first. It also uses a priority bitmap to track the presence of coroutines at each priority level. While this bitmap is not needed for user-level Executors, it aids in OS-level scheduling by giving the operating system visibility into user-level coroutines.
2) Blocking Set: This structure manages all coroutines that are blocked, holding them until the awaited event occurs and triggers their resumption.

These two data structures form the runtime foundation for coroutines and establish a basic priority scheduling mechanism for COPS. This ensures that within a single process's address space, COPS can effectively prioritize and schedule the highest-priority coroutine each time.

B. Coroutine State Transition Model

Integrating coroutines into the kernel's asynchronous I/O mechanism has transformed traditional process and thread concepts. For instance, under Kernel Page Table Isolation(KPTI) [22], the kernel acts as a special process with address space switches upon entry and return. Threads now serve as stack providers for coroutines and as multiprocessor system abstractions, rather than as the primary scheduling unit.

The traditional thread state model has been supplanted by the coroutine state model, which includes five basic states—create, ready, running, blocked, and exit—plus a special running-suspended state due to preemptive scheduling and other interruptions. When a coroutine's execution is interrupted by clock signals, exceptions, or synchronous system calls, it occupies the stack but is not actively running on the CPU, hence the term "running-suspended." This can be further divided into operation interrupt and operation exception states. The coroutine state transition model is depicted in Fig.2.

1) When a coroutine is created, it begins in the ready state and moves to the running state once it is scheduled.
2) A running coroutine can either wait for an event and enter the blocked state or yield to higher-priority coroutines, becoming ready again. This transition does not use the running stack. Alternatively, if an interrupt or exception occurs, the coroutine enters a suspended state. Upon task completion, it moves to the exit state for resource cleanup.

3) In the blocked state, a coroutine awaits an event to become ready again. If it is in a suspended state, it does not need to go through the ready state but waits for completion of the relevant handling before resuming running.

C. COPS API

Coroutines typically have three basic operations: *create*, *resume* and *yield*. In Rust, the *resume* and *yield* operators are replaced by the poll function and the await keyword respectively. Since the future must be driven by await keyword, it is not necessary to consider whether the *yield* is placed in the right places. However, developers must be careful using loop to avoid occupying the CPU for a long time. It is worth mentioning that COPS addresses the issue of accidentally using tight loops by using a global cooperative scheduling mechanism, detailed in section III-D.

COPS offers a *spawn* function to create new coroutines, along with additional APIs (*current, wake_up, set_priority, alloc_cpu*) to enhance coroutine control. The *spawn* initiates a coroutine and returns its identity, The *current* retrieves the identity of the current coroutine, The *wake_up* revives a specified coroutine, the *set_priority* adjusts a coroutine's priority, and *alloc_cpu* requests additional CPU resources. By default, applications are allocated one CPU, but *alloc_cpu(1)* can be used to request more. Table I lists the COPS APIs.

With the COPS API, developers can fully leverage coroutines in both kernel and user space with minimal restrictions.

Function	Return Value
spawn(future, priority)	cid
current()	cid
wake_up(cid)	
set_priority(cid, priority)	
alloc_cpu(cpu_num)	

TABLE I: Interface of COPS.

D. Global Cooperative Scheduling Mechanism

COPS offers an advanced global cooperative scheduling mechanism that includes both between kernel and user process and between user process. The priority bitmap, as described in III-A2, is crucial for this mechanism's operation.

COPS facilitates coordination between kernel and user process coroutines through a global cooperative scheduling approach. During time interrupts, the kernel scans user process Executors' priority bitmaps to create a global priority bitmap, giving the OS some awareness of user-level coroutines. The kernel also has an Executor for managing its coroutines.

The kernel's task scheduling integrates coroutine and process scheduling. One method is to define separate scheduling for processes and coroutines, ensuring high-priority kernel coroutines run first, followed by user processes. However, this can overcomplicate the system and not fully address kernel asynchronous I/O issues mentioned in I. A more elegant solution is to introduce a special kernel coroutine, the "switching coroutine," which identifies the highest-priority user process and handles switching operations, ensuring it never ends as long as user processes exist. It matches the highest process priority to ensure cooperative kernel and user process scheduling based on priority. At initialization, the kernel statically assigns the switching coroutine the highest priority, which then dynamically adjusts as the system runs, based on the priority bitmap scan. This allows the kernel to reuse COPS's priority scheduling mechanism for both process and coroutine scheduling. If the kernel has higher-priority coroutines, all user process coroutines are considered lower priority and wait for the kernel to finish executing. Then, the switching coroutine can schedule the highest-priority process, ensuring coordination between kernel coroutines and user processes.

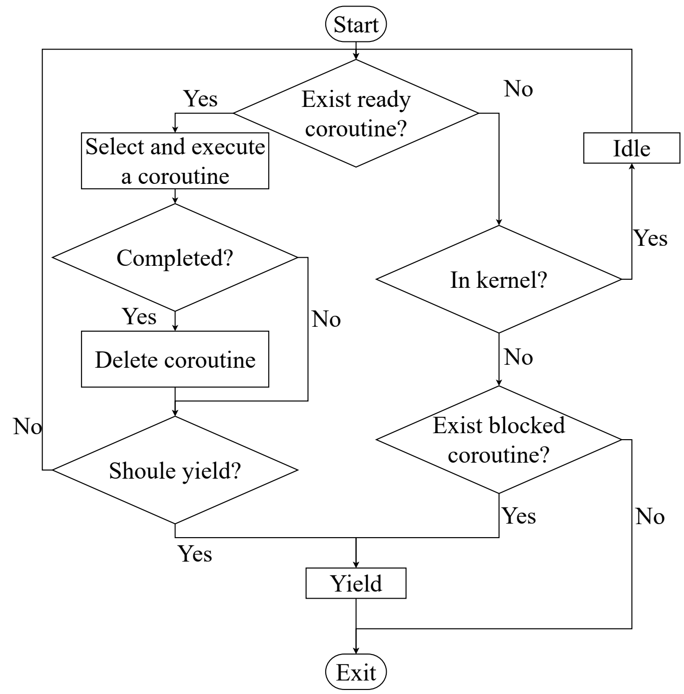


Fig. 3: The code logic of COPS.

Additionally, we share the read-only permission of the global priority bitmap with user processes to coordinate coroutines across different processes. If a user process detects a higher-priority coroutine in the system or other processes, it will proactively yield to enable mutual coordination. However, indiscriminate global coordination could lead to issues like prolonged CPU occupation by malicious processes or high switching overhead, which we plan to address in future work, but are not discussed in this paper.

This mechanism allows COPS to offer an OS-aware coroutine scheduling framework that prevents any single coroutine from monopolizing CPU resources for extended periods. Fig.3 illustrates the code logic of COPS.

IV. Common usage patterns

In this section, we demonstrate concurrent and asynchronous programming patterns using COPS. COPS creates an environment where all tasks are executed as coroutines. The application's main task is to use the *spawn* function to initiate coroutines for specific tasks. The execution of these coroutines is automatically managed by COPS's coroutine runtime, operating transparently.

A. Concurrency

A typical COPS use pattern is depicted in Algorithm 1, where the application initiates two coroutines: a producer and a consumer. The producer generates data and, when the message queue is full, signals the consumer and yields the CPU. The consumer then processes all data and waits. Subsequently, COPS reschedules the producer.

Algorithm 1 Concurrent Programming

MSG_QUEUE;
function MAIN
    $consumer\_cid \leftarrow spawn(||consumer, 1)$;
    $spawn(||producer(consumer\_cid), 0)$;
end function
function CONSUMER
    loop
        while MSG_QUEUE is empty **do**
            blocked;
        end while
        ... ▷ consume data from MSG_QUEUE
    end loop
end function
function PRODUCER(cid)
    loop
        while MSG_QUEUE is full **do**
            wake_up(cid); ▷ wake up the consumer
            yield;
        end while
        ... ▷ produce data into MSG_QUEUE
    end loop
end function

B. Asynchronous Programming

Another common COPS pattern is for asynchronous programming. By leveraging COPS's coroutine runtime environment, we can convert synchronous system calls into asynchronous ones using coroutines. However, simply changing the interface is not sufficient; the kernel must also implement support for these asynchronous system calls.

1) System Call Interfaces: We have introduced an **Asyncall** data structure that implements Rust's Future trait to handle system calls asynchronously. This structure checks system call return values to determine whether asynchronous waits are required. Rust macros ensure that synchronous and asynchronous system calls have a similar format, with asynchronous calls needing an extra parameter. An example is shown in the read system call interface 3.
2) Kernel Asynchronous I/O Support: When a user coroutine makes an asynchronous system call, the kernel creates a corresponding kernel coroutine that is not executed right away. Control returns promptly to the user coroutine, pausing the current one to allow other user coroutines to run. Once the kernel coroutine completes the asynchronous operation, it awakens the related user coroutine using the cid provided by the system call.

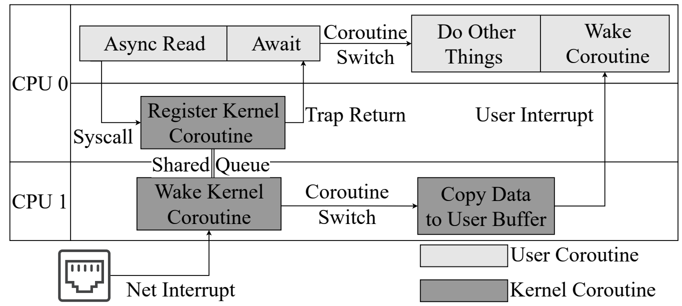


Fig. 4: Asynchronous system call.

Algorithm 2 illustrates asynchronous programming using the asynchronous system call interface. In the async_read function, it initiates an asynchronous *read!* system call. If the kernel buffer is empty, async_read yields the CPU. When data becomes available in the kernel buffer, async_read is awakened to continue execution.

Algorithm 2 Asynchronous Programming

function MAIN
    $spawn(||async\_read, 0)$;
end function
function ASYNC_READ
    $buf \leftarrow [0; buf\_len]$;
    $current\_cid \leftarrow current()$;
    $read!(buf.ptr, buf.len, current\_cid)$;
end function

To demonstrate how coroutines integrate with asynchronous I/O, consider the example of reading data from sockets asynchronously. When a read operation reaches the kernel, it is handled by a kernel coroutine, allowing the control flow to return to user space immediately. The current user coroutine is then blocked, waiting for the kernel to complete the read, while COPS switches to execute another user coroutine. The kernel coroutine may run on a different CPU. If the data is ready in the buffer, the kernel coroutine proceeds without waiting, leveraging multi-processor capabilities. If the data is not ready, the kernel coroutine waits for the network card to signal it. During this wait, other kernel coroutines can continue executing. Once the kernel detects the network card's interrupt and prepares the data, it awakens the corresponding kernel coroutine to finish the operation, such as copying data to a user-space buffer. Upon completion, the kernel sends a user-

```
read!(fd, buffer, cid); // Async
read!(fd, buffer); // Sync
```

Listing 3: System call interface of read().

FPGA	Zynq UltraScale+ XCZU15EG MPSoC [23]	
	RISC-V soft IP core	rocket-chip [24] with N extension, 4 Core, 100MHz
	Ethernet IP core	Xilinx AXI 1G/2.5G Ethernet Subsystem (1Gbps) [26]
Operating System	rCore-tutorial [27]	
Network Stack	smoltcp [28]	

TABLE II: Configuration of evaluation.

level interruption, which in turn wakes up the corresponding user coroutine.

V. Performance Evaluation

To assess COPS's capability in creating highly concurrent asynchronous programs and its precise control over coroutines, we conducted an evaluation on an FPGA. We used the Zynq UltraScale+ XCZU15EG MPSoC model [23] to construct a five-stage RISC-V pipeline processor based on the rocket-chip [24], a RISC-V soft IP core. Implementing N extension [25] on rocket-chip facilitated user-level interrupt functions, essential for asynchronous system calls. We operated an OS designed with the COPS framework on the RISC-V subsystem and evaluated COPS by simulating real-world web server application scenarios. The complete configuration parameters are detailed in Table II.

The simulated web server application scenario is divided into two parts: a client on the PC regularly sends matrix data of a certain length to the server and awaits the response; The server, hosted on the FPGA, integrates two usage patterns: it establishes a connection with the client, processes the received matrix data, and sends the results back. The server comprises three components:

1) A request receiver that takes client requests and queues them;
2) A request handler that dequeues requests, performs matrix operations, and queues the results;
3) A response sender that retrieves responses from the queue and communicates them to the client.

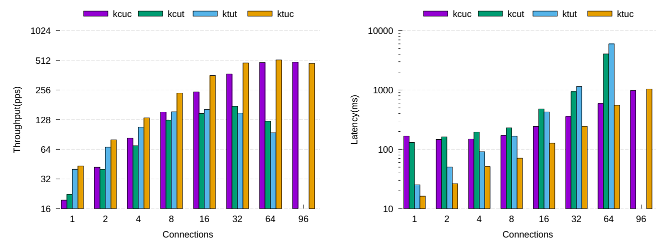
The PC client measures the latency of each request-response cycle and calculates the message throughput over a set time period. We assess COPS's performance by examining the web server's latency and throughput under various configurations.

A. Coroutine vs. Thread

To demonstrate the coroutine model's suitability for large-scale concurrency, we implemented the kernel and the web server's three components respectively using coroutines and threads[2]. The coroutine model assigns three coroutines per client-server connection, while the thread model assigns three user threads per connection, each handling a component. We defined four server models based on the use of coroutines(**C**) and threads(**T**) in the kernel(**K**) and userland(**U**):

KCUC: When a user coroutine calls read(), the kernel creates a coroutine to perform the operation, blocking the user

[2] The threads in the application are kernel-support thread.



(a) Throughput (b) Latency

Fig. 5: Throughput and message latency.

coroutine. Once data is read and copied, the kernel coroutine triggers a user-level interrupt to awaken the user coroutine.

KCUT: Similar to KCUC, but with a user thread invoking read(). The kernel coroutine executes the operation and unblocks the user thread after the copy is complete.

KTUT: A user thread calls read(), and a corresponding kernel thread reads data from the socket, blocking until the copy operation is done, allowing other threads to run in the meantime.

KTUC: Similar to KCUC, but instead of the kernel coroutine handling the copy, it delegates the read operation to a separate kernel thread, which polls sockets for data and copies it. Once the copy is complete, it sends a user-level interrupt to awaken the user coroutine.

The testing begins once all client-server connections are set up to avoid the influence of creating coroutines/threads. The client sends requests at 100ms intervals for a total of 5 seconds, with each request containing a 15x15 matrix. The results of the experiment are depicted in Fig.5.

Runtime overhead: With few connections, coroutines incur more overhead than threads, as seen in comparisons like KCUC vs KCUT, KCUT vs KTUT, and KCUC vs KTUT in Fig.5. This overhead is due to COPS's executor being lock-protected. With a small number of connections, COPS can complete tasks with fewer cores but is given extra CPUs for a balanced comparison (the coroutine model has the same core allocation as the thread model). The extra CPUs lead to increased scheduling overhead from unnecessary synchronization. Additionally, frequent yielding on the extra core due to a lack of ready coroutines causes overhead from privilege level switching. Thus, COPS is not ideal for low-concurrency applications.

Lower coroutine context-switching overhead: As the number of connections grows, the latency of the thread model (KCUT and KTUT) exceeds that of the coroutine model (KCUC). By the time connections hit 32, KCUT's latency is notably lower than KTUT's. Despite performing the same operations, coroutines have less context-switching overhead than threads, even when comparing to kernel threads with streamlined context switching. At two connections, KCUC's latency is lower than KCUT's due to most context switches happening in userland in the KCUC model, avoiding the privilege-switching overhead present in KCUT. However, as connections increase further, the throughput of KCUT and KTUT decreases, and their context-switching costs rise rapidly.

Coroutines have obvious advantages with high concurrency: With a small number of connections, the KTUC model exhibits the lowest latency due to its dedicated kernel thread that polls socket states efficiently, providing a quick response. However, this advantage diminishes as connection numbers grow, and the KTUC model's polling overhead increases. Comparing throughput, at 64 connections, the CPU is fully loaded. At 96 connections, the KCUC model shows lower latency than KTUC, as the latter, along with KCUT and KTUT models, cannot complete the test due to the heavy workload. The specific throughput and message latency are not displayed in Fig.5 for these cases. As connections continue to increase, KTUC's throughput drops significantly, whereas KCUC's throughput remains relatively stable. Even with the use of epoll, which was not part of our experiment, the KTUC model's performance is unlikely to improve significantly due to additional synchronization overhead from its producer-consumer model and increased thread context-switching costs. In conclusion, after comparing KCUC with KTUC, COPS proves more suitable for large-scale concurrent scenarios.

Less memory usage: We also compared the memory usage between coroutines and threads. User-level threads, supported by the kernel, have two stacks: one for userland execution and another for kernel execution. In contrast, both kernel and userland coroutines run on a single stack, statically sized at 0x4000 bytes. The memory footprint of the three components using coroutines is as follows: 120 bytes for the request receiver, 80 bytes for the request handler, and 64 bytes for the response sender. The kernel coroutine itself is 176 bytes. Thus, establishing a connection in the KTUT model requires 0x4000 * 2 * 3 bytes, while the KCUC model requires only 0x4000 * 2 + 176 + 120 + 80 + 64 bytes. Table III illustrates the maximum number of connections possible for both the KTUT and KCUC models under specific configurations.

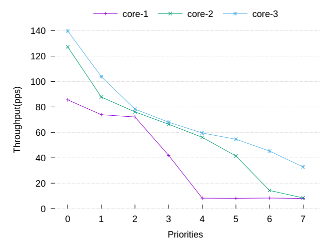
Configuration	Size(bytes)	KCUC	KTUT
kernel heap	0x80_0000		
kernel frame	0x1A0_0000	385	186
user heap	0x20_0000		

TABLE III: Maximum connections of KCUC and KTUT.The stack used by the thread is allocated from the kernel frame.

B. Priority orientation

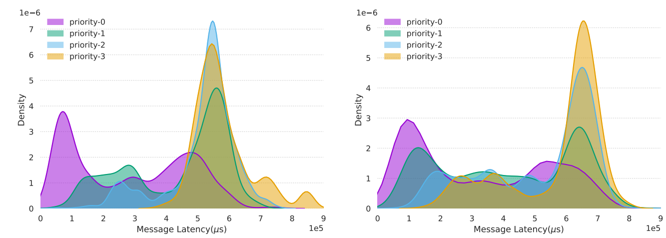
In a realistic scenario, a web server may manage tens of thousands of connections, many of which could be idle. System resources should favor active connections, prioritizing timely responses for them. We assign each connection a priority level in a tiered structure to ensure that higher-priority connections experience lower latency and less latency variability.

Similar to the previous experiment, but with both the kernel and application using coroutines. We establish 64 client-server connections with an equal distribution across 8 priority levels and measure throughput and message latency for each priority



(a) Throughput (b) Latency

Fig. 6: Throughput and message latency of different priority connections.



(a) Core-2 (b) Core-4

Fig. 7: Latency distribution of different priority connections in different amount of cores.

during the same time frame. The client sends requests to the server every 50ms over 5 seconds.

As shown in Fig.6, under limited resources, the throughput and latency for higher-priority connections are maintained. As resource availability increases(increasing the amount of CPU), lower-priority connections also see improved throughput and reduced latency, while the highest-priority connections consistently achieve the highest throughput and lowest latency.

Additionally, we created 64 connections between the client and server, evenly spread across 4 priority levels, to analyze the latency distribution for each priority. The results are depicted in Fig.7. Consistent with priority handling, higher-priority connections exhibit concentrated and low latency, whereas lower-priority connections show dispersed and higher latency. As resources increase, latency across all priorities decreases and becomes more concentrated.

VI. Related Work

Coroutines, being lightweight with efficient context switching, are well-suited for the event-driven, state-machine approach often used in I/O operations. This has led to a surge in research leveraging coroutines.

Demikernel [29] utilizes Rust coroutines to construct a system prototype, bypassing the overhead of context switches in I/O stacks, which typically take about 12 cycles. Their TCP stack assigns a coroutine per TCP connection for retransmissions, maintaining TCP state locally and eliminating the need for global state management, resulting in microsecond-level latency.

Embassy [30], an asynchronous driver framework for embedded systems built on Rust coroutines, excels in managing device interrupts. It significantly outperforms FreeRTOS, a C-based system, in interrupt handling time, thread processing time, and interrupt latency.

VII. Conclusion

This paper proposes COPS, a coroutine-based priority scheduling framework that can be perceived by the operating system. COPS make the kernel perceive the user-level coroutines by the priority bitmap mechanism and combines kernel coroutines with asynchronous I/O mechanisms. COPS facilitates the development of highly concurrent applications, reduces the overhead associated with traditional multi-threading, and offers efficient asynchronous I/O and priority scheduling.

Our evaluation demonstrates COPS's ability to deliver high throughput and low latency for highly concurrent applications. Compared to threads (KCUC vs KTUT), COPS's coroutine abstraction can increase throughput by 1.05 to 3.93 times. Additionally, COPS's coroutine priority scheduling effectively meets various requirements and ensures the rational distribution of system resources.

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