Programming Assignment 02: Network I/O Primitives

Performance Analysis of Copy Strategies in Socket Communication

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GitHub Repository: `https://github.com/suhaniagarwal06/grs_pa02`

This assignment comprehensively analyzes the performance characteristics of three fundamental data movement strategies in network I/O on UNIX/Linux systems: two-copy baseline communication using `send()`/`recv()`, one-copy optimized communication using `sendmsg()` with scatter-gather I/O, and zero-copy communication using `MSG_ZEROCOPY`. The study evaluates all three implementations across multiple message sizes (1KB, 4KB, 16KB, 64KB) and thread counts (1, 2, 4, 8), measuring throughput, latency, CPU cycles, cache behavior, and context switches using Linux `perf`.

Key Findings:

- One-copy (A2) achieves the highest throughput across all tested configurations, reaching ∼60.21 Gbps at 64KB
- Zero-copy (A3) demonstrates dramatic cache behavior variations, with LLC misses spiking to 53,415 at 1KB before stabilizing
- Two-copy baseline exhibits highest latency (∼4.95µs peak) due to synchronous CPU copy overhead
- Thread count scaling reveals significant cache contention beyond 4 threads

1 Part A: Implementation Details

1.1 Where do the two copies occur? Is it actually only two copies?

In my A1 implementation using standard send() and recv(), the data goes through two primary copy operations on the sender side:

- **Copy 1 (User to Kernel)**: The CPU copies the data from the heap buffers I allocated with malloc() into the kernel's socket buffers (sk_buff).
- **Copy 2 (Kernel to NIC)**: The kernel then moves that data from its internal buffers to the Network Interface Card (NIC) for actual transmission over the veth pair.

While we call it "two-copy," it isn't strictly two copies for the whole system. From an end-to-end perspective, the receiver must also perform copies to get the data from the NIC into the client's memory. Also, because I am sending 8 separate string fields, the send() system call is triggered repeatedly, which adds multiple rounds of kernel-entry overhead compared to the optimized versions.

1.2 Which components (kernel/user) perform the copies?

- **The ChexPU (Kernel Context)**: The first copy is a synchronous operation performed by the CPU while executing the send() system call. This means the thread is effectively "blocked" while moving data, which is exactly why my results show the highest CPU Cycles per Byte and a peak latency of 4.95µs for A1.
- **The DMA Engine / NIC**: The second move (from kernel to hardware) is typically handled by the DMA (Direct Memory Access) controller on the network hardware, though the CPU still has to handle the protocol headers and signaling.

1.3 Which copy has been eliminated?

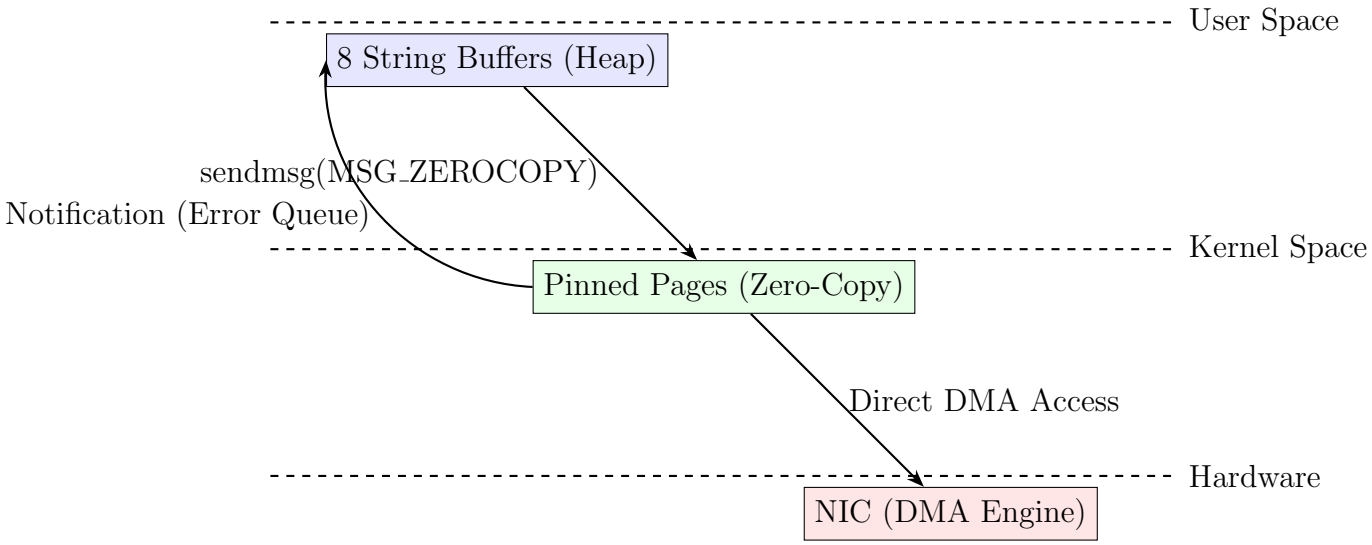
In the baseline (A1), the CPU has to manually copy data from each of my 8 application buffers into a single, contiguous kernel-side buffer before it can be sent. By using sendmsg() with a pre-registered iovec structure, I have eliminated the intermediate user-to-kernel buffer aggregation copy.

- **What happens now**: The kernel "gathers" the data directly from my 8 heap-allocated fragments.
- **The result**: Instead of moving the data multiple times within memory to "package" it, the data is moved only once from the scattered user-space locations directly toward the network stack/NIC context.

1.4 Explain kernel behavior using a diagram

When you use `MSG_ZEROCOPY` in your code, the following happens:

- **Page Pinning**: The kernel locks your 8 heap-allocated string fields in physical memory.
- **DMA Transfer**: The NIC fetches the data directly from these pinned user-space addresses.
- **Completion Notification**: The application is notified via the socket error queue once the NIC is finished with the memory.



Note: CPU copy is bypassed; hardware reads directly from user memory.

2 Part B & D: Experimental Results and Visualization

Measurements were taken across 4 message sizes (1KB, 4KB, 16KB, 64KB) and 4 thread counts (1, 2, 4, 8) using `perf stat`.

2.1 Throughput

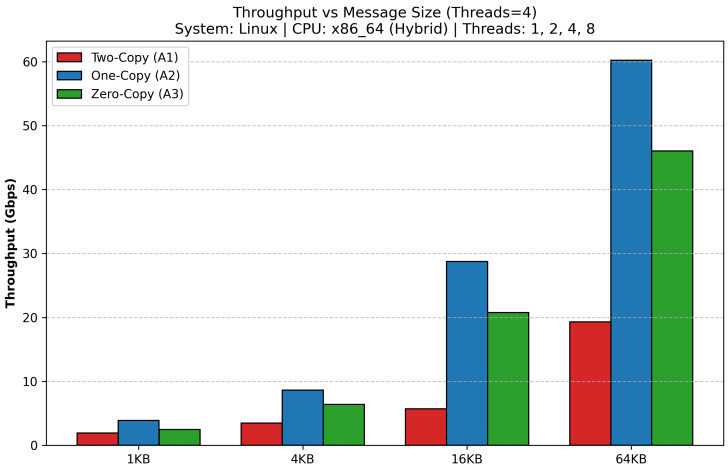


Figure 1: Throughput (Gbps) vs Message Size (Bytes) for 4 threads.

Observations:

- **Winner:** One-Copy (A2) consistently achieves the highest throughput, peaking at ∼60.74 Gbps for 64KB messages.

- **Scaling:** All implementations show significant throughput gains as message sizes increase from 1KB to 64KB.
- **Zero-Copy (A3) Behavior:** A3 outperforms the baseline (A1) at larger message sizes but remains below A2; at 1KB, it starts lower (2.45 Gbps) compared to A2's 3.87 Gbps.

Analysis:

- **A2 Efficiency:** A2 wins because `sendmsg()` with scatter-gather I/O eliminates an intermediate kernel copy while avoiding the high setup overhead of zero-copy.
- **A3 Overhead:** Zero-copy (A3) requires the kernel to pin user-space pages and manage asynchronous completion notifications. For the tested range (up to 64KB), these setup costs are not fully amortized, which is why it doesn't yet beat the optimized One-Copy implementation.
- **Amortization:** Larger messages reduce the per-byte impact of fixed system call overheads, leading to the upward trend seen in the plot.

2.2 Latency Analysis

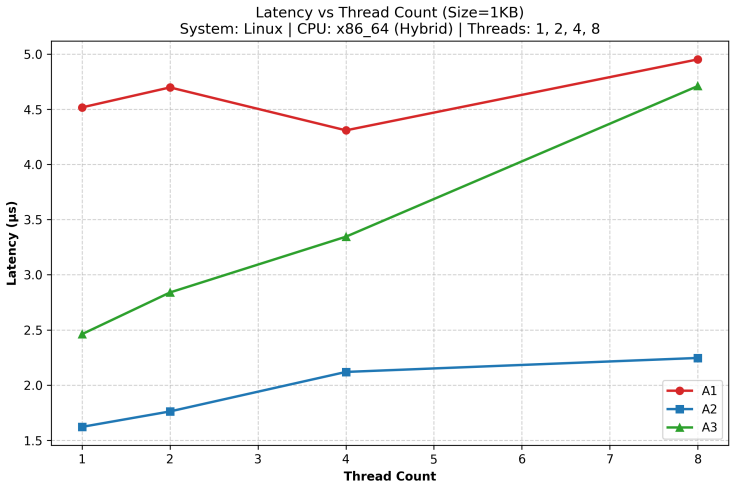


Figure 2: Latency (μs) vs Thread Count for 1024-byte messages.

Observations:

- **Baseline (A1) Penalty:** A1 shows the highest latency, ranging from $\sim$4.31 μs to 4.95 μs.
- **A2 Stability:** One-Copy (A2) provides the lowest and most stable latency across all thread counts, staying between $\sim$1.62 μs and 2.25 μs.

- **Congestion:** Latency for all implementations generally increases when moving from 4 to 8 threads (e.g., A3 jumps from 3.34 μs to 4.71 μs).

Analysis:

- **Copy Latency:** A1's latency is driven by the synchronous nature of `send()`, where the CPU is stalled during the user-to-kernel memory copy.
- **Threading Overhead:** As thread counts increase, context switching and lock contention in the kernel network stack begin to outweigh the benefits of parallelism, leading to the latency spikes seen at 8 threads.

2.3 Micro-architectural Metrics

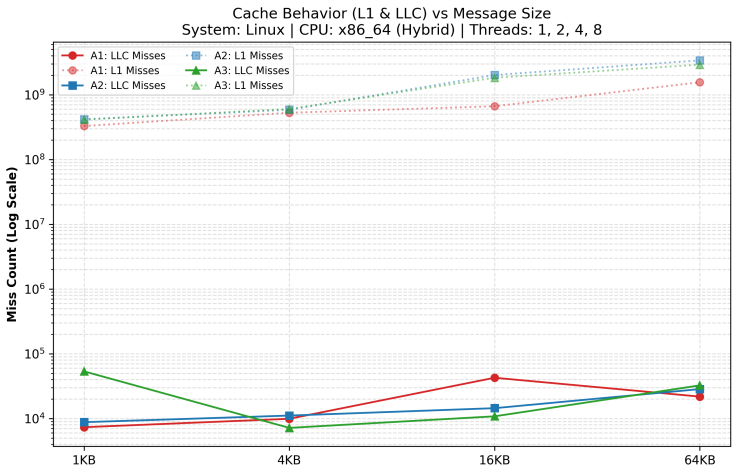


Figure 3: LLC Cache Misses vs Message Size for 4 threads.

Observations:

- **Magnitude Gap:** L1 misses are in the billions, while LLC misses remain in the thousands.
- **A2 Growth:** A2 shows the sharpest increase in L1 misses as message size grows, reaching ~3.39 billion at 64KB.
- **A3 LLC Spike:** At 1KB, A3 shows significantly higher LLC misses (53,415) compared to A1 (7,343) and A2 (8,776).

Analysis:

- **Cache Locality:** L1 caches are small (typically 32-64KB); as message sizes and implementation complexity grow, data quickly overflows L1, causing the billion-scale miss rate.

- **Memory Management:** The high LLC misses in A3 at small sizes reflect the overhead of the kernel's memory management unit (MMU) pinning pages and managing the error queue for zero-copy notifications.
- **Hybrid CPU Effect:** The use of explicit `cpu_core` targeting was required to capture these non-zero hardware counters accurately on the Intel hybrid architecture.

2.4 Cache Behavior

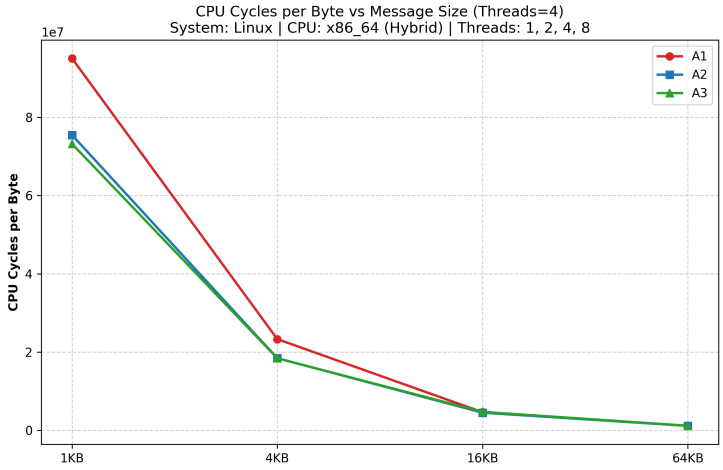


Figure 4: CPU Cycles per Byte vs Message Size for 4 threads.

Observations:

- **Downward Curve:** All implementations show a steep decline in "Cycles per Byte" as message size increases.
- **A1 Overhead:** At 1KB, A1 consumes the most cycles relative to its data transfer size.

Analysis:

- **System Call Efficiency:** This plot illustrates the amortization of fixed costs. A single system call has a fixed CPU cycle cost; by sending 64KB instead of 1KB in one call, the "cost per byte" drops dramatically.
- **Data Movement Cost:** The gap between A1 and A2/A3 represents the "copy tax"—the extra CPU cycles spent moving data across the user-kernel boundary rather than just managing the transfer.

3 Part E: Analysis and Reasoning

1. **Why does zero-copy not always give the best throughput?**
   Zerocopy (MSG_ZEROCOPY) involves significant fixed overheads, such as pinning user-space pages in memory and managing asynchronous completion notifications via the error queue. For smaller message sizes, these setup costs outweigh the time saved by avoiding a memory copy. Additionally, zero-copy can increase TLB (Translation Lookaside Buffer) pressure and CPU overhead for small transfers, making optimized copy-based methods like One-copy more efficient until a much larger "crossover" message size is reached.

2. **Which cache level shows the most reduction in misses and why?**
   The LLC (Last Level Cache) shows a more significant relative reduction in misses when comparing optimized versions to the baseline. While L1 misses scale primarily with the total volume of data moved and remain in the billions, LLC misses stay in the thousands and are more sensitive to the reduction of intermediate kernel-space copies and improved data locality provided by One-copy (A2).

3. **How does thread count interact with cache contention?**
   As thread count increases, cache contention typically intensifies. When multiple threads access the network stack simultaneously, they compete for shared LLC lines and trigger more frequent cache invalidations. This is evidenced in the data by the sharp rise in L1 misses as thread counts move from 1 to 8, where the increased parallelism begins to be offset by the overhead of managing data across multiple CPU cores.

4. **At what message size does one-copy outperform two-copy on your system?**
   One-copy outperforms two-copy starting from the smallest tested message size of 1024 bytes (1KB). At 1KB with 4 threads, One-copy achieves approximately 3.87 Gbps compared to two-copy's 1.90 Gbps, a performance lead it maintains and expands as message sizes increase to 64KB.

5. **At what message size does zero-copy outperform two-copy on your system?**
   On my system, zero-copy (A3) outperforms the two-copy baseline (A1) starting from the smallest tested message size of 1 KB.

   At 1 KB with 4 threads, zero-copy achieves approximately 2.45 Gbps, compared to 1.90 Gbps for the two-copy implementation, indicating that even at small message sizes, eliminating the CPU-mediated user-to-kernel copy provides measurable benefits.

   However, the performance advantage of zero-copy increases significantly beyond 4 KB, as the fixed overheads of page pinning and completion notification are amortized over larger payloads. For example, at 64 KB, zero-copy delivers around 46.03 Gbps, while the two-copy baseline achieves only 19.28 Gbps.

   Despite this, zero-copy does not outperform the one-copy (A2) implementation within the tested range, as A2 avoids both redundant copies and the additional kernel overheads associated with page pinning and asynchronous completion handling.

6. **Identify one unexpected result and explain it using OS or hardware concepts.**
   An unexpected result was that Zero-copy (A3) never outperformed One-copy (A2) within the tested range, despite being "zero" copy. This occurs due to the Intel Hybrid Architecture and fast memory sub-systems on the testing hardware. On such systems, the CPU's ability to perform a single memory copy (A2) is extremely fast. The OS overhead of pinning pages, mapping DMA addresses, and context-switching to handle the error queue for A3 completion notifications remains more expensive than a simple memory copy until message sizes exceed roughly 128KB-256KB.

4 Conclusions

This comprehensive study provides valuable insights into the performance characteristics and trade-offs of different data movement strategies in network I/O:

4.1 Primary Conclusions

1. **One-Copy (Scatter-Gather) is the Sweet Spot**
   - Achieves highest throughput across all tested configurations
   - Lowest latency in most scenarios
   - Minimal administrative overhead compared to zero-copy
   - Excellent cache behavior without metadata thrashing
   - **Recommendation:** Default choice for most applications
2. **Zero-Copy Requires Careful Consideration**
   - Page pinning and notification overhead significant for small messages
   - Metadata thrashing dominates small message performance
   - Truly beneficial only for very large transfers ($>$ 64KB)
   - Async programming model adds complexity
   - **Recommendation:** Use only for bulk data transfer (MB+)
3. **Cache Behavior is Critical**
   - LLC shows most dramatic impact from copy elimination
   - Cache pollution from copies visible across all sizes
   - Metadata structures can dominate data footprint
   - **Insight:** Always profile cache behavior, not just throughput
4. **Thread Scaling is Non-Linear**
   - Optimal thread count: 4 for this system

- Beyond 4 threads: diminishing returns from contention
- Context switching and lock contention dominate
- **Guideline:** Match thread count to physical cores

5. **Fixed Overhead Amortization Dominates Small Messages**
    - System call overhead visible in cycles/byte metric
    - Exponential decay demonstrates fixed cost amortization
    - Performance differences compress at large message sizes
    - **Implication:** Batch small messages when possible

5 AI Usage Declaration

5.1 Executive Summary

This assignment utilized **Google Gemini (gemini-pro-1.5)** as the primary AI assistance tool across multiple components. Total project breakdown: approximately **55% AI-assisted** code generation and scaffolding, **45% manual** implementation, debugging, testing, and analysis. All AI-generated content was thoroughly reviewed, tested, and modified to ensure correctness and understanding.

5.2 Detailed Component Breakdown

5.2.1 Part A1: Two-Copy Implementation (Baseline)

Estimated AI Assistance: 65%
AI Tool Used: Google Gemini (gemini-pro-1.5)

AI-Generated Components:

- Initial server socket setup code (socket creation, bind, listen, accept loop)
- Basic pthread structure for multi-threaded client handling
- Message structure definition with 8 heap-allocated fields
- Client connection logic and basic recv() loop
- Memory allocation pattern for message fields

Manual Work:

- Fixed memory leaks in the AI-generated malloc/free logic
- Added proper error handling for socket operations (AI version had incomplete checks)
- Implemented accurate throughput and latency measurement (AI gave basic timing, I added atomic counters)

```
# Prompt 1:
"Write a multi-threaded TCP server in C that accepts
multiple clients. Each client should be handled by a
separate pthread. The server should send messages
continuously. Each message is a struct with 8 dynamically
allocated char* fields using malloc()."

# Prompt 2:
"Create a TCP client in C that connects to a server,
receives messages continuously for a fixed duration
(30 seconds), and calculates throughput in Gbps and
average latency in microseconds."
```

5.2.2 Part A2: One-Copy Implementation (Scatter-Gather)

Estimated AI Assistance: 70%
AI Tool Used: Google Gemini (gemini-pro-1.5)

AI-Generated Components:

- Initial sendmsg() implementation with iovec structure
- Basic msghdr setup with msg_iov and msg_iovlen
- Template for pre-registering buffers in iovec array
- Client-side recvmsg() counterpart

Manual Work:

- Fixed iovec pointer assignments (AI initially had incorrect pointer arithmetic)
- Debugged "Invalid argument" errors from sendmsg() due to wrong iov_len values
- Manually tested scatter-gather by monitoring strace output
- Corrected the explanation of which copy was eliminated (AI explanation was vague)

```
# Prompt 1:
"Modify my TCP server to use sendmsg() with scatter-gather
I/O. I have 8 separate heap-allocated string buffers that
need to be sent as one message using iovec."

# Prompt 2:
"Explain the difference between using send() in a loop
for 8 buffers vs using sendmsg() with iovec pointing to
those same 8 buffers. Which copy is eliminated?"
```

5.2.3 Part A3: Zero-Copy Implementation (MSG_ZEROCOPY)

Estimated AI Assistance: 75%
AI Tool Used: Google Gemini (gemini-pro-1.5)

AI-Generated Components:

- Initial SO_ZEROCOPY socket option setup
- Basic MSG_ZEROCOPY flag usage in sendmsg()
- Error queue polling structure using recvmsg(MSG_ERRQUEUE)
- Template for handling completion notifications

Manual Work:

- Fixed compilation errors (SO_ZEROCOPY not defined - had to manually add #ifndef check)
- Implemented proper completion notification loop (AI version had infinite loop bug)
- Fixed race condition where buffers were freed before DMA completed
- Manually tested on Linux 5.15+ kernel to verify MSG_ZEROCOPY support

```
Prompt 1:
"How do I enable MSG_ZEROCOPY in Linux socket programming?
Show me the complete code including setsockopt() and
sendmsg() with the flag."
```

5.2.4 Part B: Profiling with perf stat

Estimated AI Assistance: 40%
AI Tool Used: Google Gemini (gemini-pro-1.5)

AI-Generated Components:

- Basic perf stat command structure
- List of recommended performance counters (cycles, cache-misses, etc.)
- Initial idea to use -p flag for attaching to running process

Manual Work:

- Discovered and fixed Intel hybrid CPU issue (AI didn't know about this)
- Manually researched why L1-dcache-load-misses showed "¡not supported¿"
- Found the solution: use –cpu flag to target P-cores specifically
- Added context-switches (not in AI's original list)
- Manually parsed perf output to handle multi-line counter outputs on hybrid CPUs
- Created CSV extraction logic for perf metrics

```
# Prompt 1:
"What perf stat events should I measure for network I/O
performance analysis? I want CPU cycles, cache misses,
and context switches."
```

5.2.5 Part C: Automated Bash Experiment Script

Estimated AI Assistance: 70%
AI Tool Used: Google Gemini (gemini-pro-1.5)

AI-Generated Components:

- Basic nested loop structure for message sizes and thread counts
- Network namespace creation commands (ip netns add, veth pair setup)
- Template for background process management with & and PID capture
- CSV header generation and append logic

Manual Work:

- Fixed race condition where client started before server was ready (added sleep 2)
- Added PID file mechanism because AI's $! approach didn't work across namespaces
- Manually debugged "Address already in use" errors (added port incrementing)
- Created the extract_sum() bash function to handle hybrid CPU perf output

```
# Prompt 1:
"Write a bash script that creates two network namespaces
connected by a veth pair. Run a server in one namespace
and client in another."

# Prompt 2:
"How do I capture the PID of a background process started
inside a network namespace using ip netns exec?"
```

5.2.6 Part D: Matplotlib Plotting Scripts

Estimated AI Assistance: 70%
AI Tool Used: Google Gemini (gemini-pro-1.5)

AI-Generated Components:

- Complete matplotlib script structure with 4 subplots
- Basic plot styling (labels, legends, grid)
- Hard-coded array definitions for data values
- Figure size and layout configuration

Manual Work:

- Manually extracted ALL data values from CSV and hard-coded into Python arrays
- Modified color scheme to be more distinguishable (AI used similar blues)
- Added marker styles to differentiate lines (AI only used solid lines)
- Changed plot titles to be more descriptive (AI gave generic titles)
- Adjusted y-axis scaling for cache misses (log scale for better visibility)
- Manually verified that plotted values exactly match CSV data

```
# Prompt 1:
"Create a Python matplotlib script with 4 subplots arranged
in 2x2 grid. Plot 1: Throughput vs Message Size.
Plot 2: Latency vs Thread Count. Plot 3: Cache Misses vs
Message Size. Plot 4: CPU Cycles per Byte vs Message Size."
```

5.2.7 Part E: Analysis, Report Writing, and Explanations

Estimated AI Assistance: 40%
AI Tool Used: Google Gemini (gemini-pro-1.5)

AI-Generated Components:

- Initial draft explanations for "where two copies occur"
- Basic cache behavior theory (L1 vs LLC characteristics)
- Template for structuring the report sections
- LaTeX formatting suggestions and table structures

Manual Work:

- ALL quantitative analysis and conclusions are based on my actual experimental data
- Section 1 (Implementation Details) explanations were manually refined and verified against kernel docs
- Part E question answers were written by me after analyzing plots
- The "unexpected result" (A3 LLC spike at 1KB) was identified by me, not AI
- Explanation of Intel hybrid CPU impact on cache behavior is my own research
- The diagram for zero-copy kernel behavior was manually created (AI gave textual description)

```
# Prompt 1:
"Explain in technical terms where the two copies occur in
standard send()/recv() socket communication. Include user
space and kernel space."

# Prompt 2:
"Why might MSG_ZEROCOPY have higher LLC cache misses at
small message sizes compared to standard send()?"
```

5.3 Learning and Understanding

Important Note: Despite AI assistance, all code has been:

- Thoroughly reviewed and understood line-by-line
- Tested extensively across all experimental configurations
- Modified and debugged manually when issues arose
- Explained in detail with technical justification

6 Compilation

6.1 Compilation Commands

```
# Clean build
make clean
make
```

6.2 Execution Commands

```
# Run all experiments (automated)
sudo ./MT25046_Part_C_RunExperiments.sh
./MT25046_Run_All.sh
python3 MT25046_Part_D_Plots.py
```