“To infinity and beyond!”

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CS 614

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Motivation

- Communication overheads are high!
  - e.g. results from last week's RPC paper

Table I. Performance Results for Some Examples of Remote Calls

Procedure	Minimum	Median	Transmission	Local-only
no args/results	1059	1097	131	9
1 arg/result	1070	1105	142	10
2 args/results	1077	1127	152	11
4 args/results	1115	1171	174	12
10 args/results	1222	1278	239	17
1 word array	1069	1111	131	10
4 word array	1106	1153	174	13
10 word array	1214	1250	239	16
40 word array	1643	1695	566	51
100 word array	2915	2926	1219	98
resume except'n	2555	2637	284	134
unwind except'n	3374	3467	284	196

From [Birrell84]

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Overhead is 7x transmission time!

Overhead is 1.4x transmission time!

From [Birrell84]

Sources of overhead

- Memory copies
  - User buffer → kernel buffer → protocol stack → NIC
- System call
- Scheduling delays
- Interrupts/polling overhead
- Protocol overhead (headers, checksums, etc.)
- Generality of networking code
  - Even though most applications do not need all features

How to reduce overhead?

- U-Net, von Eicken et al, 1995
  - Move networking out of the kernel
- Lightweight RPC, Bershad et al, 1990
  - Optimize for the common case: same-machine RPC calls

U-Net: A User-Level Network Interface for Parallel and Distributed Computing

T. von Eicken, A. Basu, V. Buch, W. Vogels
Cornell University

SIGOPS 1995

U-Net goals

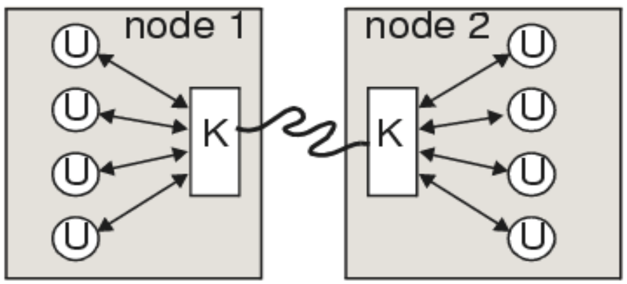
- Low-latency communication
- High bandwidth, even with small messages
- Use off-the-shelf hardware, networks
  - Show that Network of Workstations (NOW) can compete with Massively Parallel Processor (MPP) systems

U-Net strategy

- Remove (most) networking code from the kernel
  - Reduces overhead from copies, context switches
  - Protocol stack implemented in user space
- Each application gets a virtualized view of the network interface hardware
  - System multiplexes the hardware, so that separation and protection are still enforced
  - Similar to the exokernel philosophy [Engler95]

U-Net architecture compared

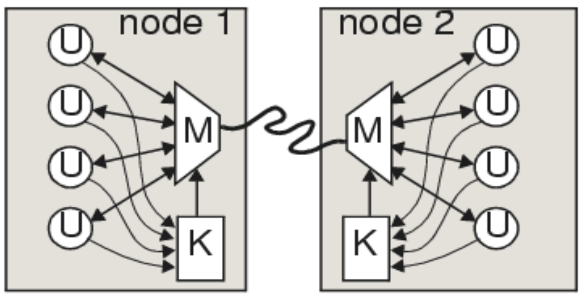
Traditional architecture



From [von Eicken95]

- Kernel (K) on critical path (sends and receives)
- Requires memory copies, mode switches between kernel (K) and apps (U)

U-net's architecture

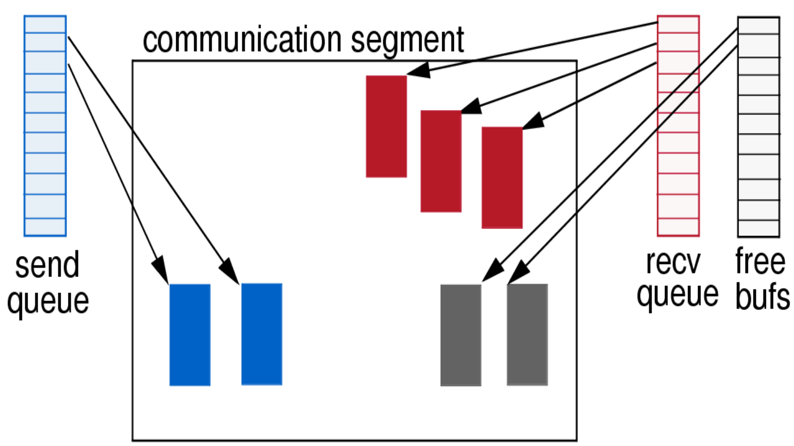


From [von Eicken95]

- Kernel (K) removed from critical path (only called on connection setup)
- Simple multiplexer (M) implemented in firmware on NIC

U-Net endpoints

- Application sees network as an *endpoint* containing communication buffers and queues
  - Endpoints pinned in physical memory, DMA-accessible to NIC and mapped into application address space
  - (or emulated by kernel)



From [von Eicken95]

Incoming messages

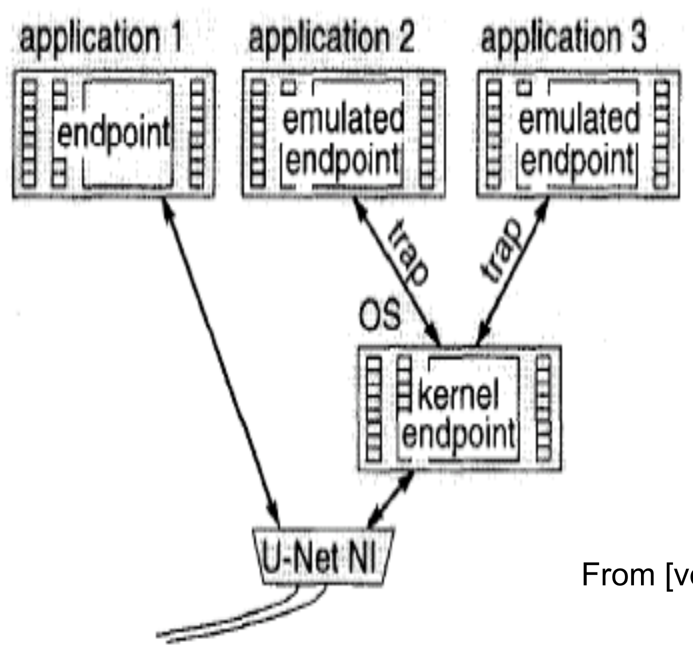
- U-Net sends incoming messages to endpoints based on a destination channel tag in message
  - Channel tags in messages identify source and destination endpoints, to allow multiplexer to route messages appropriately
- U-Net supports several receive models
  - Block until next message arrives
  - Event-driven: signals, interrupt handler, etc.
  - Polling
    - Polling is fastest for small messages: round-trip latency *half* that of UNIX signal (60 μsec vs. 120 μsec)
- To amortize notification cost, all messages in receive queue are processed

Endpoints + Channels = Protection

- A process can only "see" its own endpoint
  - Communications segments, messages queues are disjoint, mapped only into creating process's address space
- A sender can't pose as another sender
  - U-Net tags outgoing messages with sending endpoint
- Process receives only its own packets
  - Incoming messages de-multiplexed by U-Net
- Kernel assigns tags at connection start-up
  - Checks authorization to use network resources

Kernel-emulated endpoints

- NIC-addressable memory might be scarce, so kernel can emulate endpoints, at additional cost



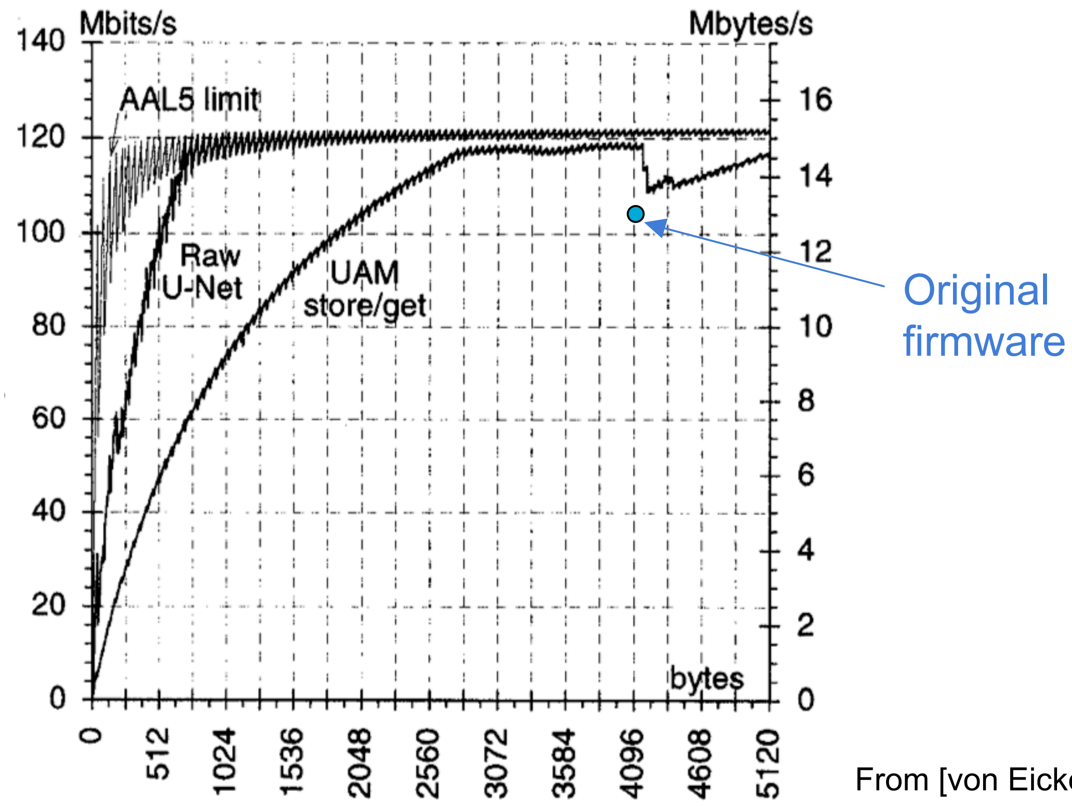
From [von Eicken95]

U-Net implementation

- Implemented U-Net in firmware of Fore SBA-200 NIC
  - Used combination of pinned physical memory and NIC's onboard memory to store endpoints
- Base-level vs. direct-access
  - Zero-copy vs. *true* zero-copy: is a copy between application memory and communications segment necessary?
  - Direct access not possible with this hardware. Requires NIC to be able to map all physical memory, and page faults must be handled.

Microbenchmarks

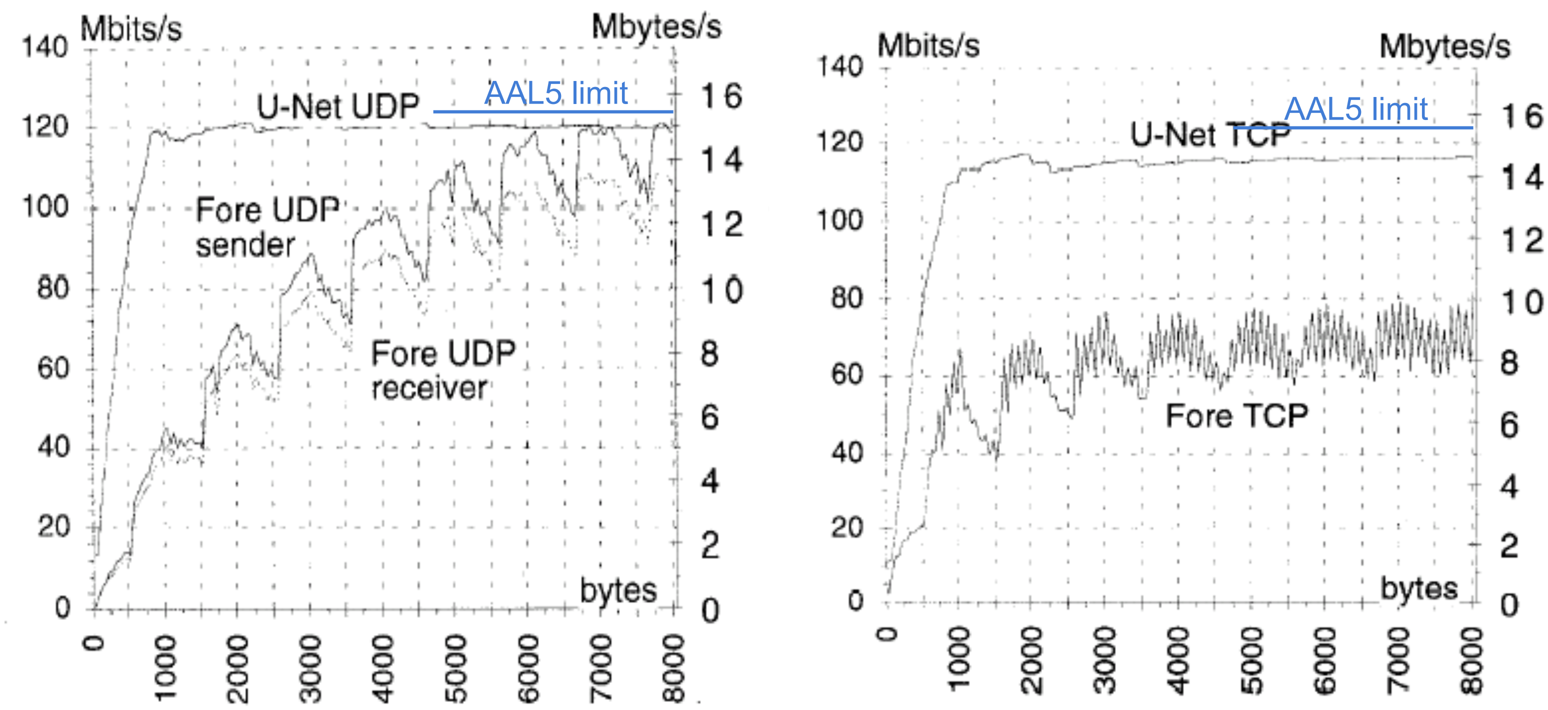
- U-Net saturates fiber with messages >1024 bytes



From [von Eicken95]

TCP, UDP on U-Net

- U-net implementations of UDP and TCP outperform traditional SunOS implementations:

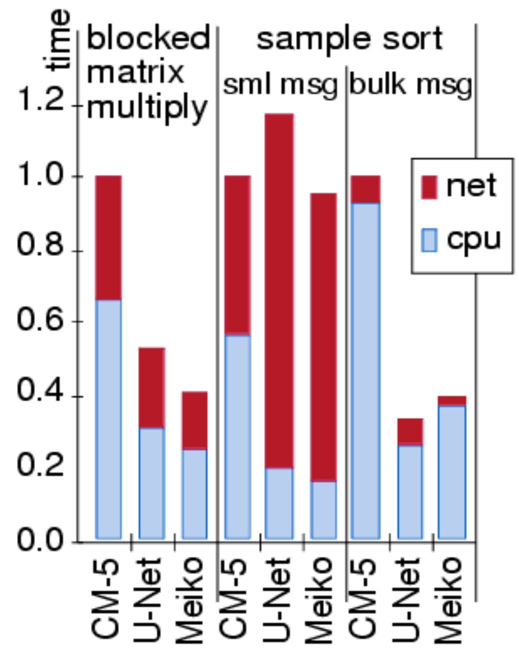


From [von Eicken95]

Application benchmarks

- Split-C parallel programs
- Compare U-Net cluster of Sun workstations to MPP supercomputers

Machine	CPU	Network	
		bandwidth	latency
CM-5	33Mhz sparc	80Mbits/s	12µs
CS-2	40Mhz supersparc	320Mbits/s	25µs
U-Net	50/60Mhz supersparc	120Mbits/s	70µs



From [von Eicken95]

- Performance is similar
  - But prices are not!
  - (very) approximate price per node: CM-5: \$50,000, NOW: \$15,000, CS-2: \$80,000

U-Net: Conclusions

- Showed that NOW could compete with MPP systems
  - Spelled the end for many MPP companies:
    - Thinking Machines: bankrupt, 1995
    - Cray Computer Corporation: bankrupt, 1995
    - Kendall Square Research: bankrupt, 1995
    - Meiko: collapsed and bought out, 1996
    - MasPar: changed name, left MPP business, 1996
- U-Net influenced VIA (Virtual Interface Architecture) standard for user-level network access
  - Intel, Microsoft, Compaq, 1998

Lightweight Remote Procedure Call

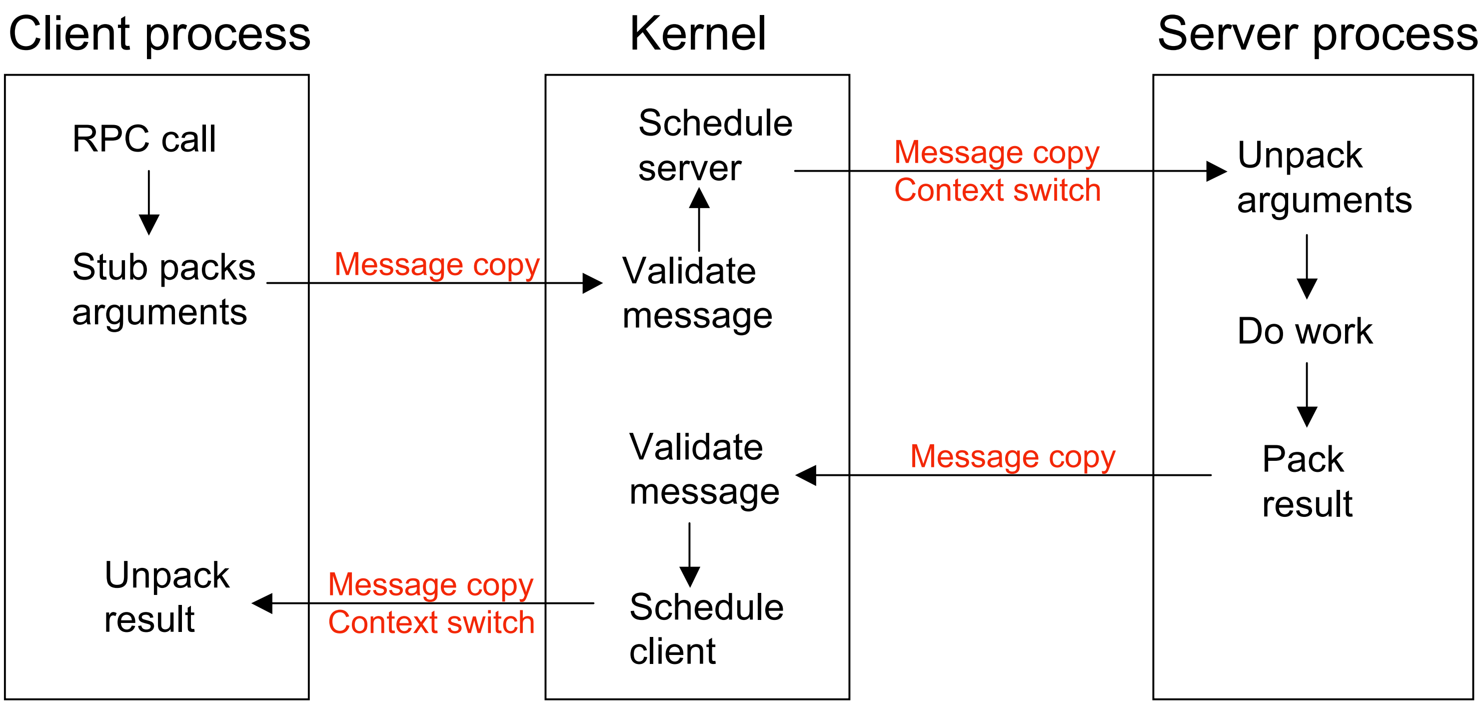
B. Bershad, T. Anderson, E. Lazowska, H. Levy
University of Washington
ACM TOCS, 1990

“Forget network overhead!”

- Most (95-99%) RPC calls are to local callees
  - i.e. same machine but different protection domain
  - (presumably not true for all systems, applications)
- Existing RPC packages treat these calls the same as “real” remote calls
  - Local RPC call takes 3.5x longer than ideal
- Lightweight RPC optimizes this common case

Traditional RPC overhead

- Costly! …stubs, message transfers, 2 thread dispatches, 2 context switches, 4 copies



Lightweight Remote Procedure Calls

- Goal: Improve performance, but keep safety
- Optimized for local RPC case
  - Handles “real” remote RPC calls using “real” RPC mechanism

Optimizing parameter passing

- Caller and server share argument stacks
  - Eliminates packing/unpacking and message copies
  - Still safe: a-stacks allocated as pairwise shared memory, visible only to client and server
    - But asynchronous updates of a-stack are possible
  - Call-by-reference arguments copied to a-stack (or to a separate shared memory area if too large)
- Much simpler client and server stubs
  - Written in assembly language

Optimizing domain crossings

- RPC gives programmer illusion of a single abstract thread "migrating" to server, then returning
  - But really there are 2 concrete threads; caller thread waits, server thread runs, then caller resumes
- In LRPC, caller & server run in same concrete thread
  - Direct context switch; no scheduling is needed
  - Server code gets its own execution stack (e-stack) to ensure safety

When an LRPC call occurs…

- Stub:
  - pushes arguments onto a-stack
  - puts procedure identifier, binding object in registers
  - traps to kernel
- Kernel:
  - Verifies procedure identifier, binding object, a-stack
  - Records caller's return address in a linkage record
  - Finds an e-stack in the server's domain
  - Points the thread's stack pointer to the e-stack
  - Loads processor's virtual memory registers with those of the server domain [requires TLB flush]
  - Calls the server's stub for the registered procedure

From [Bershad90]

LRPC Protection

- Even though server executes in client's thread, LRPC offers same level of protection as RPC
  - Client can't forge binding object
  - Only server & client can access a-stack
  - Kernel validates a-stack
  - Client and server have private execution stacks
  - Client and server cannot see each other's memory (Kernel switches VM registers on call and return)
  - Linkage record (caller return address) kept in Kernel space

Other details

- A-stacks allocated at bind time
  - Size and number based on size of procedure call argument list and number of simultaneous calls allowed
- Careful e-stack management
- Optimization with multiprocessor systems
  - Keep caller, server contexts loaded on different processors. Migrate thread between CPUs to avoid TLB misses, etc.
- Need to handle client or server termination that occurs during an LRPC call

LRPC performance

- ~3x speed improvement over Taos (DEC Firefly OS)

Times in μsec

Test	Description	LRPC/MP	LRPC	Taos
Null	The Null cross-domain call	125	157	464
Add	A procedure taking two 4-byte arguments and returning one 4-byte argument	130	164	480
BigIn	A procedure taking one 200-byte argument	173	192	539
BigInOut	A procedure taking and returning one 200-byte argument	219	227	636

From [Bershad90]

- ~25% of remaining overhead due to TLB misses after context switches
- (Caveat: Firefly doesn't support pairwise shared memory; implementation uses global shared memory, so less safety)

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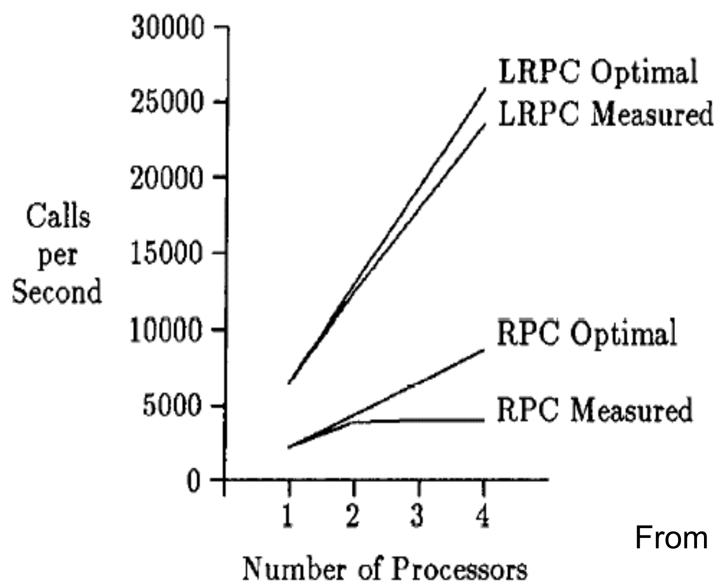
LRPC performance on multiprocessors

- Scales well on multiprocessors



From [Bershad90]

- Poor performance of RPC due to global lock

Lightweight RPC: Conclusions

- Optimize the common cases: Local RPC calls
- ~3x speed-up over conventional RPC mechanism
  - Impact on speed of apps and overall system?
  - Is MP optimization useful in practice? (how often are idle CPUs available?)
  - Additional bind-time overhead (allocating shared a-stacks)?