Unleashing Middleboxes with New Programming Abstraction

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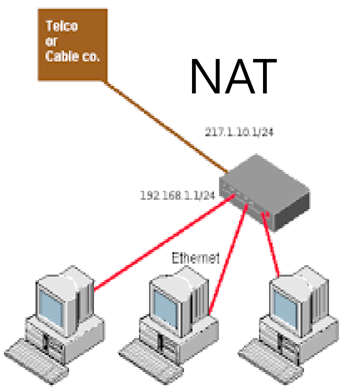
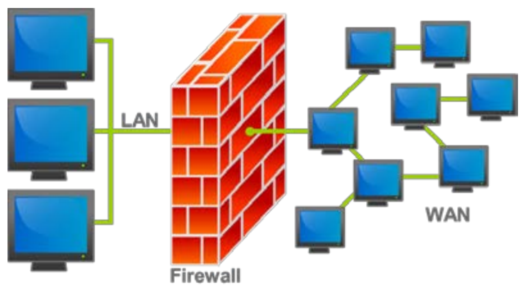
Network Middlebox

- Networking devices providing functionalities **other than** forwarding/routing
  - Switches/routers = L2/L3 devices
  - All others are called middleboxes

NAT



Firewalls



Web/SSL proxies

L7 protocol analyzers

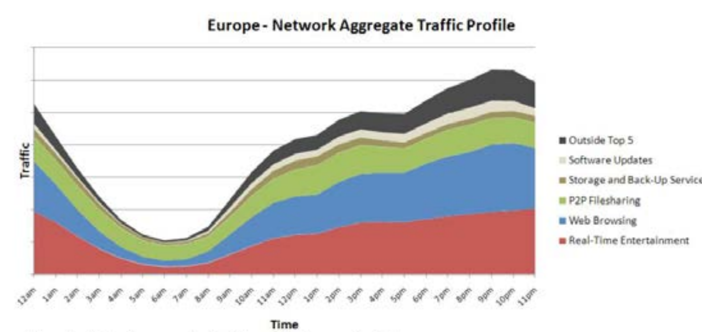


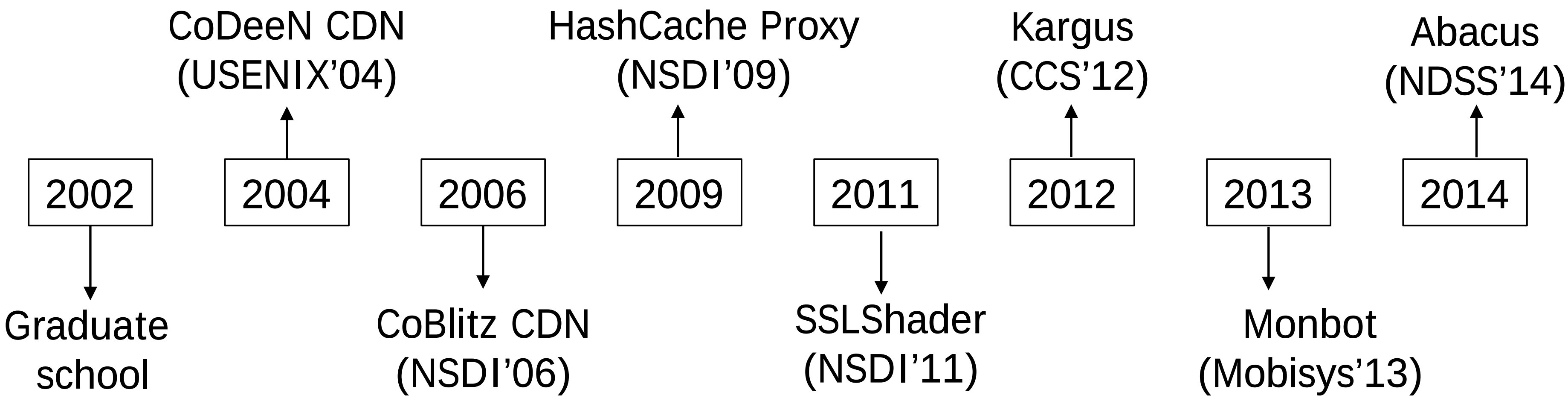
Figure 1. Network aggregate traffic profile. Source: Sandvine

IDS/IPS

SNORT®

SURICATA

My Research = Middlebox Research



- Built TCP proxies until 2011
  - Mostly scalable CDN systems
- Dived into complex (=dirty) programming environments from 2012
  - Packet + flow-level intrusion detection systems (Kargus, Haetae)
  - Packet + flow-level traffic monitoring (Monbot)
  - Packet + flow-level traffic accounting (Abacus)

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Middleboxes are Increasingly Popular

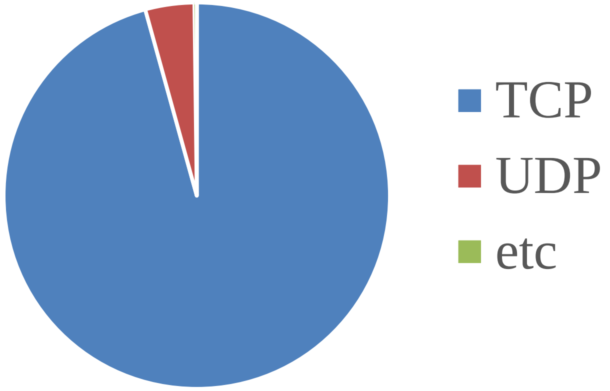
- Middleboxes are ubiquitous
  - # of middleboxes =~ # of routers [NSDI'12] (Enterprise)
  - Prevalent in cellular networks [SIGCOMM'11]
  - Network functions virtualization (NFV)
  - SDN controls network functions

- They provide key functionalities in modern networks
  - Security, caching, load balancing, etc.
  - Original Internet design lacks many features

Stateful Middleboxes Dominate the Internet

- 95+% of the Internet traffic is TCP [1]
- Most middleboxes deal with TCP traffic
  - Stateful firewalls
  - Protocol analyzers
  - Cellular data accounting
  - Intrusion detection/prevention systems
  - Network address translation

  …

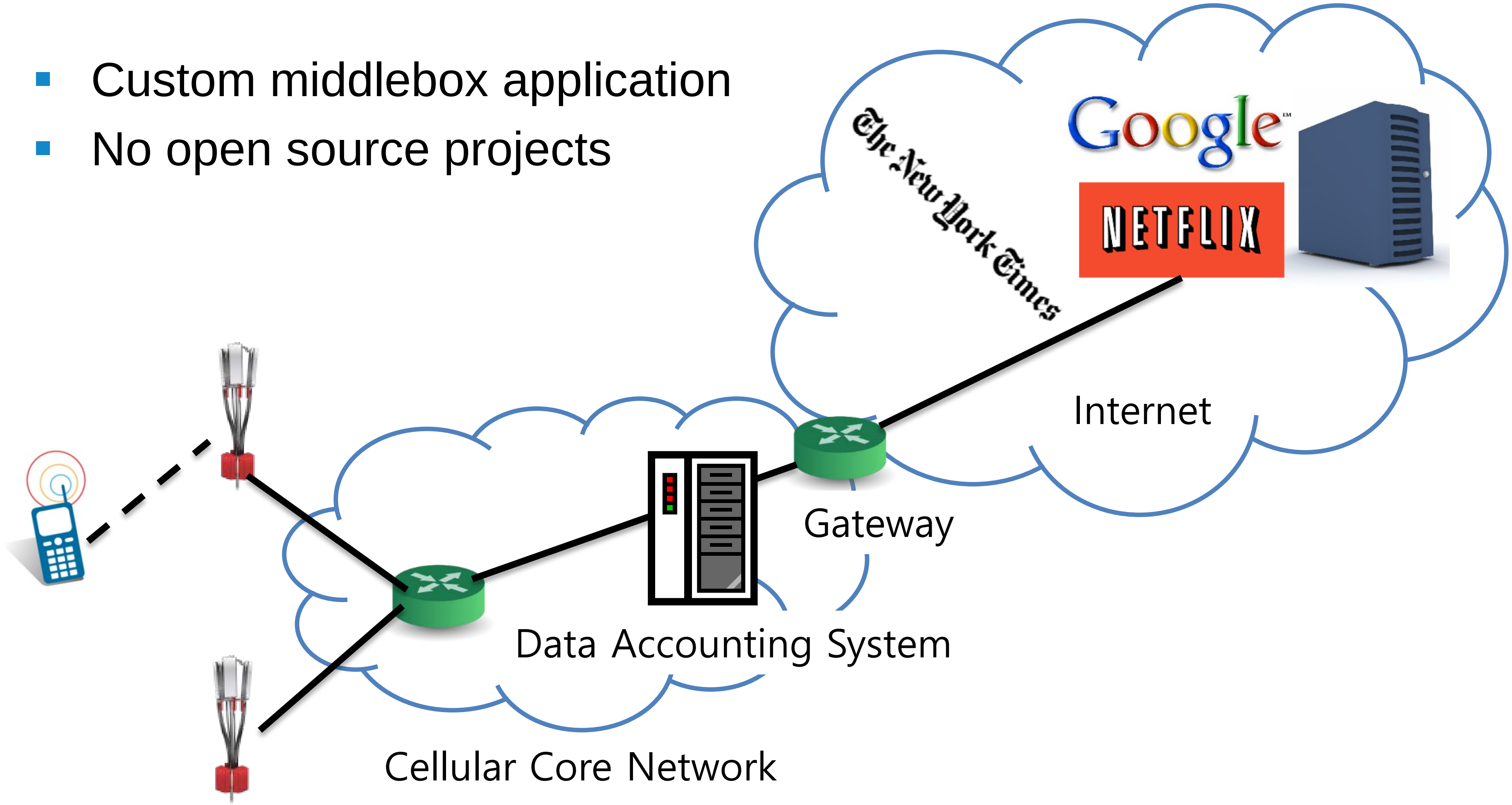


[1] Comparison of Caching Strategies in Modern Cellular Backhaul Networks, MobiSys 2013.

State management is complex and error-prone

Example: Cellular Data Accounting System

- Custom middlebox application
- No open source projects



Develop an Cellular Data Accounting System

```
For every IP packet, p
 sub = FindSubscriber(p.srcIP, p.destIP);
 sub.usage += p.length;
```

Charge for retransmission?

South Korea

```
For every IP packet, p
 if (p is not retransmitted){
   sub = FindSubscriber(p.srcIP, p.destIP);
   sub.usage += p.length;
 }
```

TCP tunneling attack? [NDSS'14]

Attack Detection

```
For every IP packet, p
 if (p is not retransmitted){
   sub = FindSubscriber(p.srcIP, p.destIP);
   sub.usage += p.length;
 } else { // if p is retransmitted
   if (p's payload != original payload) {
        report abuse by the subscriber;
   }
 }
```

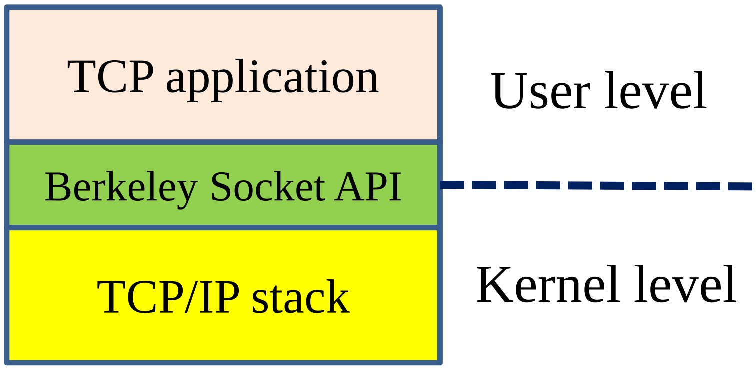
Logically, simple process!

Cellular Data Accounting Middlebox

- Core logic
  - Determine if a packet is retransmitted
  - Remember the original payload (e.g, by sampling)
  - Key: TCP flow management
- How to implement?
  - Borrow code from open-source IDS (e.g., Snort/Suricata)
  - Problem: 50~100K code lines tightly coupled with their IDS logic
- Another option?
  - Borrow code from open-source kernel (e.g., Linux/FreeBSD)
  - Problems: kernel is for one end, different from middlebox semantics
- What is the common practice? state-of-the-art?
  - Implement your own flow management
  - Problem: repeat it for every custom middlebox

Programming TCP Application

- Typical TCP applications



- Typical middleboxes?
  - Middlebox logic
  - Packet processing
  - Flow management
  - Spaghetti code?

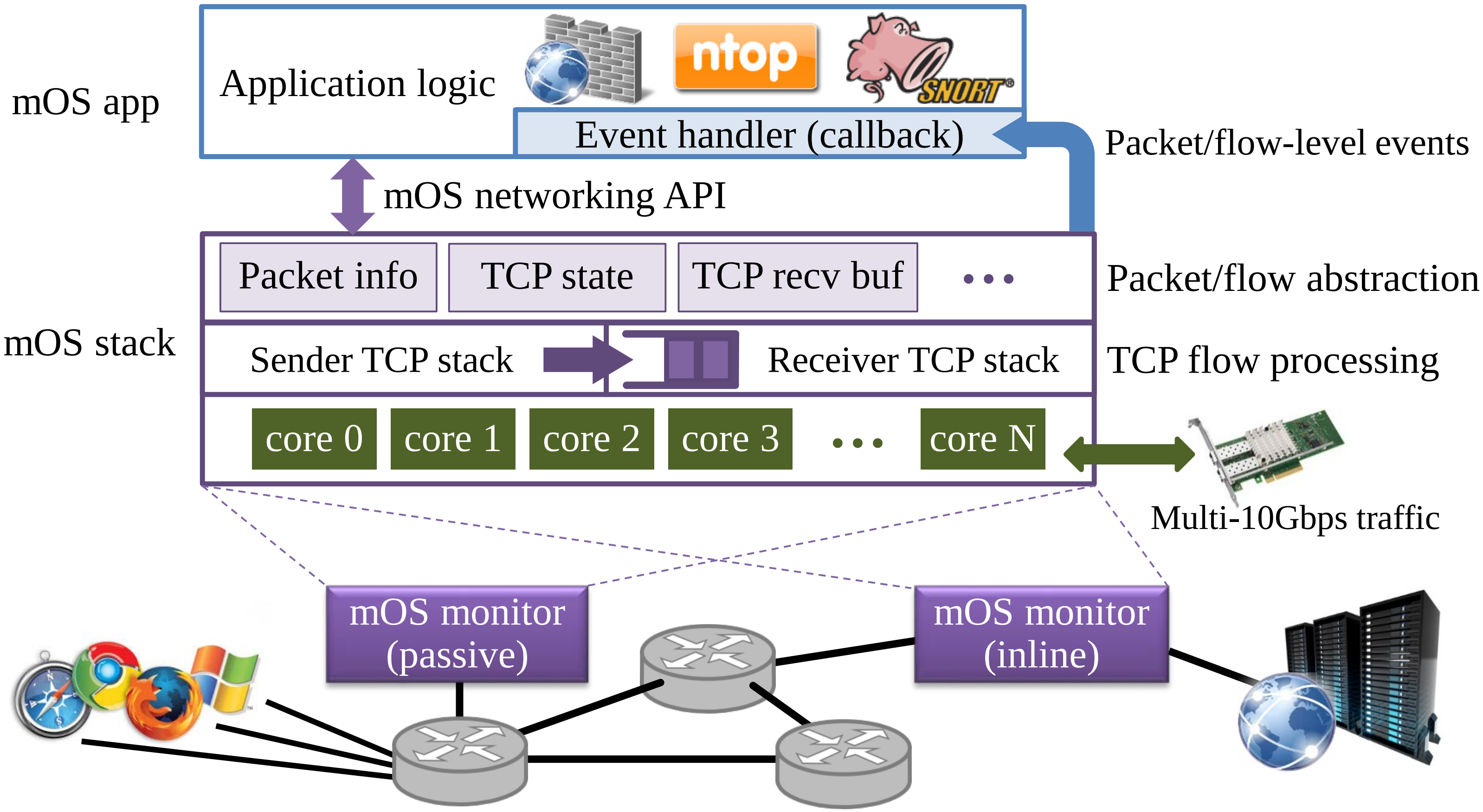
No clear separation!

- Berkeley socket API
  - Nice abstraction that separates flow management from application
  - Write better code if you know TCP
  - ***Never*** requires you to write TCP stack itself

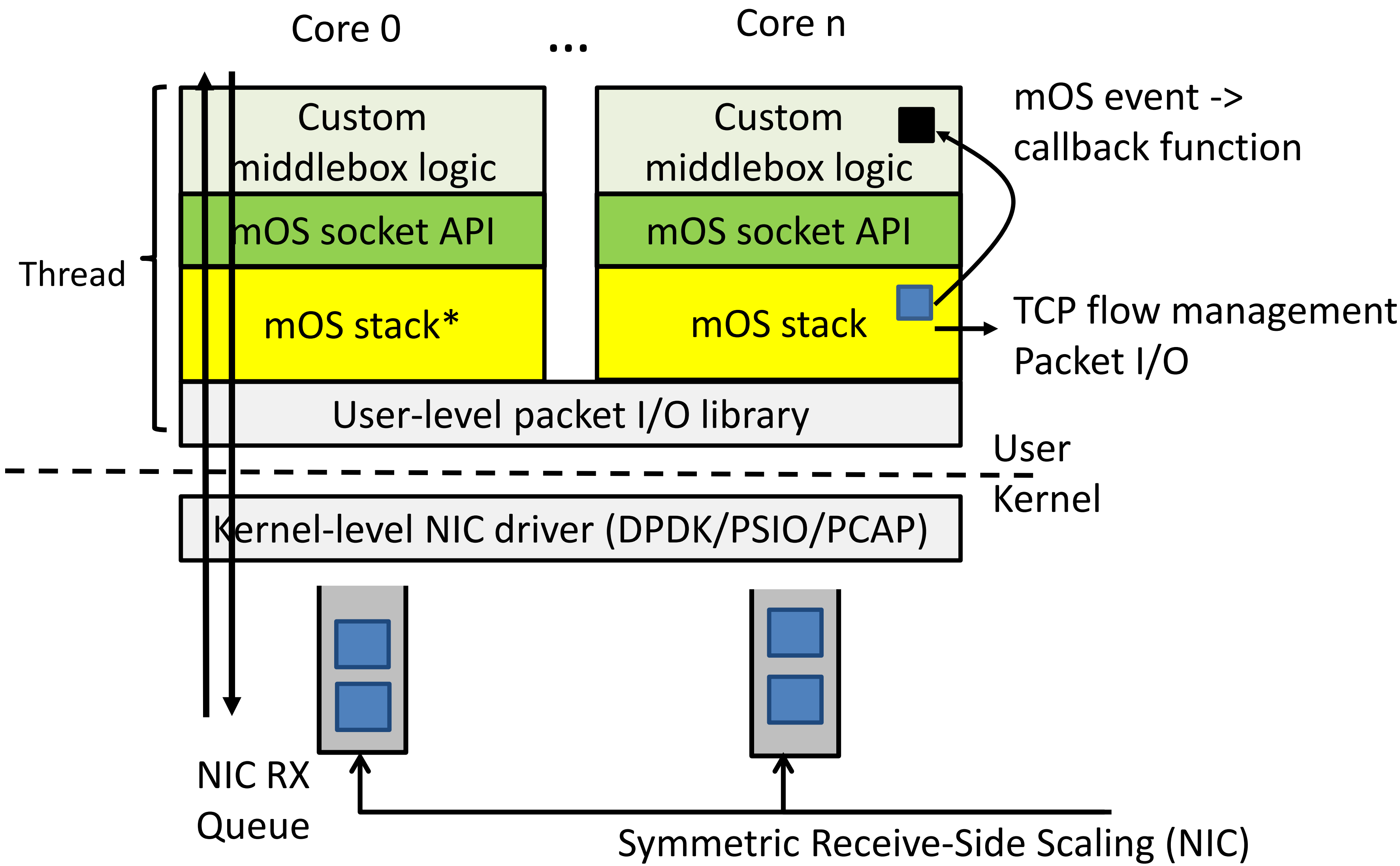
mOS Networking Stack

- Networking stack specialization for middleboxes
  - Abstraction for sub-TCP layer middlebox operations
- Key concepts
  - Separation of flow management from custom logic
  - Event-driven middlebox processing
  - Per-flow resource provisioning
- Benefits
  - Clean, modular development of stateful middleboxes
  - Developers focus on core logic rather than flow management
  - High performance flow management on mTCP stack

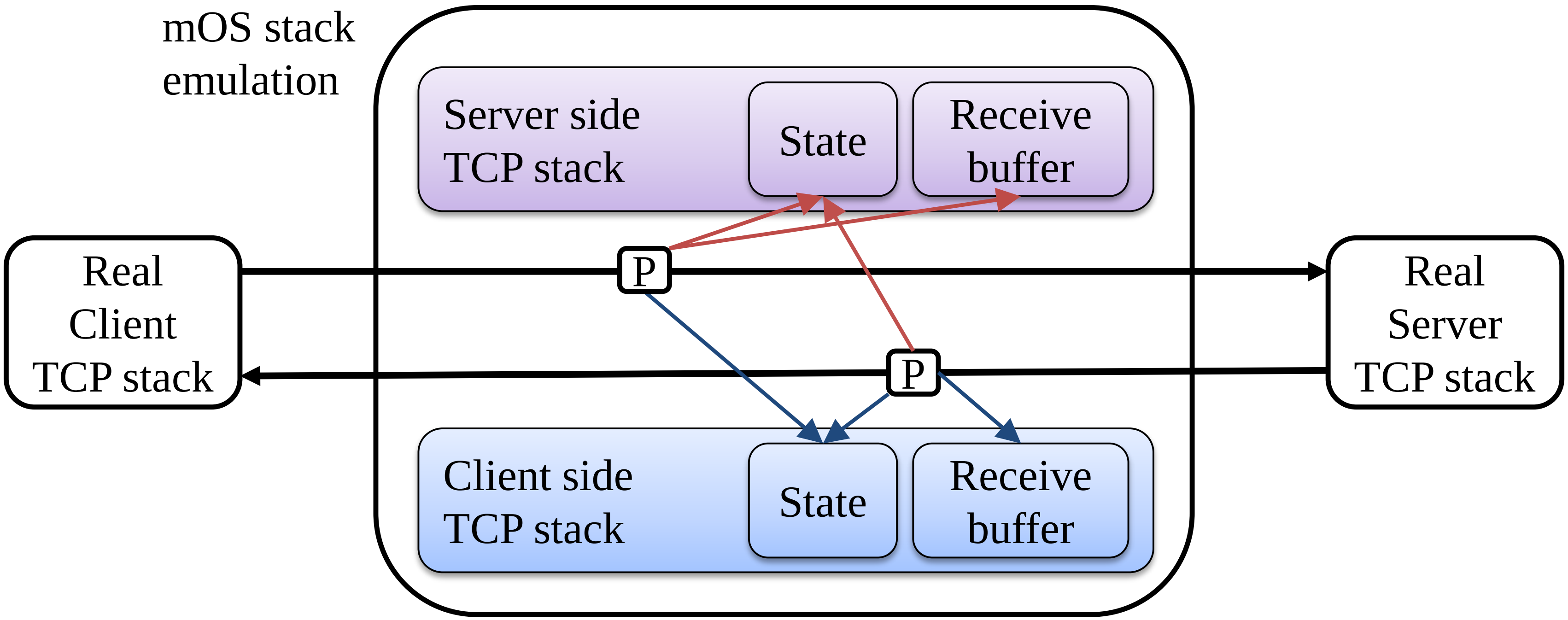
Operation Scenarios of mOS Applications



mOS Networking Stack Architecture



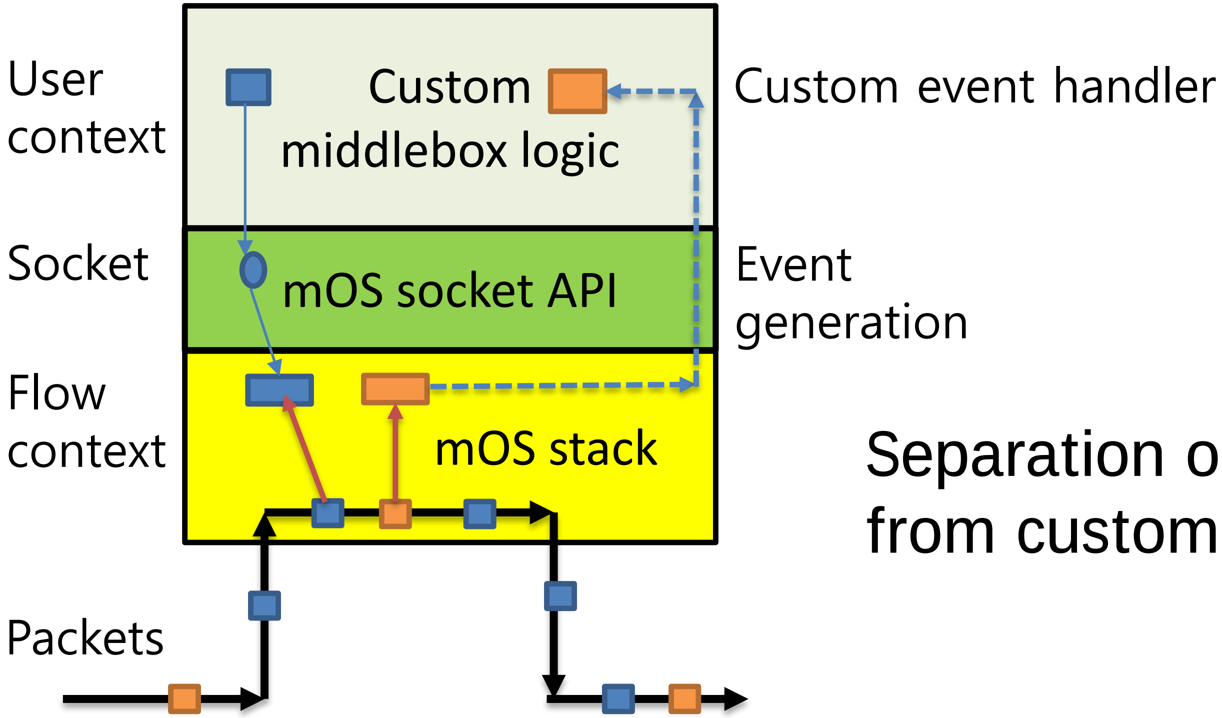
mOS Flow Management



- Dual TCP stack management
  - ***Infer*** the states of both client and server TCP stacks
- Example: a client sends a SYN packet
  - Client-side state changes from CLOSED to SYN_SENT
  - Server-side state changes from LISTEN to SYN_RECEIVED

Programming Abstraction for Traffic Monitoring

- Event programming with mOS sockets
  - Stream and raw monitoring sockets
  - Abstraction for monitoring TCP connections
  - Abstraction for monitoring IP packets



Separation of flow management from custom middlebox logic!

mOS Event

- Notable condition that merits middlebox processing
  - Different from TCP socket events
- Built-in event (BE)
  - Events that happen naturally in TCP processing
  - e.g., packet arrival, TCP connection start/teardown, retransmission, etc.
- User-defined event (UDE)
  - User can define their own event
  - UDE = base event + filter function
    - Raised when base event triggers and filter evaluates to TRUE
    - Nested event: base event can be either BE or UDE
    - e.g., HTTP request, 3 duplicate ACKs, malicious retransmission
- Middlebox logic = a set of <event, event handler> tuples

Sample Code

```
static void
thread_init(mctx_t mctx)
{
  monitor_filter ft ={0};
  int msock; event_t http_event;

  msock = mtcp_socket(mctx, AF_INET, MOS_SOCK_MONITOR_STREAM, 0);

  ft.stream_syn_filter = "dst net 216.58 and dst port 80";
  mtcp_bind_monitor_filter(mctx, msock, &ft);

  mtcp_register_callback(mctx, msock, MOS_ON_CONN_START, MOS_HK_SND, on_flow_start);

  http_event = mtcp_define_event(MOS_ON_CONN_NEW_DATA, chk_http_request);
  mtcp_register_callback(mctx, msock, http_event, MOS_HK_RCV, on_http_request);
}
```

- Initialization code
- Define a traffic filter and enforce it
- Define a user-defined event that detects an HTTP request
- Uses a built-in event that monitors a connection start event

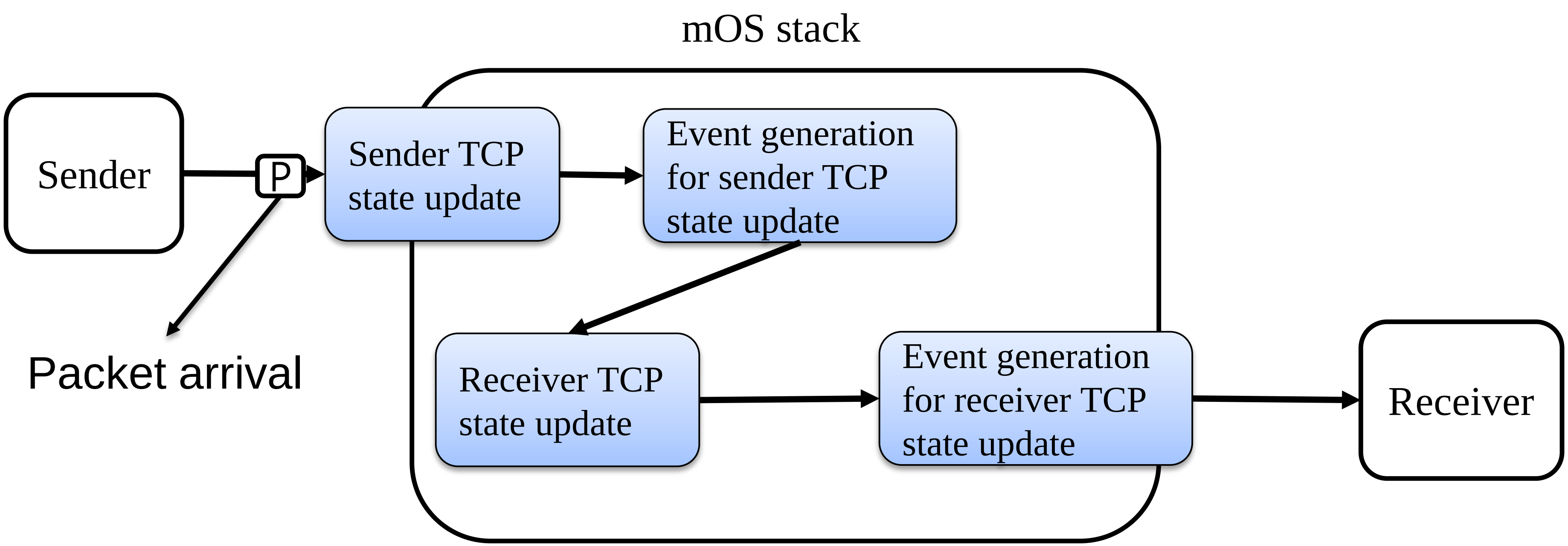
UDE Filter Function

```
static bool chk_http_request(mctx_t m, int sock, int side, event_t event)
{
   struct httpbuf *p;
   u_char* temp; int r;

   if (side != MOS_SIDE_SVR) // monitor only server-side buffer
      return false;
   if ((p = mtcp_get_uctx(m, sock)) == NULL) {
       p = calloc(1, sizeof(struct httpbuf));
       mtcp_set_uctx(m, sock, p);
   }
   r = mtcp_peek(m, sock, side, p->buf + p->len, REQMAX - p->len - 1);
   p->len += r;  p->buf[p->len] = 0;
   if ((temp = strstr(p->buf, "\n\n")) ||(temp = strstr(p->buf, "\r\n\r\n"))) {
        p->reqlen = temp - p->buf;
        return true;
   }
   return false;
}
```

- Called whenever the base event is triggered
- If it returns TURE, UDE callback function is called

Event Generation Process



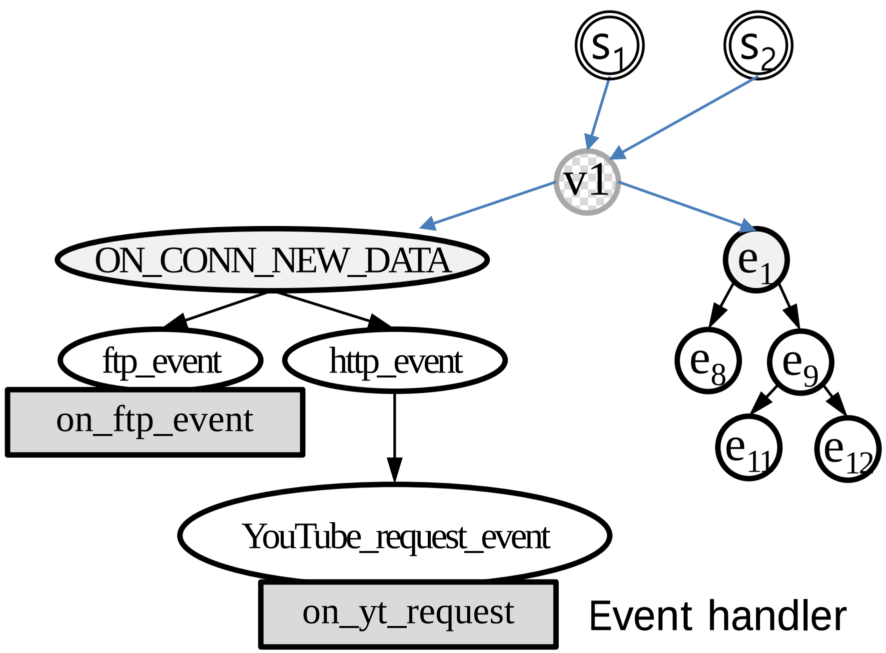
- Carefully reflects what a middlbox sees and operates on
- Based on the estimation of sender/receiver's TCP states
  - Packet arrival => sender's state has already been updated
  - Infer the receiver stack update with a new packet

Scalable Event Management

- Each flow subscribes to a set of events
- Each flow can change its own set of events over time
  - Some flow adds a new event or delete an event
  - Some flow changes the event handler for an event
- Scalability problem
  - How to manage event sets for 100+K concurrent flows?
- Observation: the same event sets are shared by multiple flows
- How to represent the event set for a flow?
- How to efficiently find the same event set?
  - When a flow updates its set of events?

Event Dependency Tree

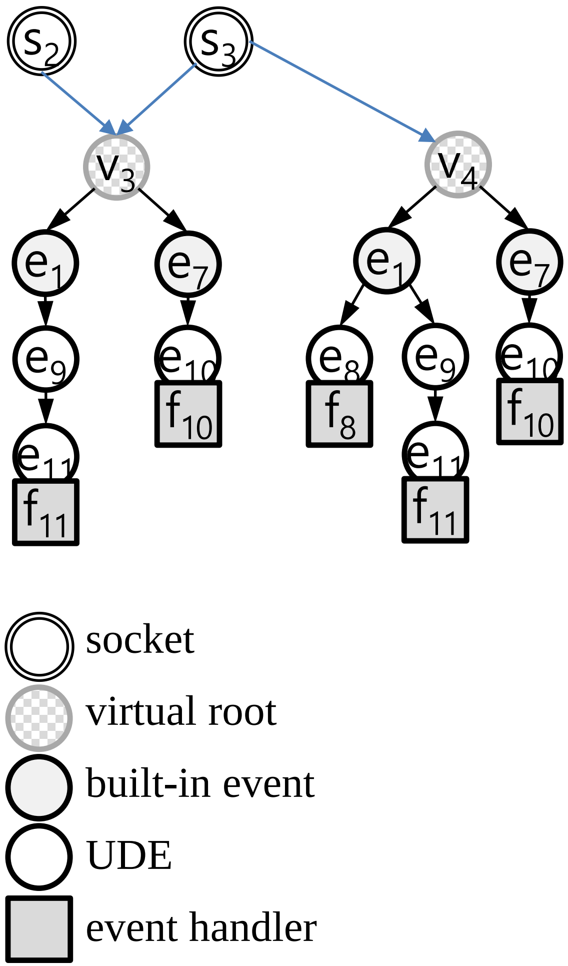
- Represents how a UDE is defined
- Start from a built-in event as root



New flow

Points to a virtual root that has a set of dependency trees

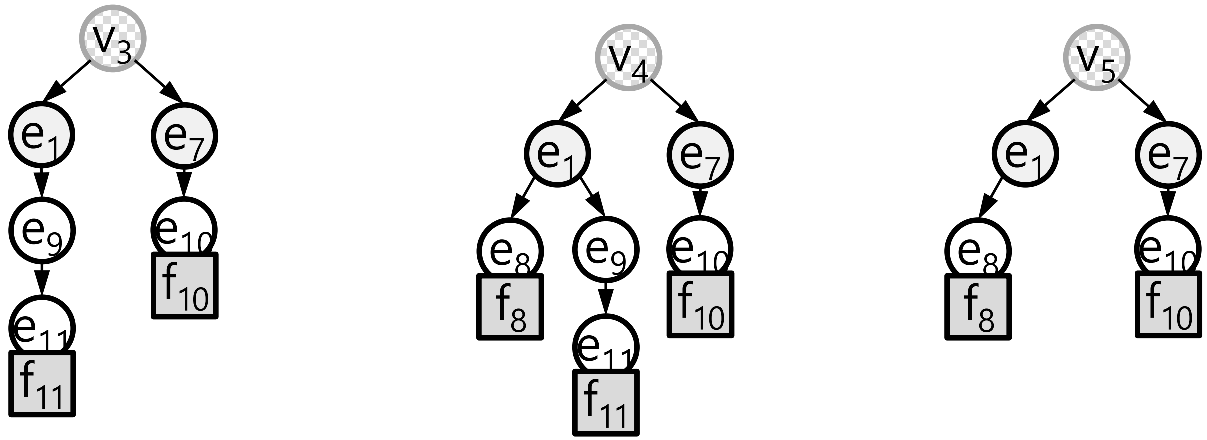
Update on Event Dependency Tree



- s3 adds a new event <e8, f8> to v3
- v4 is created with a new event and s3 points to it
- s2 adds the same event <e8, f8> to v3
- v4 already exists, but how does s2 find v4?

Efficient Search for an Event Dependency Tree

- Each event dependency tree has an ID
  - id (virtual root) = XOR sum of hash (event + event handler)
  - id (v3) = hash (e11 + f11) ⊕ hash (e10 + f10)
- New tree id after adding or deleting <e, f> from t
  - id (t') = id (t) ⊕ hash (e + f)
  - Add <e8, f8> to v3?
    - id(v4) = id(v3) ⊕ hash (e8 + f8)
  - Remove <e10, f10> from v4?
    - id (v5) = id(v4) ⊕ hash (e11 + f11)



Current mOS stack API

17 functions are currently defined

```
Socket creation and traffic filter
int      mtcp_socket(mctx_t mctx, int domain, int type, int protocol);
int      mtcp_close(mctx_t mctx, int sock);
int      mtcp_bind_monitor_filter(mctx_t mctx, int sock, monitor_filter_t ft);

User-defined event management
event_t mtcp_define_event(event_t ev, FILTER filt);
int      mtcp_register_callback(mctx_t mctx, int sock, event_t ev, int hook, CALLBACK cb);

Per-flow user-level context management
void *   mtcp_get_uctx(mctx_t mctx, int sock);
void     mtcp_set_uctx(mctx_t mctx, int sock, void *uctx);

Flow data reading
ssize_t mtcp_peek(mctx_t mctx, int sock, int side, char *buf, size_t len);
ssize_t mtcp_ppeek(mctx_t mctx, int sock, int side, char *buf, size_t count, off_t seq_off);
```

Current mOS stack API

Packet information retrieval and modification

```
int     mtcp_getlastpkt(mctx_t mctx, int sock, int side, struct pkt_info *pinfo);
int     mtcp_setlastpkt(mctx_t mctx, int sock, int side, off_t offset, byte *data, uint16_t
datalen, int option);
```

Flow information retrieval and flow attribute modification

```
int     mtcp_getsockopt(mctx_t mctx, int sock, int l, int name, void *val, socklen_t *len);
int     mtcp_setsockopt(mctx_t mctx, int sock, int l, int name, void *val, socklen_t len);
```

Retrieve end-node IP addresses

```
int     mtcp_getpeername(mctx_t mctx, int sock, struct sockaddr *addr, socklen_t *addrlen);
```

Per-thread context management

```
mctx_t  mtcp_create_context(int cpu);
int     mtcp_destroy_context(mctx_t mctx);
```

Initialization

```
int     mtcp_init(const char *mos_conf_fname);
```

Fine-grained Resource Allocation

- Not all middleboxes require full features
  - Some middleboxes do not require flow reassembly
  - Some middleboxes monitor only client-side data
  - No more monitoring after handling certain events
- Fine-control resource consumption
  - Disable flow reassembly but keep only metadata
  - Enable flow monitoring for one side
  - Stop flow monitoring in the middle
  - Per-flow manipulation with setsockopt()

```
// disabling receive buffers for both client and server stacks
int zero = 0;
if (!(config_monitor_side & MOS_SIDE_CLI))
    mtcp_setsockopt(mctx, sock, SOL_MONSOCKET, MOS_CLIBUF, &zero, sizeof(zero));
 if (!(config_monitor_side & MOS_SIDE_SVR))
    mtcp_setsockopt(mctx, sock, SOL_MONSOCKET, MOS_SVRBUF, &zero, sizeof(zero));
```

mOS Networking Stack Implementation

- Per-thread library TCP stack
  - ~26K lines of C code (mTCP: ~11K lines)
  - Based on mTCP user level TCP stack [NSDI '14]
  - Exploits parallelism on multicore systems
- Event implementation
  - Designed to scale to arbitrary number of events
  - Identical events are automatically shared by multiple flows
- Applications ported to mOS: ~9x code line reduction

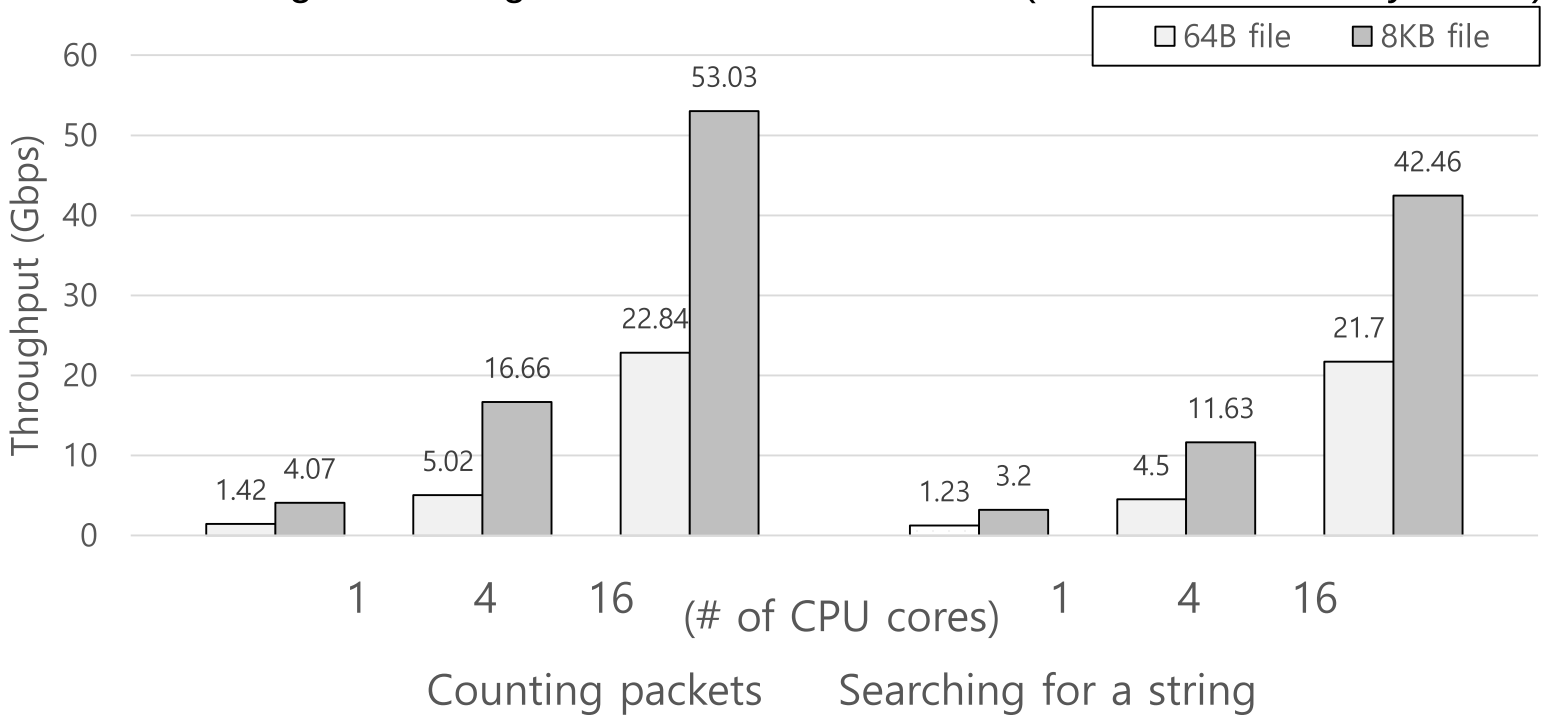
Application	Modified	SLOC	Output
Snort	884	79,889	HTTP/TCP inspection
nDPI	765	25,483	Stateful session management
PRADS	615	10,848	Stateful session management
Abacus	-	4,091→486	Detect out-of-order packet retransmission

Evaluation: Experiment Setup

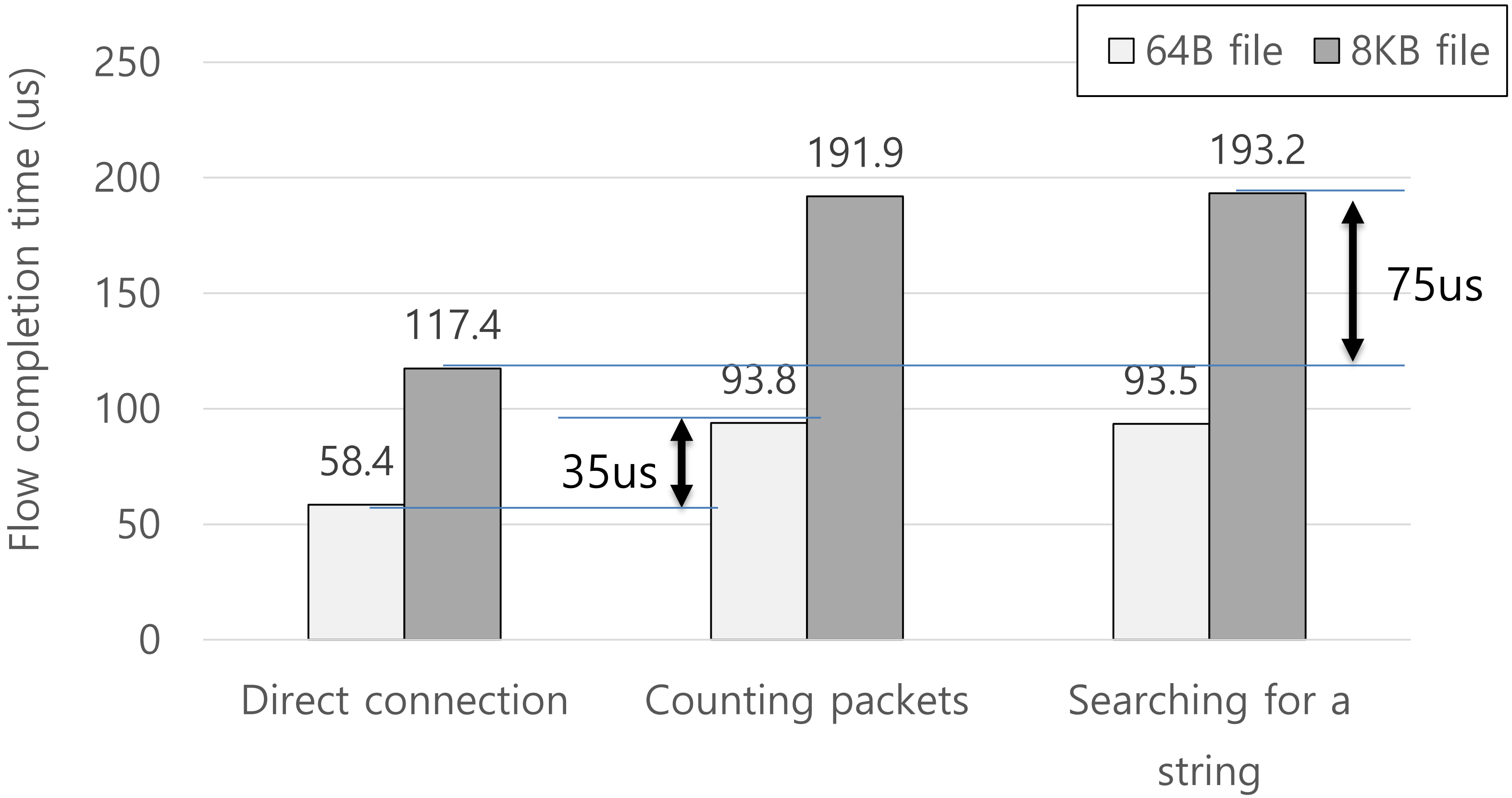
- Operating as **in-line** mode: clients ⬄ mOS applications ⬄ servers
- mOS applications with mOS stream sockets
  - Flow management and forwarding packets by their flows
  - 2 x Intel E5-2690 (16 cores, 2.9 GHz)
  - 20 MB L3 cache size, 132 GB RAM
  - 6 x 10 Gbps NICs
- Six pairs of clients and servers: 60 Gbps max
  - Intel E3-1220 v3 (4 cores, 3.1 GHz)
  - 8 MB L3 cache size
  - 16 GB RAM
  - 1 x 10 Gbps NIC per machine

Performance Scalability over # of CPU cores

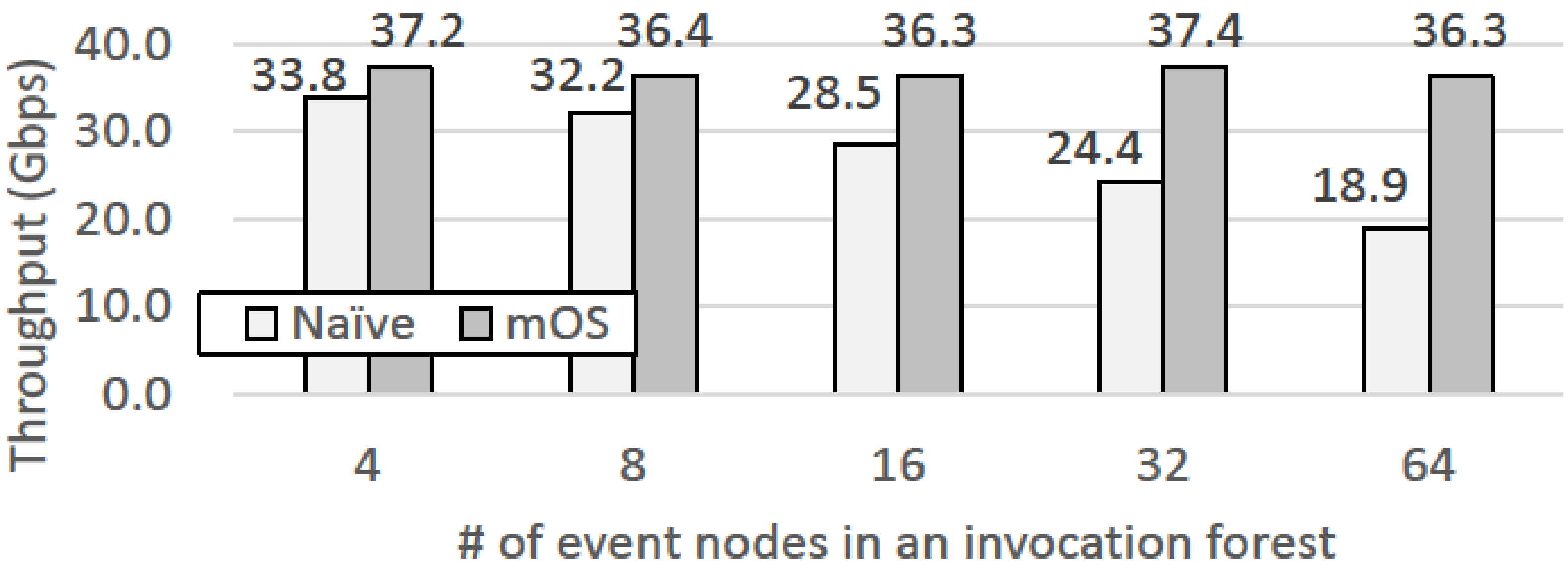
- Concurrent number of flows: 192,000
  - Each flow downloads an X-byte content in one TCP connection
  - A new flow is spawned when a flow terminates
- Two simple applications
  - Counting packets per flow (packet arrival event)
  - Searching for a string in flow reassembled data (full flow reassembly & DPI)



Latency Overhead by mOS Applications

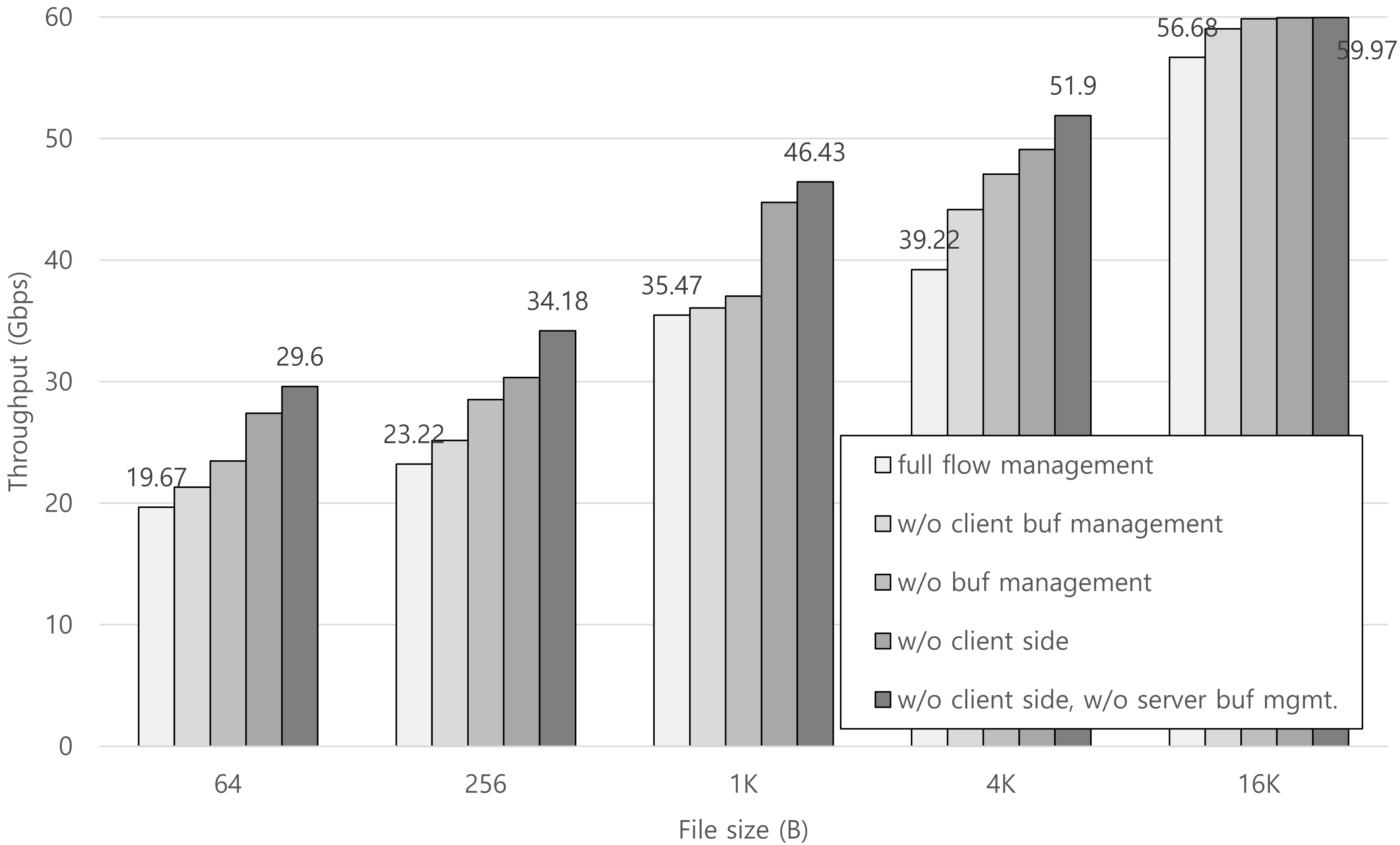


Event Management Performance



- 192,000 concurrent flows downloading large files
- mOS application searches for a string
- Increases the number of events per flow (4 to 64)
- mOS improves the performance by 3.5 to 17.3 Gbps

Performance Under Selective Resource Consumption



Real Application Performance

Application	original + pcap	original + DPDK	mOS port
Snort-AC	0.57 Gbps	8.18 Gbps	9.17 Gbps
Snort-DFC	0.82 Gbps	14.42 Gbps	15.21 Gbps
nDPIReader	0.66 Gbps	28.92 Gbps	28.87 Gbps
PRADS	0.42 Gbps	2.03 Gbps	1.90 Gbps

- Workload: real LTE packet trace (~67 GB)
- 4.5x ~ 28.9x performance improvement
- Mostly due to multi-core aware packet processing (DPDK)
- mOS additionally brings code modularity and correct flow management

Conclusion

- Current middlebox development suffers from
  - Lack of modularity
  - Lack of readability
  - Lack of maintainability
- Key idea: reusable, common flow management for middleboxes
- mOS stack: abstraction for flow management
  - Programming abstraction with socket-based API
  - Event-driven middlebox processing
  - Efficient resource usage with dynamic resource composition

Thank You!

- mOS API and documentation:
  http://www.ndsl.kaist.edu/mos/
- We will release the source code soon!
- Questions?