Packet Filters
Proposed solutions and current trends

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04/14/2010
Outline

1. Introduction
   - Overview
   - Why bother?

2. Packet Filters
   - CMU/Stanford Packet Filter (CSPF)
   - The BSD Packet Filter (BPF)
   - The Mach Packet Filter (MPF)
   - Dynamic Packet Filters (DPF)
   - The BSD Packet Filter+ (BPF+)
   - xPacket Filter (xPF)
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Packet Filter
What is it anyway?

- Kernel-level mechanism (typically, but not always)
- Allows direct access to the packets (frames?) received from the network interface controller (NIC) – “tap” NICs
- Integral part of every modern operating system (OS)
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Almost every user-space network protocol implementation utilizes such facilities

Utilized by modern network monitoring tools (tcpdump, wireshark)

Provides a critical handle to intrusion detection systems (Snort, Bro)
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Historically, the first user-level “packet filter” appeared on Xerox Alto [1]

Special-purpose process (demux) for deciding where each packet should go

Multiple context switches and three system calls per received packet

CSPF
User-level packet demultiplexing

Figure: User-level packet demultiplexing
Motivation

- User-space packet demultiplexing is expensive
- TCP/IP has yet to become the de-facto standard; experimental network protocols are flourishing
- User-level protocol implementations are necessary to allow experimentation without kernel hacking (tedious, error-prone, overwhelming) – no fancy kernel-level debugging facilities!
CSPF
Kernel-level packet demultiplexing

- Kernel facility that offers packet demultiplexing services to user-level network implementations
- Avoids the “dashed” part illustrated in Figure 1
- Flexible, protocol independent, mechanism for “selecting” packets
CSPF Design

- Uses a special-purpose language for a stack pseudo-machine (VM in nowadays)
- Applications use the language to describe arbitrary predicates for the packets they are interested in (filters are “programs” of that language)
- Instructions are made from 16-bit words that encode typical arithmetic/logical and stack-based operations
- Each filter is “executed” with a packet as input
- If the top of the stack is non-zero at the end, a copy of the packet is delivered to the process installed the filter
struct enfilter f = {
10, 12, /* priority and length */
PUSHWORD+1, PUSHLIT | EQ, 2, /* packet type == PUP */
PUSHWORD+3, PUSH00FF | AND, /* mask low byte */
PUSHZERO | GT, /* PupType > 0 */
PUSHWORD+3, PUSH00FF | AND, /* mask low byte */
PUSHLIT | LE, 100, /* PupType <= 100 */
AND, /* 0 < PupType <= 100 */
AND /* && packet type == PUP */
};

**Figure:** Example of a filter program for the Pup protocol
CSPF
User-level packet demultiplexing

Figure: The Pup protocol header (inside an Ethernet frame)
CSPF
Implementation & usage

- CSPF was implemented in 4.3BSD UNIX (DEC VAX 11/790, PDP-11)
- Usage procedure:
  1. A special-purpose character device is called from the user code via the usual system calls: open(2), close(2), read(2), write(2)
  2. Assemble some filters, similar to the one showed in Figure 2, and use the ioctl(2) system call to bind them to the character device opened in the previous step
- Evaluation of CSPF [2] indicated that kernel-level packet demultiplexing can gratefully assist user-level protocol implementations (minimize processing latency)

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4.3BSD UNIX brought a new TCP/IP implementation

- Quickly became the authoritative reference, inherited by many other free/commercial Unixes
- User-level protocol implementation declined
- Packet filtering facilities were mostly utilized for monitoring purposes
**BPF**

**Motivation**

- CSPF was designed around the ISA of old DEC machines
- Worked well on a 64K PDP-11, but performed sub-optimally on RISC-based architectures
- Why?
BPF
Motivation

- CSPF was designed around the ISA of old DEC machines
- Worked well on a 64K PDP-11, but performed sub-optimally on RISC-based architectures
- Why?
- The stack-based VM requires multiple memory references for the execution of a single filter
- Memory references result in hundreds of wasted CPU cycles (divergence between CPU clock speed and memory speed)
BPF uses a new register-based VM and a redefined language
Maintains the flexibility and generality of CSPF
Performs better on modern, RISC, machines
Two main components:
  1. the network tap
  2. packet filter
BPF
The network tap

- Part of BPF responsible for packet collection
- “Taps” NICs; for every NIC with filters installed, it calls BPF (Figure 4)
- If the packet is accepted, a copy of it (actually a part of it) is copied in a per-filter buffer
- Can batch multiple packets and deliver them with one system call (minimizes context switches)
BPF

Network tap overview

Figure: BPF architecture
Most applications tend to reject more packets than they accept
A filter should reject a packet after few instructions and avoid redundant computations
CSPF filters are modeled as trees (Figure 5)
BPF
CSPF filter model

- Simulated operand stack
- Unnecessary or redundant computations
- Cannot handle variable length packet headers
- Requires multiple instructions to deal with 32-bit fields

Figure: CSPF tree example
BPF
VM design constraints

- Protocol-independent design (handle future protocols)
- Generality (rich ISA for handling unforeseen cases)
- Simplified instruction decoding (performance)
- One-to-one matching (ideally) between VM registers and physical machine registers
ldh [12]
jeq #0x800 jt 2 jf 6
ld [26]
jeq #0xd0448b59 jt 12 jf 4
ld [30]
jeq #0xd0448b59 jt 12 jf 13
jeq #0x806 jt 8 jf 7
jeq #0x8035 jt 8 jf 13
ld [28]
jeq #0xd0448b59 jt 12 jf 10
ld [38]
jeq #0xd0448b59 jt 12 jf 13
ret #65535
ret #0

**Figure:** Example of a BPF program for “host optimus”

- **tcpdump** monitoring utility (v4.0.0) on Mac OS X 10.6
- `tcpdump -d -i en0 host optimus`
Figure: CFG representation of filter “host foo”
BPF
Implementation & usage

- BPF was implemented in 4.3BSD Tahoe/Reno UNIX, 4.4BSD UNIX, HP-UX BSD variants, SunOS 3.5...
- Currently is supported by every modern free BSD flavor (e.g., FreeBSD, NetBSD, OpenBSD) as well as by Linux
- Using BPF from application processes shared a great similarity with CSPF
- Evaluation of BPF [3] showed that it offers 20x times faster filtering than CSPF and 150x times faster packet filtering than Sun’s Network Interface Tap (NIT) – now known as Data Link Provider Interface (DLPI)

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In early 90’s research in microkernel OSes made efficient packet demultiplexing a hot topic, again.

In a microkernel OS, traditional kernel-space facilities (e.g., protocol processing) are pushed to user-level processes.

CSPF seems an adequate solution...

A single point of primary dispatch for all network traffic results in an increased communication overhead (Figure 8).
The original packet filters (CSPF and BPF) shared two primary goals: protocol independence and generality. The filters did not depend on any protocol, and future protocols could be accommodated without changing the kernel. MPF shares these two goals, as it is implemented as an extension to the base BPF language. Consequently, a packet filter program built for BPF will work with our system. Although MPF has been implemented for the Mach operating system, it requires no changes to the Mach microkernel interface, and has no Mach-specific aspects. Other BPF implementations could be extended to support MPF programs, and our implementation should port easily to other operating systems that support packet filters.

1.1 Motivation

A packet filter is a small block of code installed by users at or close to a network interrupt handler of an operating system kernel. It is intended to carry an incoming packet up to its next logical level of demultiplexing through a user-level process. An operating system kernel implements an interpreter that applies installed filters against incoming network packets in their order of arrival. If the filter accepts the packet, the kernel sends it to its recipient address space. Two packet filters, CSPF and BPF, are common in today's systems. CSPF is based on a stack machine. A CSPF program can push data from a network packet, execute ALU functions, branch forward, and accept or reject a packet. BPF is a more recent packet filter mechanism which, instead of being stack-based, is register-based. BPF programs can access two registers (\(A\) and \(X\)), an input packet (\(P[]\)), and a scratch memory (\(M[]\)). They execute load, store, ALU, and branch instructions, as well as a return instruction that specifies the size of the packet to be delivered to the target endpoint. BPF admits a somewhat more efficient interpreter than CSPF [McCanne and Jacobson 93].

With a microkernel, where traditional operating system services such as protocol processing are implemented outside the kernel, the original packet filter provided a convenient mechanism to route packets from the kernel to a dedicated protocol server. Scalability was not important because relatively few packet filters would ever be installed on a machine (typically two: one to recognize IP traffic and another to recognize other traffic). Unfortunately, as a single point of primary dispatch for all network traffic resulted in communication overhead for microkernel-based systems substantially larger than for monolithic systems, in which the protocols are implemented in the kernel [Maeda and Bershad 92]. To address this problem, we have decomposed the protocol service architecture so that each application is responsible for its own protocol processing [Maeda and Bershad 93]. That is, every address space contains, for example, a complete TCP/IP stack. Figure 1 illustrates the structural differences between the two different protocol strategies.

Figure: Protocol processing approaches in microkernel OSes
MPF Details

- Kernel-level facility that efficiently dispatches incoming packets to multiple endpoints (e.g., address spaces)
- Support for multiple active filters (scalable)
- Flexible and generic (5 additional instructions in BPF)
- Why not use BPF then?
Kernel-level facility that efficiently dispatches incoming packets to multiple endpoints (e.g., address spaces)

Support for multiple active filters (scalable)

Flexible and generic (5 additional instructions in BPF)

Why not use BPF then?

1. **scalability issues.** The dispatching overhead increases with the number of different endpoints

2. **cannot handle multi-packet messages.** BPF cannot identify packet fragments (it cannot “remember” what it has seen)
MPF

Efficient dispatching

- MPF exploits structural and logical similarity among different, but not identical filters
- Identifies filters that have common “prefixes”
- **Collapses** common filters into one
- Uses associative matching for dispatching to the final communication endpoint (Figure 9)
Introduction
Packet Filters

MPF
Associative model

Figure: MPF associative model
/ Part (A) */
begin ; MPF identifier
ldh P[#OFFETHER_TYPE] ; A = ethernet type field
jeq #ETHER_TYPE_IP, L1, fail; if no IP fail
L1: ld P[#OFF_DST_IP] ; A = dst IP address
jeq #dst_addr, L2, fail ; if not from dst_addr fail
L2: ldb P[#OFFPROTO] ; A = protocol
jeq #IPPROTO_TCP, L3, fail ; if not TCP, fail
L3: ldh P[#OFF_FRAG] ; A = fragmentation flags
jset #!DF_BIT, fail, L4 ; if DF_bit = 1, fail
L4:
/* Part (B) */
ld P[#OFF_SRC_IP] ; A = src IP address
st M[0] ; M[0] = A
ldxb 4 * (P[OFF_IHL] & 0xf) ; X = TCP header offset
ldh P[x + #OFFSRC_PORT] ; A = src TCP port
st M[1] ; M[1] = A
ldh P[x + #OFF_DST_PORT] ; A = dst TCP port
/* Part (C) */
ret_match_imm #3, #ALL ; compare keys with M[0..2]
key #src_addr ; if matched, accept the
key #src_port ; whole packet. If not,
key #dst_port ; reject it
fail:
ret #0

Figure: Example of an MPF program for a TCP/IP session
MPF
Dispatching multi-packet messages

- Typical case when IP fragmentation is used
- A large TCP/UDP packet is divided into multiple IP fragments
- Only one has the TCP/UDP header
- MPF response:
  1. *filter state*. Per-filter “state” buffers
  2. additional *instructions* for handling fragments. *Postpone* the dispatch decision for a while
Critique

- 8x faster than CSPF and 4x faster than BPF [4]
- But...

MPF
Critique

- 8x faster than CSPF and 4x faster than BPF [4]
- But...
- MPF was designed for Mach 3.0 (microkernel OS). No port exists for other OSes, yet
- It demands from the filters to have specific structure in order to optimize them (collapse into one). Reduced flexibility in expressions
- Associative search instructions make extensive use of BPF’s scratch memory. Depending of how memory accesses are emulated, MPF might lead in memory spills – recall BPF’s original purpose

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DPF
Motivation

- Similar to MPF:
  - Minimize end-to-end latency of user-level protocol stacks
  - Applications can explore new networking mechanisms without kernel modifications
  - Usually trade flexibility for performance
- Fast and flexible message demultiplexing is important
- Proposed solutions sacrifice one for the other
  - BPF: flexible and general, but not scalable
  - MPF: less flexible, more scalable
Design & architecture

- Kernel-level facility for rapid packet demultiplexing
- New, carefully-designed, declarative language
- Aggressive dynamic code generation
- Performance is equivalent, or can exceed, hand-coded demultiplexers
DPF
Packet filter language

- Declarative language; general, flexible, protocol agnostic
- Filters are described as sequences of boolean comparisons (atoms) linked by conjunctions
- Set of active filters are stored into a prefix tree data structure (Figure 11)
DPF
Trie structure (prefix tree)

Figure: A trie for keys "A", "to", ..., "inn" (courtesy of Wikipedia)
Introduction
Packet Filters

The Packet Filter
The BSD Packet Filter
The Mach Packet Filter
Dynamic Packet Filters
The BSD Packet Filter+
xPacket Filter

Figure: Example of a DPF program for a TCP/IP session

```c
{
    # check ethernet header
    (12:16 == 0x8) && # IP datagram?
    # skip ether header (14 bytes)
    (SHIFT(6 + 6 + 2)) &&

    # check IP header
    (9:8 == 6) && # check protocol : TCP is 6
    # check IP src addr (192.12.69.1)
    (12:32 == 0xc00c4501) &&

    # skip IP header (assume fixed sized; 20 bytes)
    (SHIFT(20)) &&

    # check TCP header

    # check source port (2 bytes)
    (0:16 == 1234) &&

    # check destination port (2 bytes)
    (2:16 == 4321) &&
}
```
DPF
Filter handling

- New filters are stored in the trie along with path with the longest prefix match – similar to MPF, this leads in prefix “collapse”
- Duplicate checks are eliminated
- Filters that cannot merge with the trie, or they form a new one, are connected with it using an or branch
- “Forest” of prefix trees
DPF
Dynamic code generation

- Eliminates interpretation overhead by compiling into native code
- Aggressive optimization
  - Runtime information is encoded in the instruction scheme (e.g., constants that are known only after a connection is established)
  - Fast disjunctions. Avoids hash-based lookups for disjunctive filters that have been merged, but the necessary checks are relatively few
  - Atom coalescing (Figure 13)
  - Alignment estimation
  - Bounds checking
# TCP header before coalescing
(0:16 == 1234) && # check source port
(2:16 == 4321) # check destination port

# TCP header after coalescing
(0:32 == 283182290) # 283182290 ==
# ((4321 << 16) | 1234)

**Figure:** Coalescing example
DPF
Critique

- 25–50x times faster than MPF [5]
- But...

DPF
Critique

- 25–50x times faster than MPF [5]
- But...
- DPF was designed for Aegis (exokernel OS). No port exists for other OSes, yet
- Relies on VCODE dynamic code generation system (portability?)
- No side-effects; what about variable-length headers? multi-packet messages?

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BPF has limitations (reason to have MPF, DPF, ...)
Decision tree reduction is NP-complete
But...
BPF+
Motivation

- BPF has limitations (reason to have MPF, DPF, ...)
- Decision tree reduction is NP-complete
- But...
- Filters have a *regular* structure that can be exploited from optimization frameworks
- MPF, DPF use local optimizations and they do not eliminate common subexpressions
  - Restrict the expressibility of the filters by imposing a specific structure (MPF)
  - Rely on the programmer to express the filter in an optimized and compact way (DPF)
**BPF+**

**Motivation**

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  - Rely on the programmer to express the filter in an optimized and compact way (DPF)
- Bottom line: we need *global* filter optimization
BPF+ Features

- Exploits data-flow algorithms for generalized optimization among filters (Figure 14)
- Eliminates *redundant* predicates
- Allows for matching header fields against one another
- Enables arithmetic operations on header words before matching
- Can generate native code using just-in-time (JIT) compilation
- Relies upon a refined VM (more GPR, branch instructions can use register values)
BPF+
Generalized optimization

Figure: Typical (DPF) CFG for “(src host X and dst host Y) or (src host Y and dst host X)”
BPF+
Architecture overview

Figure: BPF+ architecture
Filter specifications written in a high-level predicate language (*libpcap*)

- 
- Typical compiler structure (*front end, back end*)
- Straightforward code generator (on the fly translation to the intermediate SSA form)
- The CFG is guaranteed to be acyclic (forward branches only)
- Optimizer eliminated redundancies and performs register allocation
Misses juxtaposition (BPF, MPF, DPF, ...) [6]
No per-filter state (MPF)
No side-effects on user-level state variables or packets
No backward branches (cannot implement loops, counting)
Return value is still true/false. What about #predicates matched?

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xPF
Motivation & enhancements

- Need for more elaborate computational capabilities
- Engine for *executing* monitoring applications in kernel-space rather than a demultiplexing mechanism
- Persistent memory (per-filter)
- Support for backward branches
xPF was implemented in OpenBSD [7]
No comparative evaluation
No safety guarantees because of the backward branches