Securing Network Traffic Tunneled Over Kernel managed TCP/UDP sockets

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Agenda

- What problem are we trying to solve?
  - Privacy, integrity protection, authentication of traffic that gets tunneled over kernel managed TCP and UDP sockets
- Options at socket layer: TLS, DTLS
  - Pros and cons
- Options at the IP layer: IPsec
  - Pros and cons
- Ongoing and future work

What problem are we trying to solve?

- Security for kernel-managed TCP and UDP sockets
  - VXLAN, GUE, Geneve, and other NVO3 solutions
  - RDS-TCP, KCM: Application traffic sent over PF_RDS/PF_KCM socket, which gets tunnelled over TCP in the kernel
- Security, with reasonable performance
  - Crypto has an unavoidable cost, but the rest of the perf should be streamlined
- Security, without regressing on Failover requirements for Cluster/HA

Typical model for kernel TCP/UDP sockets

- Application data from sender: can come from Virtual Machine, DB application, HTTP/2..
- Typically gets encapsulated in some protocol specific header (VXLAN, GUE, Geneve, RDS) that tracks control plane state (Tenant ID, VNI, OVS state, RDS port numbers..)
- Tunneled in the kernel over a UDP/TCP socket
- Receiver parses control plane header and delivers to the appropriate sender (tenant VM, DB application)

Privacy and Security Concerns

- Traffic tunneled over kernel sockets goes out in the clear today.
- As we scale multi-tenant Cloud environments, we have multiple tenants sharing the same physical infrastructure
- Attack vectors that need to be considered:
  - Protecting tenant payload and tunneling protocol header (privacy, integrity protection, authentication)
  - Protecting the control plane (TCP/IP, for RDS-TCP and KCM)

Privacy for tenant traffic

- Traffic that can traverse long internet paths: attackers should not be able to snoop/impersonate end-points
  - encrypt tenant data using encryption parameters that have been securely installed on both end-points after appropriate authentication.
- Typical solution to provide this is by using TLS/DTLS at the socket layer
- TLS has some attractive properties
  - Per-user authentication
  - Implemented at the application level, not the kernel. So easier support in multiple environments
- But there are some issues with using TLS/DTLS with kernel sockets

Challenges to using TLS/DTLS with RDS-TCP

- Cannot use DTLS/TLS directly on new socket types like PF_RDS and PF_KCM.
- No TLS in the kernel
- TLS is a complex protocol- handshake and control-plane is complex
- Can we move the TLS control-plane (including Handshake) to user-space, and just use the TLS negotiated keys for encryption in the kernel?
  - Attempted by Netflix for acceleration of encrypted `sendfile`()
  - Basis of recent kTLS RFC

Netflix/OCA

- Improve sendfile() throughput of encrypted data for the Netflix OpenConnect Appliance
  - https://people.freebsd.org/~rrs/asiabsd_2015_tls.pdf
- Traditional implementation: web-server gets client request for object on disk, retrieves object into a local buffer, encrypts/sends over TLS on network.
- Netflix optimization: when the client request comes in, issue sendfile() call on the file descriptor and socket descriptor: data would then never leave kernel address space.

Netflix/OCA: TLS based encryption in kernel

- Kernel needs to encrypt the data before sending it out on the socket to the network
- Netflix model: TLS session parameters are negotiated in user-space, and pushed down via socket options to the kernel
  - TLS session management in user-space
  - Encryption in kernel
- Primary goal is to provide faster encryption, not full support for a kernel TLS.

Netflix/OCA: TLS customizations

- Netflix/OCA ran into many questions when implementing this proposal
  - Encrypted messages like “Finished” can arrive before CCS has been processed, and keys are in place, so kernel data plane may end up having to buffer a lot of data
  - How will the kernel handle re-keying?
  - “..when you consider .. that messages in the TCP stream may arrive out of order, adding TLS for both sending and receiving adds a lot of complexity to the kernel” [Netflix/OCA]
- Netflix/OCA proposal only implements sender side of TLS, since it is primarily interested in accelerating sendfile()

Netflix/OCA results

- The Netflix/OCA finds that the performance improvements were not that significant for BSD
- Even if a Linux implementation could achieve better perf, the issues identified in the OCA experiment remain
  - Splitting the protocol into a control plane and a data plane is not what TLS intends, and such a split will result in new forms of asynchronicity.
- For securing kernel TCP/UDP sockets, we want a complete security solution.

HA/Failover in the split TLS model

- CCS, Re-keying etc: Control plane changes state, data-plane needs to be correctly synchronized with that change.
- HA/failover: data-plane can restart. Control plane needs to be in tandem with that. Examples:
  - Address/service migration for TCP connection, RDS-TCP module restart
  - RDS resets connection because it detects spurious headers or other compromise.

Protecting from TCP attacks

- TLS only secures the application data.
- TCP connection is still exposed and vulnerable to RST attacks, sequence number attacks
- Attacks to TCP throw off the state machine in RDS-TCP reassembly.
  - Sender depends on TCP ack# to determine when it can take a dgram off the resend queue. Bogus sequence number reinjection is not acceptable.
- HA: when the RDS-TCP connection breaks, we try to re-connect today. If reconnecting, we should restart authentication, and preferably re-key.

Alternatives to TLS?

- TLS encrypts/authenticates at the socket layer
- Alternative to TLS: IPsec
- IPsec encrypts/authenticates at the IP layer
  - Fully integrated into the Linux kernel
  - Mature implementation; Interfaces between key management and kernel are well-understood.

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What is IPsec?

- IP Security
- Suite of protocols for encryption (adding a "ESP" header) and Authentication (adding a "AUTH" header)
- ESP/AH are each applied to a "Security Association" (SA) that is pushed to kernel from user-space.
  - SA is defined by Admin.
  - Parameters: IP endpoint addresses, ports, IP protocol. Ports, protocol can be wild-cards
  - MAY be a TCP/UDP 4-tuple
- IKE (Internet Key Exchange) protocol for establishing keys (using pre-shared key, CA etc) from user-space

IPsec encryption with ESP

- Encrypts data (either TCP/UDP payload for transport mode, or IP packet for tunnel mode)
  - Confidentiality, data-origin authentication, integrity, anti-replay service.
- Adds an ESP header with an “Security Parameter Index” (SPI) and sequence number
  - SPI uniquely identifies a “Security Assocation” (SA) for which the security parameters (keys, crypto algo etc) are defined. Thus SPI essentially identifies a flow for IPsec
  - Sequence number is used to protect against replay attacks
- Adds an ESP trailer which contains the “original protocol” of the data that was encrypted.

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IPsec Transport vs Tunnel mode

- IPsec Transport mode: ESP/AH transforms apply to L4 (TCP or UDP) header and payload.
  - Protects TCP header
  - L3/routing information is not modified
  - Typically used for host-host IPsec
- IPsec tunnel mode: IP packet is encapsulated inside another IP packet. The IPsec transforms are applied to the inner (original) IP packet.
  - Protects IP and TCP header of the original packet
  - Typically used for VPNs
  - Routing information MAY be modified
- For Cloud/Cluster solutions IPsec Transport mode is sufficient as we do not wish to modify routing information.

Feasibility of using IPsec for kernel TCP/UDP sockets

- IPsec meets the security requirements for kernel TCP/UDP sockets. Linux supports a mature implementation, with all the needed features, and a variety of key distribution functions via the IKEv2 implementation.
- But what is the performance profile?
- We will now look at some performance instrumentation experiments, the findings, and ongoing work to evaluate IPsec impact on performance

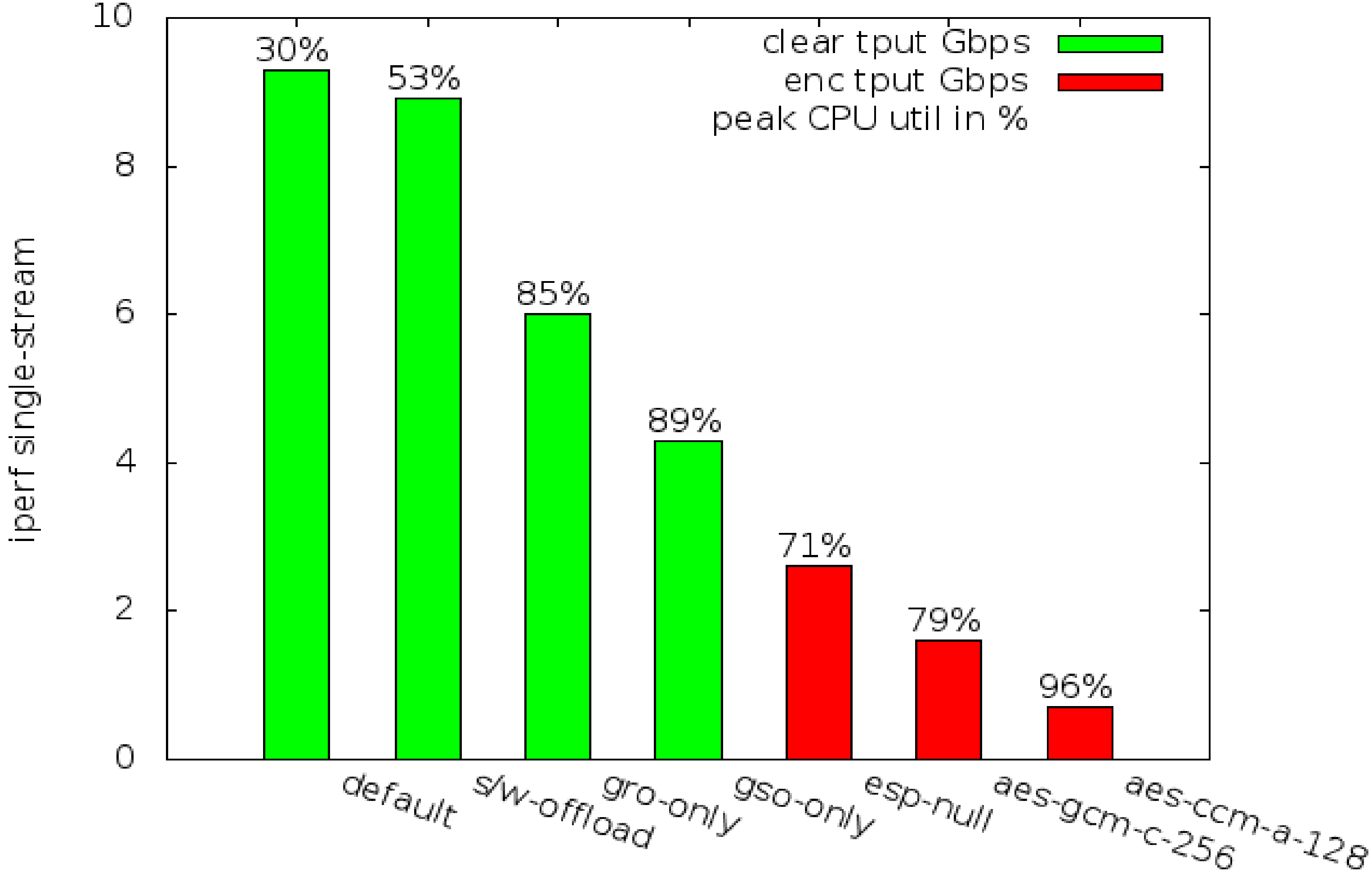
IPsec performance evaluation environment

- Evaluate iPerf single-stream throughput and CPU utilization profile for a 10G line on an X5-4, using Intel's ixgbe driver
- Test permutations generated with the following parameters
  - With/Without TSO, GSO, GRO
  - Clear traffic vs IPsec with null encryption (thus no crypto overhead)
  - IPsec with 2 types of encryption:
    - AES-GCM-256 (Galois Counter Mode, keysize 256)
    - AES-CCM-128 (Counter with CBC MAC, keysize 128)
    - GCM: parallelizable in hardware. CCM: smaller gate-count but typically slower implementation.

IPsec test cases used for analysis

- Clear traffic, defaults for TSO, GRO, checksum offload
- Clear traffic, GSO on sender, GRO on receiver, no checksum offload on sender
- Clear traffic, GRO-only: no segmentation or checksum offload on sender, GRO on receiver
- Clear traffic, GSO-only: no TSO on sender, no GRO on receiver
- IPsec with null-encryption, default settings
- IPsec with AES-GCM-256, ICV len 16
- IPsec with AES-CCM-128, ICV len 8

IPsec impact on performance



Observations:

- Loss of Segmentation/Receive offload (TSO, GSO, GRO has a severe performance penalty even in the absence of IPsec
- IPsec transforms TCP/UDP payload.
  - MUST be done after segmentation
  - Stack implicitly disables TSO, GSO, GRO today when IPsec is engaged
- Manual Rx side iPerf placement and IRQ balancing was needed for IPsec cases. (loss of RSS/RFS/RPS for IPsec)
- Some inefficiencies in the way IPsec code manages memory

Retaining offload benefits for IPsec

- GSO/GRO are software offload implementations, and can be extended easily to apply IPsec transform after segmentation/receive offload
  - Work with Steffen Klassert for s/w offload
- IPsec transform after GSO segmentation
- Decrypt before GRO coalesce.

IPsec offload to GSO/GRO

- Steffen Klassert is working on patches to offload IPsec to GSO/GRO for Tunnel Mode
- Extended that patch-set to work for Transport Mode

	Throughput Gbps (peak CPU Utilization %)	
	ESP-NULL	AES-GCM-256
Baseline	2.6 Gbps (71%)	2.17 Gbps (83%)
GSO/GRO offload	8 Gbps (95%)	4.2 Gbps (100%)

Reducing CPU utilization

- Hardware offload to NIC TSO? Many Intel 10G NICs (Niantic, Twinville, Sageville) already support IPsec offload but Linux stack needs enhancements
  - Microsoft Driver API that uses Intel IPsec offload: https://msdn.microsoft.com/en-us/library/windows/hardware/ff556996%28v=vs.85%29.aspx

Receive side flow hashing

- When IPsec was enabled on the flow, had to manually do IRQ and process-CPU pinning to achieve the best performance
- On the receiver, this is achieved when the IRQs and iPerf process are pinned to separate CPUs.
- For clear traffic, this balancing would have been automatically achieved by RFS/RSS
  - RFS/RSS: Increase performance by steering packets to different queues based on filters applied to packet to determine flows
- RFS/RSS flow determined from TCP/UDP 4-tuple
- TCP/UDP header is encrypted by IPsec so port numbers are not available to RSS/RFS.

RSS/RFS/RPS for IPsec

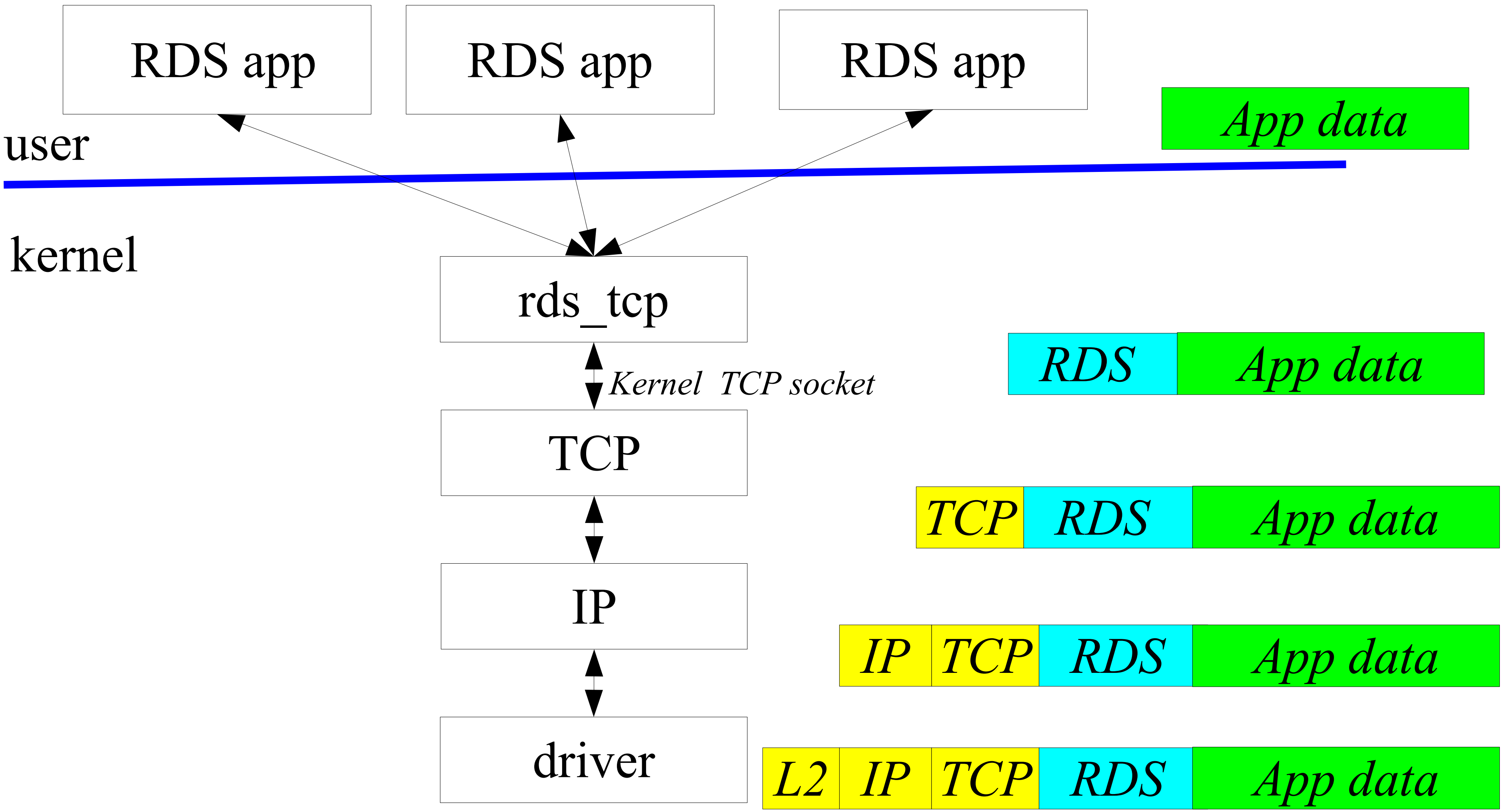
- Can we use the SPI for flow hashing? Yes.
- SPI identifies the SA (Security Association), i.e., the “flow” for Ipsec.
  - Already used by Tx path via proto_ports_offset()
- Drivers should be able to return a rxhash based on SPI, at least for ESP.
- Need to work the software RSS/RFS to do the same

Ongoing work

- Hardware offload of IPsec
  - Will reduce cpu util
  - NIC has to be updated with SA
  - Microsoft APIs give some clues about what is already available
- Better Rx flow hashing in h/w and s/w
- S/W tweaks to IPsec code paths to keep latency down
- Others? More benchmarks, IPsec offload deployment from within a VM..

Backup Slides

Case study: RDS-TCP Architectural Overview



Synchronizing the control and data plane in the split TLS model

- Either client can send a “CCS” (ChangeCipherSpec) mid-stream, and the protocol mandates that both sides MUST start using the new parameters immediately after a CCS.
  - Encrypted data arrives before CCS has been procesed
- Re-keying
- HA/failover: data-plane can restart. Control plane needs to be in tandem with that.

What does each transform look like for RDS? Clear vs TLS encrypted packet

Clear (unencrypted packet):

Eth header	IP header; proto TCP 10.0.0.1 → 10.0.0.2	TCP hdr	TCP Payload

TLS encrypted packet

Eth header	IP header; proto TCP 10.0.0.1 → 10.0.0.2	TCP hdr	TCP payload

Effect of IPsec transforms

IPsec transport-mode encaps (ESP only)

Eth header	IP header; proto ESP 10.0.0.1 → 10.0.0.2	ESP header SPI, seq#	TCP hdr & payload	ESP trailer proto TCP

IPsec tunnel mode. The outer src/dst are determined by VPN config. They would be the 10.0.0.1 and 10.0.0.2 if no VPN gw is used.

Eth hdr	Outer IP header; Proto ESP osrc → odst	ESP header SPI, seq#	Orig TCP/IP packet for 10.0.0.1 → 10.0.0.2, with TCP hdr and payload	ESP trailer Proto (4) IP-in-IP

Acronyms: TSO, GSO, GRO

- Segmentation Offload: Split up the TCP packet into segments as late as possible at the sender during TCP transmission for better performance.
- Can be done in the NIC (TSO) or in software (GSO) just before handing off TCP/IP packet to NIC
  - http://www.linuxfoundation.org/collaborate/workgroups/networking/gso
- GRO: Generic Receive Offload: mirrors GSO on the receiver. “Identical” packets that match on constraints applied to the MAC/TCP/IP headers are merged and passed up the stack
  - https://lwn.net/Articles/358910/

Acronyms: RPS/RFS/RSS

- What is RPS/RFS/RSS
  - RPS: Receive Packet Steering, RFS: Receive Flow Steering
  - RSS: Receive Side scaling, hardware equivalent of RPS
  - See Documentation/networking/scaling.txt
- Increase performance by steering packets to different queues based on filters applied to packet to determine flows.
- Flow is typically a hash function applied to IP and/or TCP/UDP headers (port numbers)
- TCP/UDP header is encrypted by IPsec so port numbers are not available to RSS/RFS.