Implementation of the Internet Checksum

TSVWG, IETF113

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Internet checksums

- Checksums are 16-bit values
- Protocols define a two byte checksum field
- Computation: Ones’ complement two byte sum from a start offset (e.g. first byte of TCP header) to end offset (e.g. end of packet)
- Sender and receiver perform same algorithm and get same answer if data not corrupted
- Examples: TCP and UDP checksum, IPv4 header checksum, GRE checksum

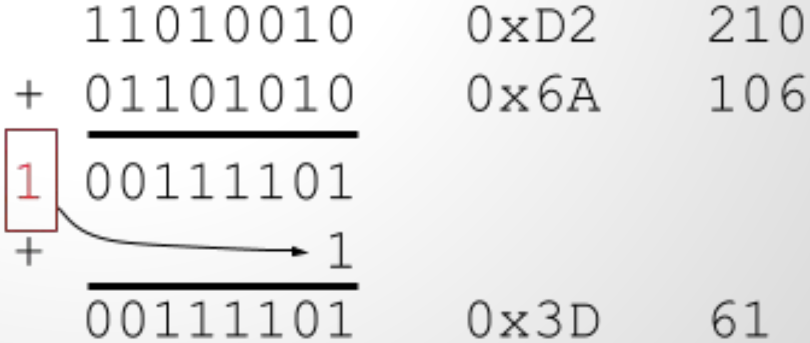
Checksum computation

The Internet checksum employs **ones' complement sum** to validate correct receipt of data (indicate by $\oplus$)

1. Add two binary numbers of some word size
2. Add generated carry (1 or 0) to the sum to get result

Example:

0xD2 $\oplus$ 0x6A=0x3D



	11010010	0xD2	210
+	01101010	0x6A	106
1	00111101		
+	1		
	00111101	0x3D	61

Arithmetic properties

- 0xFFFF mathematically equivalent to 0
  - `A⟴0xFFFF = A⟴0 = A`
- Commutative and associative
  - `A⟴B = B⟴A, (A⟴B)⟴C = A⟴(B⟴C)`
- Checksum subtraction via “not” operation
  - `A⟴~A = 0xFFFF // i.e checksum 0`
- Checksums of a larger word size can be folded to a smaller word size with equivalency

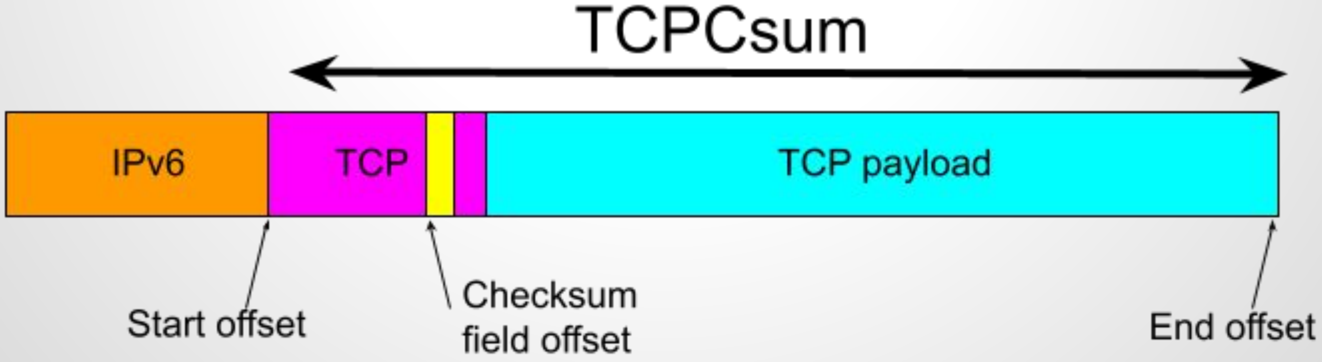
Setting an Internet checksum

1) Perform one's complement sum from start offset (e.g. first byte of TCP header) to end offset (e.g. end of packet)

2) Include pseudo header in sum if required by protocol

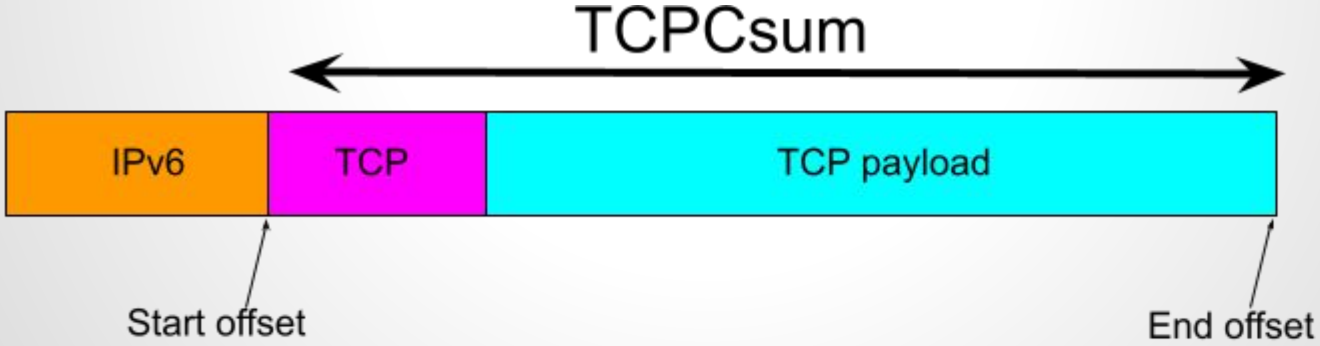
3) Not the result (i.e.. Res=~Sum)

4) Set the result in the checksum field



Validating a protocol checksum

1) Perform one's complement sum from start offset (e.g. first byte of TCP header) to end offset (e.g. end of packet)
2) Include pseudo header in sum if required by protocol
3) If result == 0xFFFF then checksum is valid



TCPCsum ⊕ PseudoHdrCsum = 0xFFFF?

Optimizing checksum calculation

- Computation of the Internet checksum is pretty expensive (add ins. & cache misses)
- Checksum over small data, like IP header checksum, warrants specialized instructions
- Checksum over large payload, like TCP checksum, warrants checksum offload

Pseudo code (naive method)

```
sum16 = 0;
if (len % 2 == 1) { data[len] = 0; len++ }
for (i = 0; i < len / 2; i++) {
    sum16 = sum16 + *(__u16 *)&data[i*2];
    if (sum16 > 0xffff) {
        sum16 = sum & 0xffff;
        sum++;
    }
}
```

Optimization: add larger words

- Consider computing checksum over four 16 bit words: $A_0 A_1 A_2 A_3$

$$S = A_0 \mathbin{\oplus\!\!\!\!\!\rightarrow} A_1 \mathbin{\oplus\!\!\!\!\!\rightarrow} A_2 \mathbin{\oplus\!\!\!\!\!\rightarrow} A_3$$

- Perform ones’ complement 32-bit addition

$$T_0 T_1 = A_0 A_1 \mathbin{\oplus\!\!\!\!\!\rightarrow} A_2 A_3$$

- “Fold checksum” to 16 bits

$$S = T_0 \mathbin{\oplus\!\!\!\!\!\rightarrow} T_1$$

Pseudo code for 32-bit words

```
sum32 = 0;
for (i = 0; i < len / 4; i++) {
   sum32 = sum32 + *(__u32 *)&data[i*4];
   if (sum32 > 0xFFFFFFFF) {
      sum32 = sum32 & 0xFFFFFFFF;
      sum32++;
   }
}
/* “Fold checksum to 16 bits */
```

Folding a checksum to 16 bits

- Convert 32-bit 1s’ complement value to 16 bits
- Ones’ complement add the low word to the high word

```
sum16 = sum32 & 0xFFFF;
sum16 = sum16 + (sum32 >> 16)
if (sum16 > 0xFFFF) {
    sum16 = sum16 & 0xFFFF;
    sum16++;
}
```

Add with carry instruction

- Many CPU architectures have specialized instruction to perform one’s complement add
- In x86:
    - Carry bit is in a processor control register
    - Plain **add** instructions set carry bit
    - **adc** performs an addition and includes the value of the carry bit

Example: IPv4 header (8 byte words)

```
//Computing checksum (64-bit checksum)
movq (%1), %0     // Load first eight bytes
adcq 8(%1), %0    // Add second word to first, set carry
adcl 16(%1), %0   // “Add with carry” third word
adcq $0, %0       // Add in final carry

// Folding 64-bit checksum to 16 bits
movl %0, %2       // Fold to thirty-two bits
shrq $32, %0
adcl %2, %0       // Fold to sixteen bits
movw %0, %2
shrl $16, %0
adcw %w2, %w0
adcw $0, %w0
```

Checksum delta

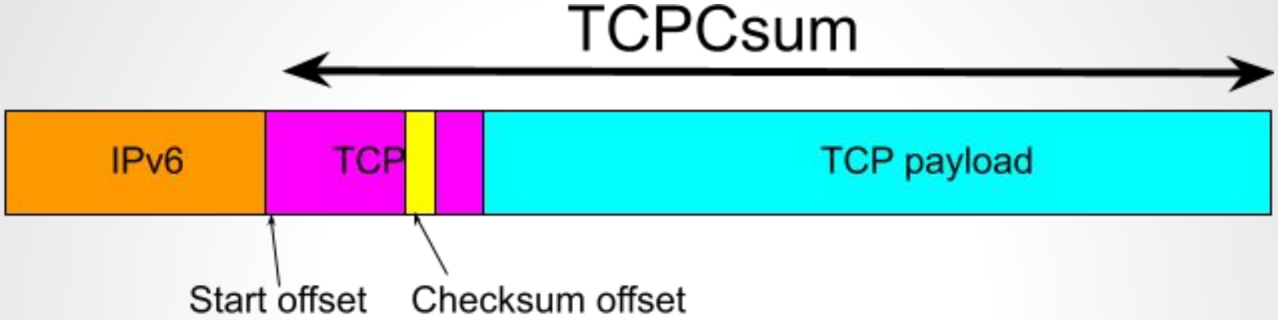
- A change in one field of packet can be offset by another to maintain correct checksum
  - e.g. updating TCP checksum for NAT addr changea
- Example: consider: $A_0 A_1 A_2 A_3 \ldots A_N$
  - where A_3 is checksum field. Support contents of A_1 are modified to make A'_1 then
  - $\text{Delta} = \sim(A'_1 \oplus \sim A_1) = A_1 \oplus \sim A'_1$
  - $A'_3 = A_3 \oplus \text{Delta} = A_3 \oplus (A_1 \oplus \sim A'_1)$
  - Which gives: $A_0 A'_1 A_2 A'_3 \ldots A_N$

Checksum offload

- Preferred method: protocol agnostic offload
  - Any Internet checksum for arbitrary protocols
  - Work for encapsulated checksum
  - Validate multiple checksums in one packet

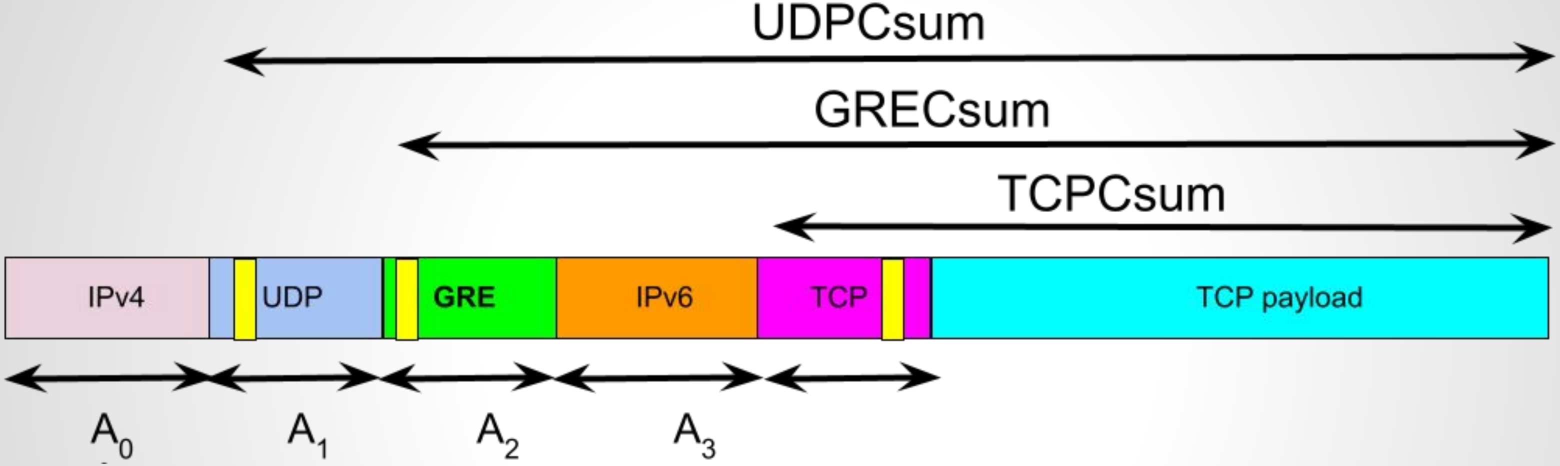
- Legacy method: protocol specific offload
  - Device performs checksum validation of specific protocol combinations
  - E.g. may handle simple TCP/IP but not TCP/IP/GRE/IP

Transmit checksum offload



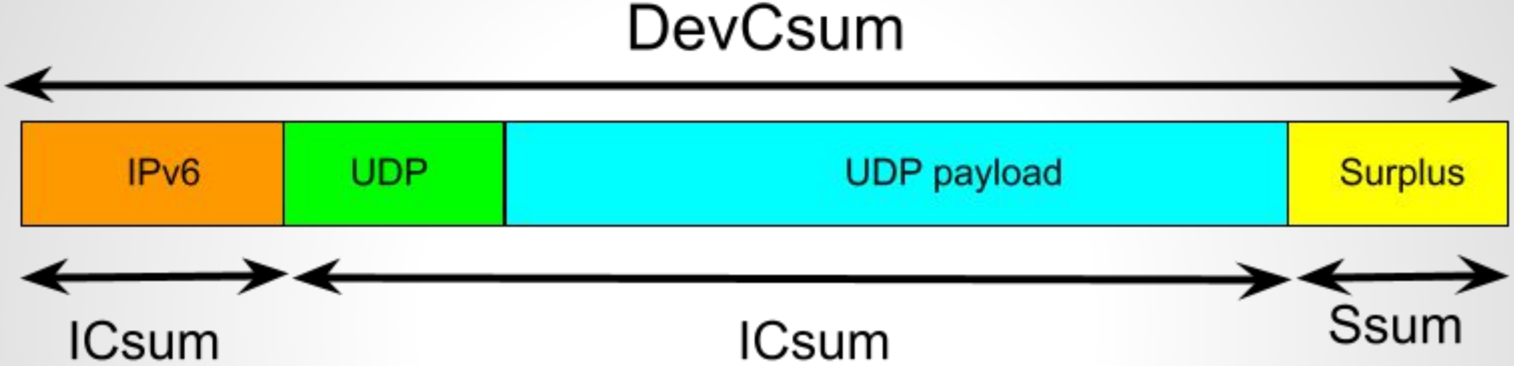
1. Host OS specifies offset of checksum field and starting offset of checksum coverage in a transmit descriptor
2. Host initializes checksum field to “not” of 1s’ complement sum of pseudo header (or 0xFFFF if no pseudo header)
3. Device performs sum from start offset to end of packet and writes result in checksum field

Multi-TX csum (local csum offload)



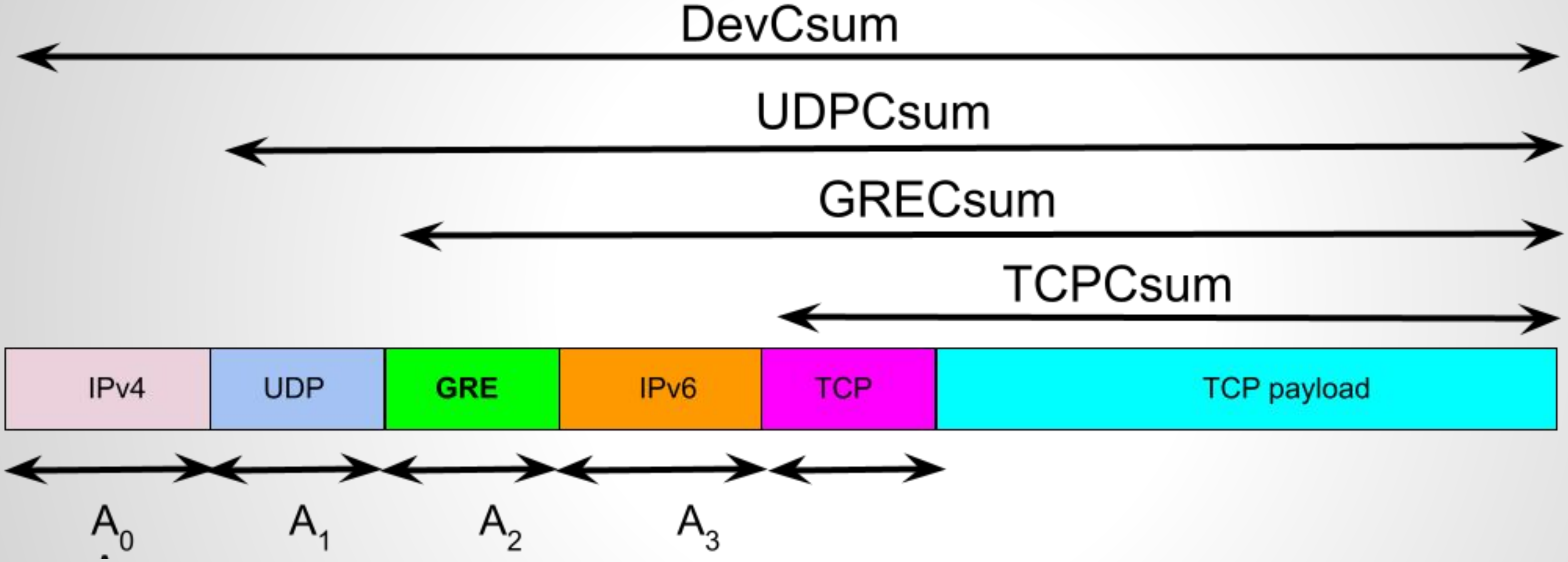
1. Offload inner most checksum (i.e. TCP in this ex.)
2. $\text{TCPCsum} = \text{0xFFFF} \oplus \sim\text{PHsum} = \sim\text{PHsum}$
3. $\text{GRECsum} = \text{A2} \oplus \text{A3} \oplus \text{TCPCsum} = \text{A2} \oplus \text{A3} \oplus \text{PHsum}$
4. $\text{UDPCsum} = \text{A1} \oplus \text{GRECsum} = \text{A1} \oplus \text{A2} \oplus \text{A3} \oplus \text{TCPCsum}$

Rx csum offload (csum complete)



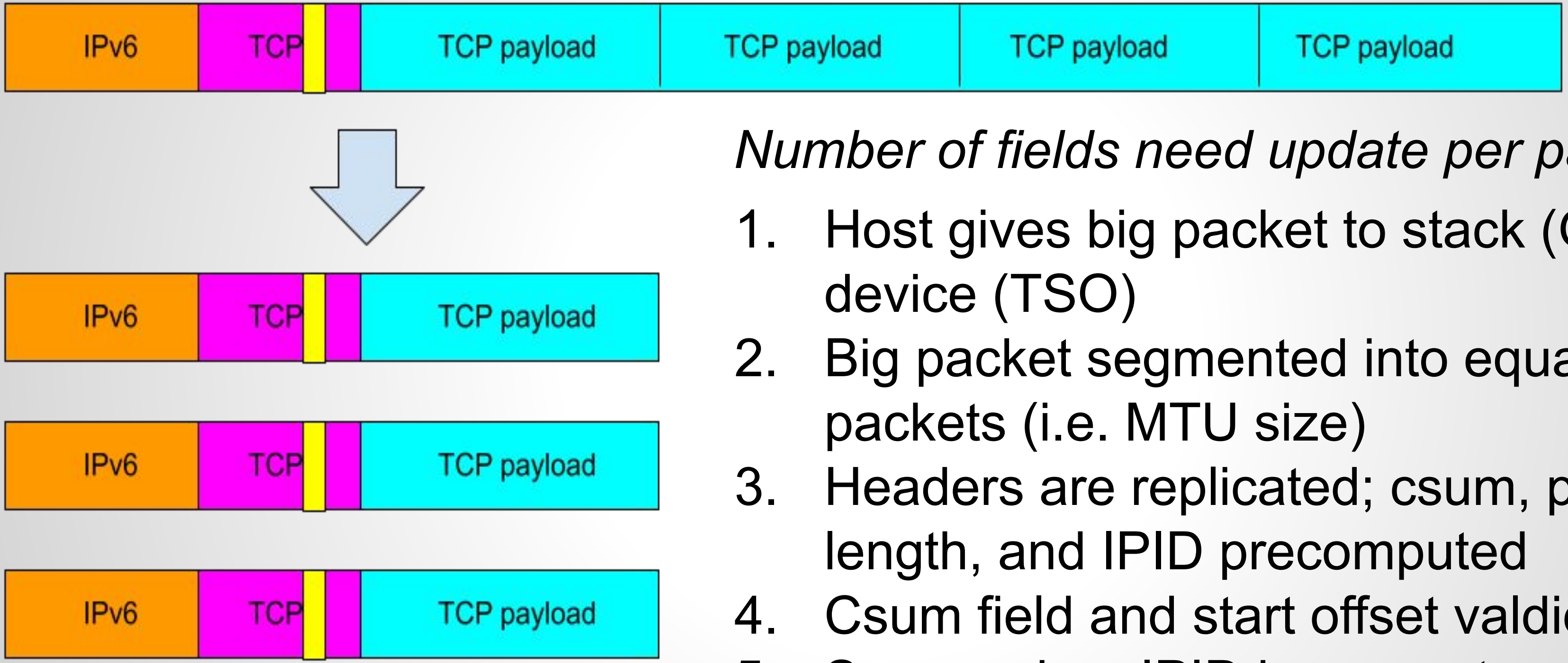
1. Device provides checksum of packet in RX descriptor (DevCsum)
   Csum = DevCsum
2. Process IPv6 header and pull up checksum
   Compute ICsum in CPU, Csum = Csum $\oplus$ ~ICsum
3. Process UDP header (pullup and validate)
   Compute Ssum in CPU, Csum = Csum $\oplus$ ~SCsum
   Csum = Csum $\oplus$ PHsum, if Csum == 0xFFFF then sum valid

Recv offload three checksums



UDPCsum=DevCsum $\oplus$ ~A_0 (note A_0==CS0)
GRECsum=UDPCsum $\oplus$ ~A_1
TCPCsum=GREsum $\oplus$ ~A_2 $\oplus$ ~A_3

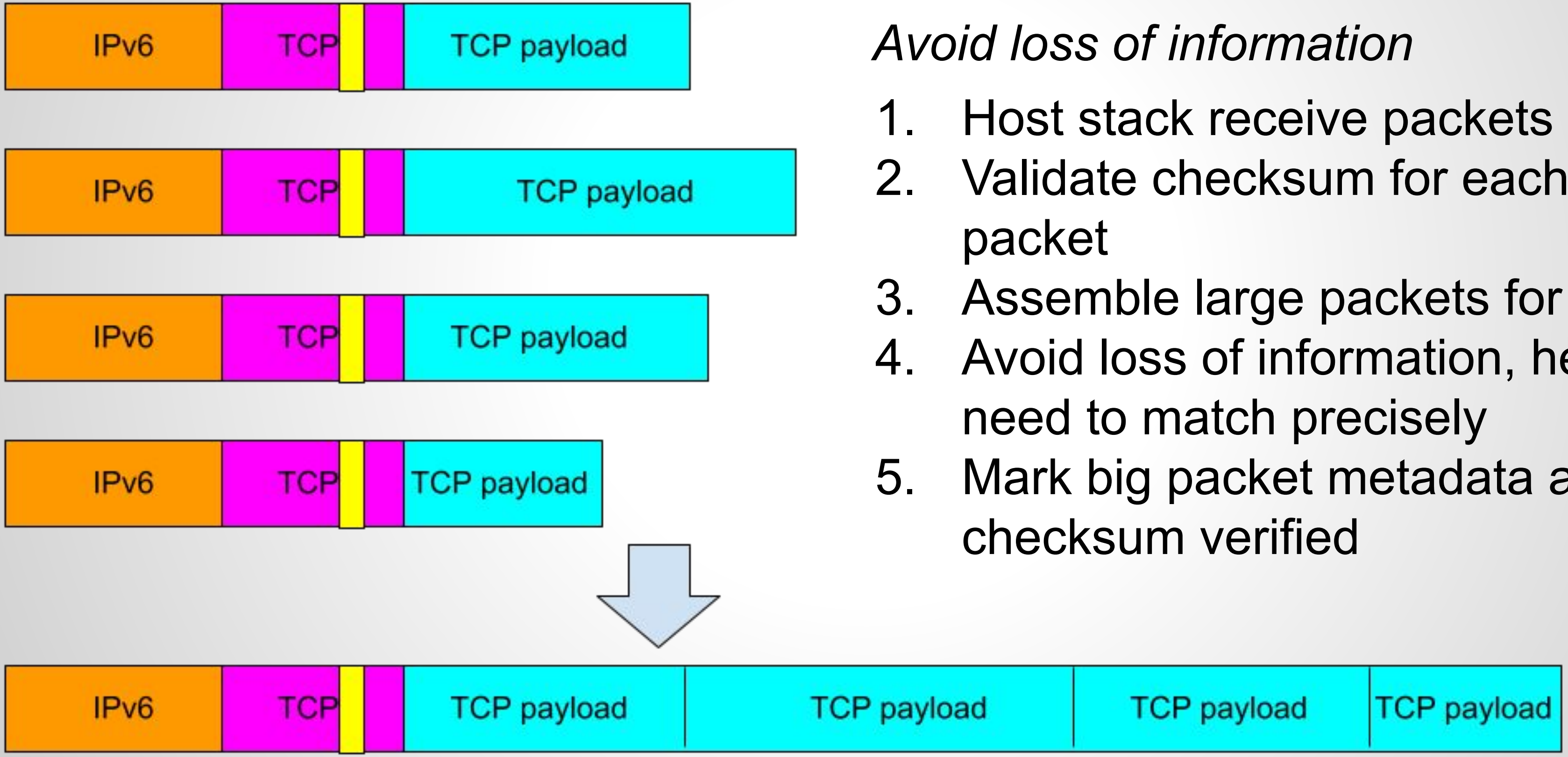
Checksum and GSO/TSO



Number of fields need update per packet?

1. Host gives big packet to stack (GSO) or device (TSO)
2. Big packet segmented into equal sized packets (i.e. MTU size)
3. Headers are replicated; csum, payload length, and IPID precomputed
4. Csum field and start offset valdidate
5. Seq number, IPID increment per pkt
6. IPv4 delta csum cancel IPID
7. TCP csum cancel payload len

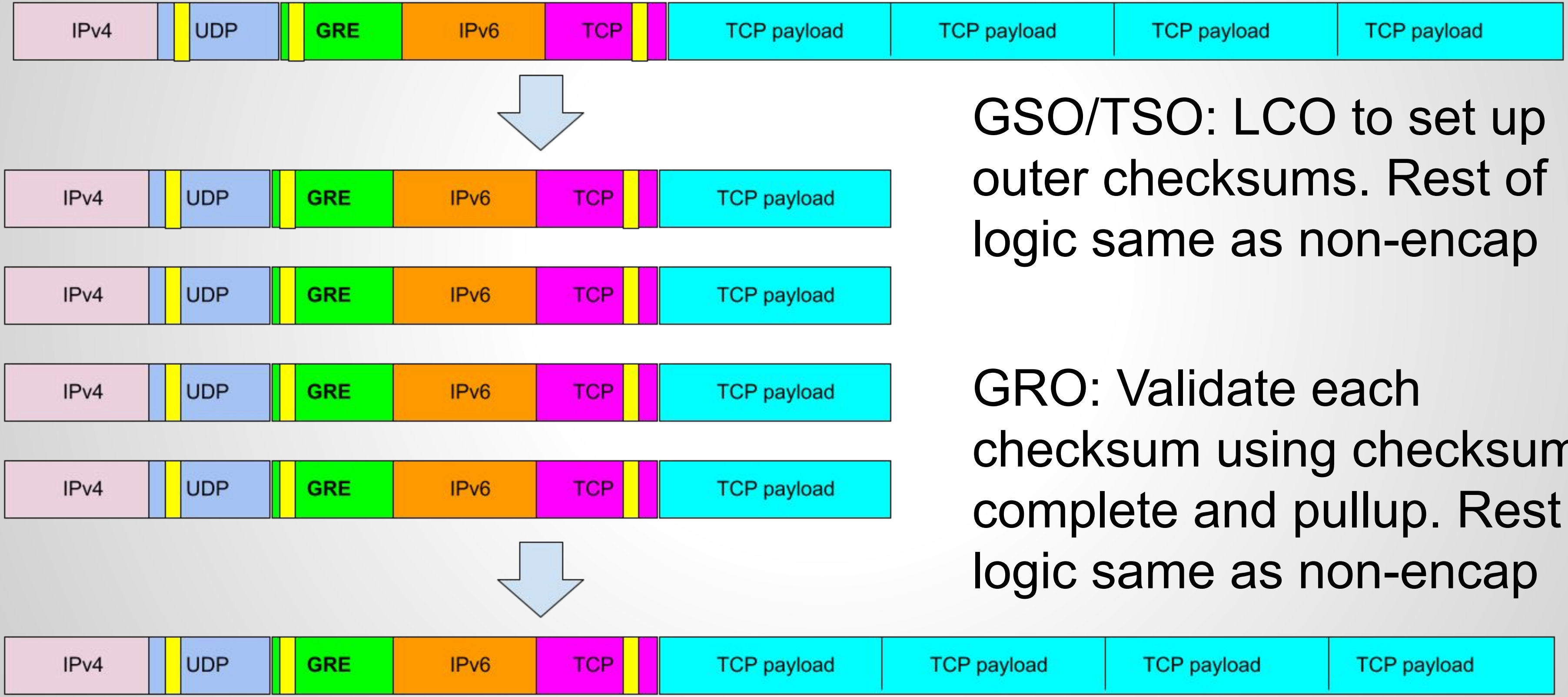
Checksum and GRO



Avoid loss of information

1. Host stack receive packets
2. Validate checksum for each packet
3. Assemble large packets for a flow
4. Avoid loss of information, headers need to match precisely
5. Mark big packet metadata as checksum verified

GSO/TSO/GRO w/encapsulation



GSO/TSO: LCO to set up outer checksums. Rest of logic same as non-encap

GRO: Validate each checksum using checksum complete and pullup. Rest of logic same as non-encap

References

- Linux documentation: checksum offloads
    - https://www.kernel.org/doc/html/latest/networking/checksum-offloads.html
- LCO,GSO_PARTIAL,TSO_MANGLEID, and Why Less is More
    - https://legacy.netdevconf.info/1.2/papers/LCO-GSO-Partial-TSO-MangleID.pdf
- UDP encapsulation in Linux
    - https://people.netfilter.org/pablo/netdev0.1/papers/UDP-Encapsulation-in-Linux.pdf

Thank you!