

Ethernet / IEEE 802.3 Header and EtherTypes																																															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31															
0B																	Destination Address																														
4B																	Source Address																														
8B																																															
12B	EtherType																																														
IEEE 802.3 Header																																															
EtherType		Keyword		Protocol																																											
0x8800		IPv4		Internet Protocol, version 4																																											
0x8806		ARP		Address Resolution Protocol																																											
0x8842		WoL		Wake-on-LAN magic packet																																											
0x8035		RARP		Reverse Address Resolution Protocol																																											
0x814c		SNMP		Simple Network Management Protocol																																											
0x86dd		IPv6		Internet Protocol, version 6																																											

IPv4/6 Header and IPv4 Protocol and IPv6 Next Header																																																				
0B	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31																				
4B	Version				IHL (4 B)								TOS								Total Length																															
8B	Identification																Reserved				Fragment Offset (8 B)																															
12B	TTL								Protocol								Header Checksum																																			
16B	Source Address																Destination Address																																			
20B	Options / Padding (optional)																																																			
IPv4 Header																																																				
0B	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31																				
4B	Version				Traffic Class												Flow Label								Next Header																											
8B	Payload Length (including Extension Headers)																Source Address																Hop Limit																			
24B																	Destination Address																																			
40B	Extension Headers (optional)																																																			
IPv6 Header																																																				
0B	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31																				
4B	Next Header								Reserved								Fragment Offset (8 B)								Reserved				M/F																							
8B	Identification																additional Extension Headers (optional)																																			
IPv6 Fragmentation Header																																																				
No / NH		Protocol		No / NH		Protocol		No / NH		Protocol		No / NH		Protocol		No / NH		Protocol		No / NH		Protocol		No / NH		Protocol		No / NH		Protocol																						
0x01		ICMPv4 (Internet Control Message P)		0x2f		GRE (General Routing Encapsulation)		0x01		ICMPv6 (ICMP for IPv6)		0x3a		No Next Header		0x84		SCTP (Stream Control Transmission P)		0x02		UDP (User Datagram Protocol)		0x03		TCP (Transmission Control Protocol)		0x04		Fragment Header																						
0x06		ICMPv4 (Internet Control Message P)		0x2f		GRE (General Routing Encapsulation)		0x01		ICMPv6 (ICMP for IPv6)		0x3a		No Next Header		0x84		SCTP (Stream Control Transmission P)		0x02		UDP (User Datagram Protocol)		0x03		TCP (Transmission Control Protocol)		0x04		Fragment Header																						
0x11		UDP (User Datagram Protocol)		0x03		No Next Header		0x84		SCTP (Stream Control Transmission P)		0x02		UDP (User Datagram Protocol)		0x03		TCP (Transmission Control Protocol)		0x04		Fragment Header		0x03		TCP (Transmission Control Protocol)		0x04		Fragment Header																						
0x2c		Fragment Header		0x84		SCTP (Stream Control Transmission P)		0x02		UDP (User Datagram Protocol)		0x03		TCP (Transmission Control Protocol)		0x04		Fragment Header		0x03		TCP (Transmission Control Protocol)		0x04		Fragment Header		0x03		TCP (Transmission Control Protocol)																						

TCP/UDP Header and selected well-known ports																																								
0B	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31								
4B	Source Port																Destination Port																							
8B	Sequence Number																																							
12B	Acknowledgement Number																																							
16B	Offset (4B)				Reserved				URG				ACK				PSH				RST				SYN				FIN				Window							
20B	Checksum																Urgent Pointer																							
Options (0 or more multiples of 4 B)																																								
TCP Header																																								
0B	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31								
4B	Source Port																Destination Port																							
	Length																Checksum																							
UDP Header																																								
Port		Service Name		Port		Service Name		Port		Service Name																														
20		ftp (data)		53		domain (dns)		115		sftp																														
21		ftp (command)		67		bootps/dhcp server		143		imap																														
22		ssh		68		bootpc/dhcp client		443		https																														
23		telnet		69		tftp		514		syslog																														
25		smtp		80		http		546		dhcpv6-client																														
43		whois		110		pop3		547		dhcpv6-server																														

Physical Layer

Constants:

Speed of light:
 $c_0 \approx 3 \cdot 10^8$ m/s

Relative propagation speed in copper / glass:
 $\nu \approx 2/3$

Relative propagation speed in vacuum / air:
 $\nu \approx 1$

Wavelength in the medium:
 $\lambda = c/f$

Information content and entropy:

Memoryless source emits characters $x \in \mathcal{X}$, expressed by random variable X :

Information content of $x \in \mathcal{X}$:
 $I(x) = -\log_2(\Pr[X = x])$

Entropy of the source:
 $H(X) = -\sum_{x \in \mathcal{X}} \Pr[X = x] \log_2(\Pr[X = x])$

Fourier series:

angular frequency $\omega = 2\pi/T$

$$s(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos(k\omega t) + b_k \sin(k\omega t)$$

where $a_k = \frac{2}{T} \int_{-T/2}^{T/2} s(t) \cos(k\omega t) dt$, $b_k = \frac{2}{T} \int_{-T/2}^{T/2} s(t) \sin(k\omega t) dt$.

Fourier transform:

$s(t) \longleftrightarrow S(f)$

$$S(f) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s(t) e^{-j2\pi ft} dt = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s(t) (\cos(2\pi ft) - j \sin(2\pi ft)) dt$$

j refers to the imaginary unit

Sampling, Quantization and Reconstruction:

Sampling theorem (Nyquist):
 $f_N = 2B$ (B is the single-sided cutoff frequency in the baseband)

Sampled signal:
 $\hat{s}(t) = s(t) \sum_{n=-\infty}^{\infty} \delta(t - nT_a)$, where $\delta(t - nT_a) = \begin{cases} 1 & \text{for } t = nT_a \\ 0 & \text{otherwise} \end{cases}$

Sampled values:
 $\hat{s}[n] = s(nT_a)$

Step width:
 $\Delta = \frac{b-a}{M}$, with $M = 2^N$ steps at N bit accuracy

Quantization levels:
 $Q = \{a + \Delta/2, a + \Delta(1 + 1/2), \dots, a + \Delta(M - 1 + 1/2)\}$
 $\mathbb{R} \rightarrow Q, \hat{s}[n] \mapsto \tilde{s}[n]$ (rounded)

Quantized signal:
 $\tilde{s}(t) = \sum_{n=-\infty}^{\infty} \hat{s}[n] \cdot \text{rect}(t - nT_a) \cdot \text{rect}(t) = \begin{cases} 1 & \text{for } -T_a/2 \leq t \leq T_a/2 \\ 0 & \text{otherwise} \end{cases}$

Quantization error:
 $q_e(t) = s(t) - \tilde{s}(t) \leq \Delta/2$, if $a \leq s(t) \leq b$

Reconstruction
 $s(t) \approx \sum_{n=-\infty}^{\infty} \hat{s}[n] \cdot \text{sinc}\left(\frac{t - nT_a}{T_a}\right), \text{sinc}(t) = \frac{\sin(\pi t)}{\pi t}$

Channel bandwidth:

C_{\max} is an upper bound for the achievable net data rate in bit/s, i.e. transmission of redundancy-free data. For this purpose it may be necessary to add redundancy (channel coding), but this does not change the information content of the message.

Hartley:
 $C_H = 2B \log_2(M)$ bit

Shannon/Hartley:
 $C_S = B \log_2(1 + \text{SNR})$ bit

Signal-to-noise ratio: $\text{SNR} = \frac{P_S}{P_N} = \frac{\text{signal power}}{\text{noise power}} = 10 \log_{10}(\text{SNR})$ dB

Upper bound:
 $C_{\max} \leq \min\{C_H, C_S\}$

Channel coding:

Example - Block codes: Blocks with length k bit are mapped to channel words with length n bit where $n > k$. Depending on the code, it is possible to correct $m < n - k$ bit bit errors per channel word.

$$X \xrightarrow{k} \boxed{C} \xrightarrow{n} X'$$

Code rate: $R = k/n$

Modulation:

$$s(t) = \left(\sum_{n=0}^{\infty} d_1[n] g_T(t - nT) \right) \cos(2\pi f_0 t) - \left(\sum_{n=0}^{\infty} d_0[n] g_T(t - nT) \right) \sin(2\pi f_0 t)$$

Baseband

Passband

Data Link Layer

Serialization time, Propagation delay, Transmission time, Bandwidth delay product:

Serialization time:
 $t_s = L/r$

Propagation delay:
 $t_p = d/(\nu c_0)$

Transmission time:
 $t_d = t_s + t_p$

Bandwidth delay product: $C = t_p r$

Cyclic redundancy check (CRC):

addition = XOR

Checksum:
 $c(x) = m(x)x^n \bmod r(x)$, where $n = \deg r(x)$

Sent message:
 $s(x) = m(x)x^n + c(x)$

Verification:
 $c'(x) = (s(x) + e(x)) \bmod r(x) \stackrel{!}{=} 0$, with error pattern $e(x)$

Structure of MAC addresses according to IEEE 802 standards (e.g. Ethernet, WiFi, Bluetooth):

Offset in B

bit

0: Unicast
1: Multicast

0: Globally unique
1: Locally administered

Graphs

Adjacency and distance matrices:

Adjacency matrix: $A = (a)_{ij} = \begin{cases} 1 & \exists (i, j) \in \mathcal{A} \\ 0 & \text{otherwise} \end{cases}$

Distance matrix: $D = (d)_{ij} = \begin{cases} c_{ij} & \exists (i, j) \in \mathcal{A} \\ 0 & \text{if } i = j \\ \infty & \text{otherwise} \end{cases}$

min-plus-product: $D^n = D^{n-1} \otimes D$, where $d_{ij}^n = \min_{k \in \mathcal{N}} \{d_{ik}^{n-1} + d_{kj}\}$, $n \geq 1$

Network Layer

Switching modes:

Transmission time for a message with length L via n intermediary nodes with constant data rate r over a total distance d :

Circuit switching:
 $T_{CS} = t_s + 4t_p = \frac{L}{r} + \frac{4d}{\nu c_0}$

Message switching:
 $T_{MS} = (n+1)t_s + t_p = (n+1)\frac{L_H + L}{r} + \frac{d}{\nu c_0}$, L_H = length of the message header

Packet switching:
 $T_{PS} = \frac{1}{r} \left(\left\lceil \frac{L}{p_{\max}} \right\rceil L_H + L + n(L_H + p_{\max}) \right) + \frac{d}{\nu c_0}$, L_H = length of the packet header

Round Trip Time (RTT):

RTT between the nodes $s, t \in \mathcal{N}$ via the path $P = \{(s, 1), (1, 2), \dots, (n, t)\}$ and the - in general non-symmetric - return path P' :

RTT (general):
$$\text{RTT}(s, t) = \sum_{(i,j) \in P} (t_s(i, j) + t_p(i, j)) + \sum_{(i,j) \in P'} (t_s(i, j) + t_p(i, j))$$

RTT (symmetric paths): $\text{RTT}(s, t) = 2 \sum_{(i,j) \in P} (t_s(i, j) + t_p(i, j))$

Special IP addresses and address ranges:

Address Range	Function	Address Range	Function
0.0.0.0/8	Hosts in this network	::/128	unspecified address
127.0.0.0/8	Loopback, typically 127.0.0.1	:::ffff::/128	loopback
10.0.0.0/8	private addresses	::ffff::0/96	IPv4-mapped addresses
100.64.0.0/10	shared addr. for carrier-grade NAT	fe80::/10	link-local addresses
172.16.0.0/12	private addresses	fc00::/7	unique-local unicast addresses
192.168.0.0/16	private addresses	ff00::/8	multicast addresses
169.254.0.0/16	Automatic Private IP Addressing	ff02::1/128	all nodes
255.255.255.255/32	Global Broadcast	ff02::1:ff00:0/104	solicited node addresses

IPv4/6 address format:

(Examples)

Prefix

Host

Prefix

Subnet Identifier

Interface Identifier

Transport Layer

Sliding window protocols

Cardinality of the sequence number range: N . Maximum size of the send window w_s to prevent sequence number mismatches:

Go-Back-N: $w_s \leq N - 1$

Selective Repeat: $w_s \leq \left\lfloor \frac{N}{2} \right\rfloor$

Windows in TCP

TCP-Handshake and TCP-Tear-down

Sender

Receiver

Sender

Receiver

TCP throughput

during the congestion avoidance phase under the assumption that segment loss occurs in the network when $w_s \geq x \cdot \text{MSS}$.

Time between segment losses:
 $T = \left(\frac{x}{2} + 1 \right) \cdot \text{RTT}$

Number of sent segments in T :
 $n = \frac{3}{8}x^2 + \frac{3}{4}x$

Lossrate:
 $\theta = \frac{1}{n}$

Throughput:
 $r_{TCP} = \frac{n \cdot \text{MSS}}{T} \cdot (1 - \theta)$

Application Layer

Prefix-free codes

Valid codewords of a prefix-free code are never prefix of another codeword of the same code. An optimal prefix-free code minimizes the average codeword length.

$$\sum_{i \in \mathcal{A}} p(i) \cdot |c(i)|,$$

where $p(i)$ denotes the probability of occurrence of a character $i \in \mathcal{A}$ and $c(i)$ denotes the mapping to a corresponding codeword.

Application Layer (cont.)

DNS Resource Records

Record Type	Function
SOA	(Start of Authority) marks the root of a zone
NS	specifies the FQDNs of authoritative name servers of a zone
A	associates an FQDN with an IPv4 address
AAAA	associates an FQDN with an IPv6 address
CNAME	Alias that maps to a „Canonical Name“ which itself is an FQDN
MX	associates an FQDN with a mail server
TXT	associates an FQDN with a string (text)
PTR	associates an IPv4 or IPv6 address with an FQDN (Reverse DNS)

Reverse DNS Zones

IPv4: in-addr.arpa., IPv6: ip6.arpa.

Probability Distributions

Discrete Uniform Distribution: $X \sim U(a, b)$:

Expresses the probability of the occurrence of a certain event out of several equally probable events, e.g. fair dice.

$\Pr[X = k] = \frac{1}{b - a + 1}$

$\Pr[X \leq k] = \frac{k - a + 1}{b - a + 1}$

$E[X] = \frac{a + b}{2}$

$\text{Var}[X] = \frac{(b - a + 1)^2 - 1}{12}$

Geometric Distribution: $X \sim \text{Geo}(p)$:

Expresses a discrete-time waiting problem, e.g. the number of attempts until success (or the number of unsuccessful attempts until success, if the exponent is shifted accordingly).

$\Pr[X = k] = (1 - p)^{k-1} p$

$\Pr[X \leq k] = 1 - (1 - p)^k$

$E[X] = \frac{1}{p}$

$\text{Var}[X] = \frac{1 - p}{p^2}$

Binomial Distribution: $X \sim \text{Bin}(n, p)$:

Expresses the probability of $0 \leq k \leq n$ successes at constant probability of success p , e.g. lottery. For $n \rightarrow \infty$ and $p \rightarrow 0$ the Poisson distribution is obtained. For $n \geq 10$ and $p < 0.5$, the Poisson distribution can be used as an approximation for the binomial distribution.

$\Pr[X = k] = \binom{n}{k} p^k (1 - p)^{n-k}$

$\Pr[X \leq k]$ no short hand

$E[X] = np$

$\text{Var}[X] = np(1 - p)$

Poisson Distribution: $X \sim \text{Po}(\lambda)$:

Counts the occurrence of independent and equally distributed events with rate λ . For $\lambda = np$, the distribution represents the limit of the binomial distribution ($n \rightarrow \infty, p \rightarrow 0$).

$\Pr[X = k] = \frac{\lambda^k}{k!} e^{-\lambda}$

$\Pr[X \leq k]$ no short hand

$E[X] = \lambda$

$\text{Var}[X] = \lambda$

Layer Model

Data exchange between the layers

Layer ($N+1$)

Layer N

Layer ($N-1$)