

Ethernet / IEEE 802.3 Header and EtherTypes

0 B	Destination Address																												
4 B	Source Address																												
8 B	EtherType																												
IEEE 802.3 Header																													
EtherType	Keyword	Protocol																											
0x0800	IPv4	Internet Protocol, version 4																											
0x0806	ARP	Address Resolution Protocol																											
0x0842	WoL	Wake-on-LAN magic packet																											
0x0803	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

0 B	Version IHL (4 B) TOS																													
4 B	Identification Reserved DF MF Fragment Offset (8 B)																													
8 B	TTL Protocol Source Address																													
12 B	Destination Address																													
16 B	Options / Padding (optional)																													
IPv4 Header																														
0 B	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																													
4 B	Version Traffic Class Flow Label																													
8 B	Payload Length (including Extension Headers)	Next Header	Hop Limit																											
12 B	Source Address	Destination Address																												
16 B	Extension Headers (optional)																													
IPv6 Header																														
0 B	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																													
4 B	Next Header Reserved Identification																													
8 B	additional Extension Headers (optional)																													
IPv6 Fragmentation Header																														
No / NH	Protocol																													
0 B	0x01 ICMPv4 (Internet Control Message P.)	0x2f GRE (General Routing Encapsulation)																												
4 B	0x06 TCP (Transmission Control Protocol)	0x3a ICMPv6 (ICMP for IPv6)																												
8 B	0x11 UDP (User Datagram Protocol)	0x3b No Next Header																												
12 B	0x2c Fragment Header	0x84 SCTP (Stream Control Transmission P.)																												

Selected ICMP4 Types/Codes

Type	Code	Description
0	reserved	
1 – Destination Unreachable	0 echo reply	
1 and 2	reserved	
3 – Destination Unreachable	0 destination network unreachable	
	1 destination host unreachable	
	2 destination protocol unreachable	
	3 destination port unreachable	
4 – Source Quench	0 source quench (congestion control)	
5 – Redirect Message	0 redirect datagram for the network	
	1 redirect datagram for the host	
8 – Echo Request	0 TTL expired in transit	
	1 fragment reassembly time exceeded	
11 – Time Exceeded	0 TTL expired in transit	
	1 fragment reassembly time exceeded	

Selected ICMPv6 Types/Codes
Number Systems 1/2
dec hex binary ASCII
128 a0 10000000 192 c0 11000000 224 e0 11100000
129 b1 10000001 193 c1 11000001 225 e1 11100001
130 b2 10000010 194 c2 11000010 226 e2 11100010
131 b3 10000011 195 c3 11000011 227 e3 11100011
132 b4 100000100 164 a4 101000100 196 c4 110000100 228 e4 111000100
133 b5 100000101 165 a5 101000101 197 c5 110000101 229 e5 111000101
134 b6 100000110 166 a6 101000110 198 c6 110000110 230 e6 111000110
135 b7 100000111 167 a7 101000111 199 c7 110000111 231 e7 111000111
136 b8 100010000 168 a8 101000100 200 c8 110000100 232 e8 111000100
137 b9 100010001 169 a9 101000101 201 c9 110000101 233 e9 111000101
138 b10 100010002 170 a10 101000102 202 c10 110000102 234 e10 111000102
139 b11 100010003 171 a11 101000103 203 c11 110000103 235 e11 111000103
140 b12 100010004 172 a12 101000104 204 c12 110000104 236 e12 111000104
141 b13 100010005 173 a13 101000105 205 c13 110000105 237 e13 111000105
142 b14 100010006 174 a14 101000106 206 c14 110000106 238 e14 111000106
143 b15 100010007 175 a15 101000107 207 c15 110000107 239 e15 111000107
144 b16 100010008 176 a16 101000108 208 d16 110000108 240 f0 111000000
145 b17 100010009 177 b17 101000109 209 d17 110000109 241 f1 111000001
146 b18 100010010 178 b18 101000110 210 d18 110000110 242 f2 111000002
147 b19 100010011 179 b19 101000111 211 d19 110000111 243 f3 111000003
148 b20 100010012 180 b20 101000112 212 d20 110000112 244 f4 111000004
149 b21 100010013 181 b21 101000113 213

Physical Layer

Constants:

Speed of light:	$c_0 \approx 3 \cdot 10^8 \text{ m/s}$
Relative propagation speed in copper / glass:	$\nu \approx 2/3$
Relative propagation speed in vacuum / air:	$\nu \approx 1$
Wavelength in the medium:	$\lambda = c/\nu$

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

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

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

Fourier series: angular frequency $\omega = 2\pi/T$

$$s(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos(k\omega t) + b_k \sin(k\omega t) \text{ where } a_k = \frac{2}{T} \int_{-T/2}^{T/2} s(t) \cos(k\omega t) dt, b_k = \frac{2}{T} \int_{-T/2}^{T/2} s(t) \sin(k\omega t) dt.$$

Fourier transform: $s(t) \mapsto S(f)$

$$S(f) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s(t) e^{-j2\pi ft} dt = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s(t) (\cos(2\pi ft) - j\sin(2\pi ft)) dt \quad (j \text{ refers to the imaginary unit})$$

Sampling, Quantization and Reconstruction:

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

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

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

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

$$\text{Quantization levels: } Q = \{a + \Delta/2, a + \Delta(1+1/2), \dots, a + \Delta(M-1+1/2)\}$$

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

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

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

Channel bandwidth: C_{\max} is an upper bound for the achievable net data rate in bits/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.

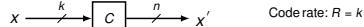
$$\text{Hartley: } C_H = 2B \log_2(M) \text{ bit}$$

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

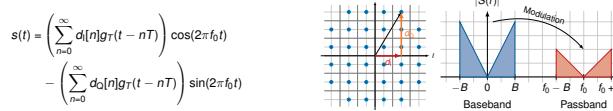
$$\text{Signal-to-noise ratio: } \text{SNR} = \frac{P_S}{P_N} = \frac{\text{signal power}}{\text{noise power}} = 10 \log_{10}(\text{SNR}) \text{ dB}$$

$$\text{Upperbound: } C_{\max} \leq \min\{C_H, C_S\}$$

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 errors per channel word.



Modulation:



Data Link Layer

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

$$\text{Serialization time: } t_s = L/r$$

$$\text{Propagation delay: } t_p = d/(v_c)$$

$$\text{Transmission time: } t_d = t_s + t_p$$

$$\text{Bandwidth delay product: } C = t_p r$$

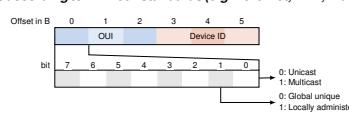
Cyclic redundancy check (CRC): addition = XOR

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

$$\text{Sent message: } s(x) = m(x)x^n + c(x)$$

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

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



Graphs

Adjacency and distance matrices:

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

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

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

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 :

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

$$\text{Message switching: } T_{MS} = (n+1)t_s + t_p = (n+1) \left[\frac{L_H + L}{r} + \frac{d}{v_C} \right], L_H = \text{length of the message header}$$

$$\text{Packet switching: } T_{PS} = \frac{1}{r} \left(\left[\frac{L}{p_{\max}} \right] L_H + L + n(L_h + p_{\max}) \right) + \frac{d}{v_C}, L_h = \text{length of the packet header}$$

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

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

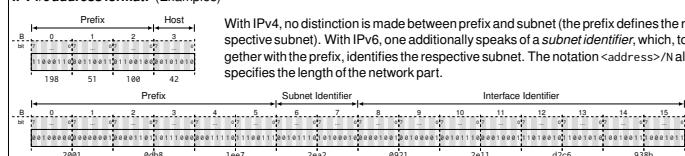
$$\text{RTT (symmetric paths): } \text{RTT}(s, t) = 2 \sum_{(i,j) \in P} (t_s(i, j) + t_p(i, j))$$

Special IP addresses and address ranges:

Address Range	Function
0..0..0..0/8	Hosts in this network
127..0..0..0/8	Loopback, typically 127.0.0.1
10..0..0..0/8	private addresses
100..64..0..0/10	shared addr. for carrier-grade NAT
172..16..0..0/12	private addresses
192..168..0..0/16	private addresses
169..254..0..0/16	Automatic Private IP Addressing
255..255..255..252/32	Global Broadcast

Address Range	Function
::1/128	unspecified address
::1/128	loopback
::ffff:0:0/96	IPv4-mapped addresses
fe80::/10	link-local addresses
fc00::/7	unique-local unicast addresses
ff00::/8	multicast addresses
ff02::1/128	all nodes
ff02::1:ff00::/104	solicited node addresses

IPv4/6 address format:



Transport Layer

Sliding window protocols

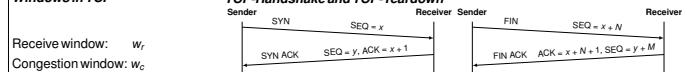
Cardinality of the sequence number range: N . Maximum size of the send window w_s to prevent sequence number mismatches:

$$\text{Go-Back-N: } w_s \leq N-1$$

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

Windows in TCP

TCP-Handshake and TCP-Teardown



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

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

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

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

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

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)

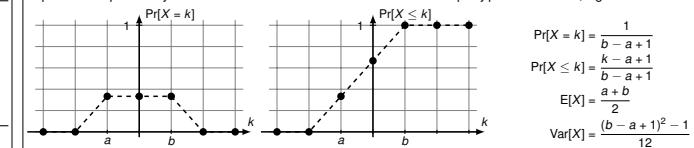
Reverse DNS Zones

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

Probability Distributions

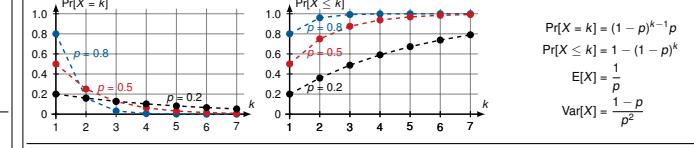
Discrete Uniform Distribution: $X \sim U(a, b)$:

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



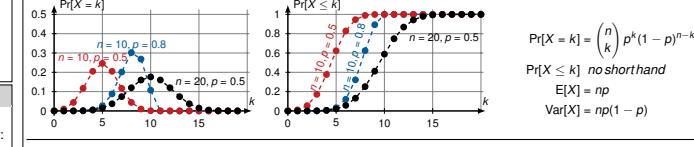
Geometric Distribution: $X \sim Geo(p)$:

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).



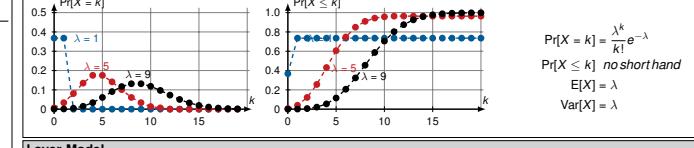
Binomial Distribution: $X \sim Bin(n, p)$:

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.



Poisson Distribution: $X \sim Po(\lambda)$:

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



Layer Model

Data exchange between the layers

