Data Link Layer

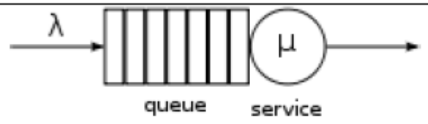
		Protocol Description	Link Utilization: Percentage of the time during which the link transmits useful information.	Bits for SN	Max Window Size	SN Range	Note
Flow Control	Stop-and-Wait	• Source transmits frame • Destination receives frame and replies with ACK • Source waits for ACK before sending next frame • Destination can stop flow by not sending ACK	$U = \frac{1}{1+2a}$	1	$W = 1$		$a = \frac{T_{prop}}{T_{frame}}$ $T_{prop} = \frac{Distance}{c}$ $T_{frame} = \frac{Length}{Bit\ Rate}$ Note: • convert bytes to bits in calculation • unify all the units in calculation $U = \frac{T_{frame}}{T_{cycle}}$ $U = \frac{r}{R}$ Note: • U is normalized throughput • R is transmission rate • r is throughput
	Sliding Window	• Sender can send up to W frames without receiving ACK • ACK includes number of next frame expected	$U = \begin{cases} 1, & W \geq 1+2a \\ \frac{W}{1+2a}, & W < 1+2a \end{cases}$	k	2^k	$[0, 2^k - 1]$	
ARQ	Stop-and-Wait	• Destination sends an ACK if frame received correctly • Source transmits next frame if ACK is received; otherwise, if no ACK is received within timeout, resource retransmits the frame	$U = \frac{1-P}{1+2a}$	1	1		
	Go-Back-N	• Source transmits frames sequentially based on sliding window • Destination sends ACK normally for error-free frames; otherwise, it sends NAK • Source retransmits that frame with all subsequent frames if NAK is received	$U = \begin{cases} \frac{1-P}{1+2aP}, & W \geq 1+2a \\ \frac{W(1-P)}{(1+2a)(1-P+WP)}, & W < 1+2a \end{cases}$	k	$2^k - 1$	$[0, 2^k - 1]$	
	Selective-Reject	• Receiver informs transmitter of rejected frame n by sending 'SREJ n' • After receiving an erroneous frame, subsequent frames are accepted by receiver and buffered	$U = \begin{cases} 1-P, & W \geq 1+2a \\ \frac{W(1-P)}{(1+2a)}, & W < 1+2a \end{cases}$	k	2^{k-1}	$[0, 2^k - 1]$	

Local Area Network

<table>
<tr><th colspan="2" rowspan="2">MAC Protocols</th><th colspan="3">Transmission Protocol</th><th rowspan="2">Throughput/
Utilization</th><th rowspan="2">Note</th></tr>
<tr><th>Carrier Sensing</th><th>Frame Transmission</th><th>Collision Detection</th></tr>
<tr><td rowspan="2">Aloha</td><td>Slotted</td><td rowspan="2">• None</td><td>• Each transmits in a slot immediately with probability p</td><td rowspan="5">• When a collision is detected, the colliding frames are transmitted up to their last bits.</td><td>$S = Np(1-p)^{(N-1)} = Ge^{-G}$</td><td rowspan="2">Number of Stations: N
Probability of Attempt: p
Attempt Rate: $G = Np$</td></tr>
<tr><td>Pure</td><td>• Each transmits immediately with probability p</td><td>$S = Np(1-p)^{2(N-1)} = Ge^{-2G}$</td></tr>
<tr><td rowspan="3">CSMA</td><td>Non-Persistent</td><td rowspan="3">• Must sense channel before transmission</td><td>• When a busy channel is sensed, a station defers for a random period of time before next sense</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>P-Persistent</td><td>• When a busy channel is sensed, a station continues to sense until the channel turns idle. Then, with probability p, it transmits, and with probability $1-p$, it defers to next time slot.</td></tr>
<tr><td>1-Persistent</td><td>• A special case of P-Persistent where $p = 1$</td></tr>
<tr><td colspan="2">CSMA/CD
(Ethernet)</td><td>• Must sense channel before transmission</td><td>• The same as CSMA</td><td>• When a collision is detected, transmissions are aborted to reduce the channel wastage.</td><td>$S = \frac{1}{1+6.44a}$
$a = \frac{T_{Prop}}{T_{frame}}$</td><td>Minimum Frame Size
• $T_{frame} \geq 2\tau$
Binary Exponential Backoff
• In i-th retransmission, the slot is chosen from a uniformly distributed random variable R, in the range of $[0, 2^K - 1]$, where $K = \min(i, 10)$.</td></tr>
<tr><td colspan="2">CSMA/CA
(802.11)</td><td>• Must sense channel before transmission</td><td>Sender:
• If sense channel idle for DIFS, then transmit entire frame (no CD).
• If sense channel busy, then start random backoff time. Transmits when timer expires.
• If no ACK, increase random backoff interval
Receiver:
• If frame received OK, return ACK after SIFS</td><td>• No collision detection due to hidden terminal</td><td colspan="2">Multi-Access Reservation
• Use random-access with mini-frame (v unit of time) to reserve the channel
• If reservation successful, transmit u unit of data frame<table><tr><td></td><td>$\frac{u}{u+v/S_r}$</td><td>$\frac{u}{(u-v)+\frac{v}{S_r}}$</td><td>$\frac{u+v}{u+v/S_r}$</td></tr><tr><td>Total data length</td><td>u</td><td>u</td><td>$u+v$</td></tr><tr><td>Data bit in mini-frame</td><td>No</td><td>Yes</td><td>Yes</td></tr></table></td></tr>
</table>

NANYANG TECHNOLOGICAL UNIVERSITY

Queuing Theory and MISC

Queue Model	Key Components	Diagram	Input Parameter	Statistics	Note
M/M/1	M/M/1/∞/FCFS		λ : mean packet arrival rate (packet/sec) μ: mean packet service rate (packet/sec) Note: $\lambda < \mu$	Queue Statistics: $\rho = \frac{\lambda}{\mu}$: system utilization $T = \frac{1}{\mu-\lambda}$: average delay $N = \frac{\rho}{1-\rho}$: average queue occupancy $T_q = \frac{\rho}{\mu-\lambda}$: average queuing delay Delay Components for Packet: • Average residual service time: ρ/μ • Average waiting time for early arrival: $(N-\rho)/\mu$ • Average service time: $1/\mu$ • Total delay: $T = \frac{\rho}{\mu} + \frac{N-\rho}{\mu} + \frac{1}{\mu}$	• Splitting Poisson Process: • Merging Poisson Processes • M/M/1 departure process: Poisson process with rate λ • Queue with feedback

Network Design Patterns	HDLC Frame Exchange Sequence	Network Reliability	Packet Transmission Delay in Pipeline
Communication Module • Communication tunnel • Flow control & error control Layering Structure • Four interfaces • NEWS Separation of Mechanism and Policy • Policy: when to do • Mechanism: how to do	High-Level Strategy • One side first • The other next	• Link failure probability: b • Link success probability: $r = 1 - b$ • Links in series $r = \prod_{i=1}^{n} (1 - b_i)$ • Links in parallel $b = \prod_{i=1}^{n} b_i$	Assumptions • N bits, m packets • Header: Lbits/packet • Transmission rate: R bps • # of hops: h End-to-End Delay: no queuing $T = m \times \frac{\frac{N}{m} + L}{R} + (h-1) \times \frac{\frac{N}{m} + L}{R}$