Performance of Packet-Switched Networks
(Desempenho de Redes com Comutação de Pacotes)

Modelação e Desempenho de Redes e Serviços

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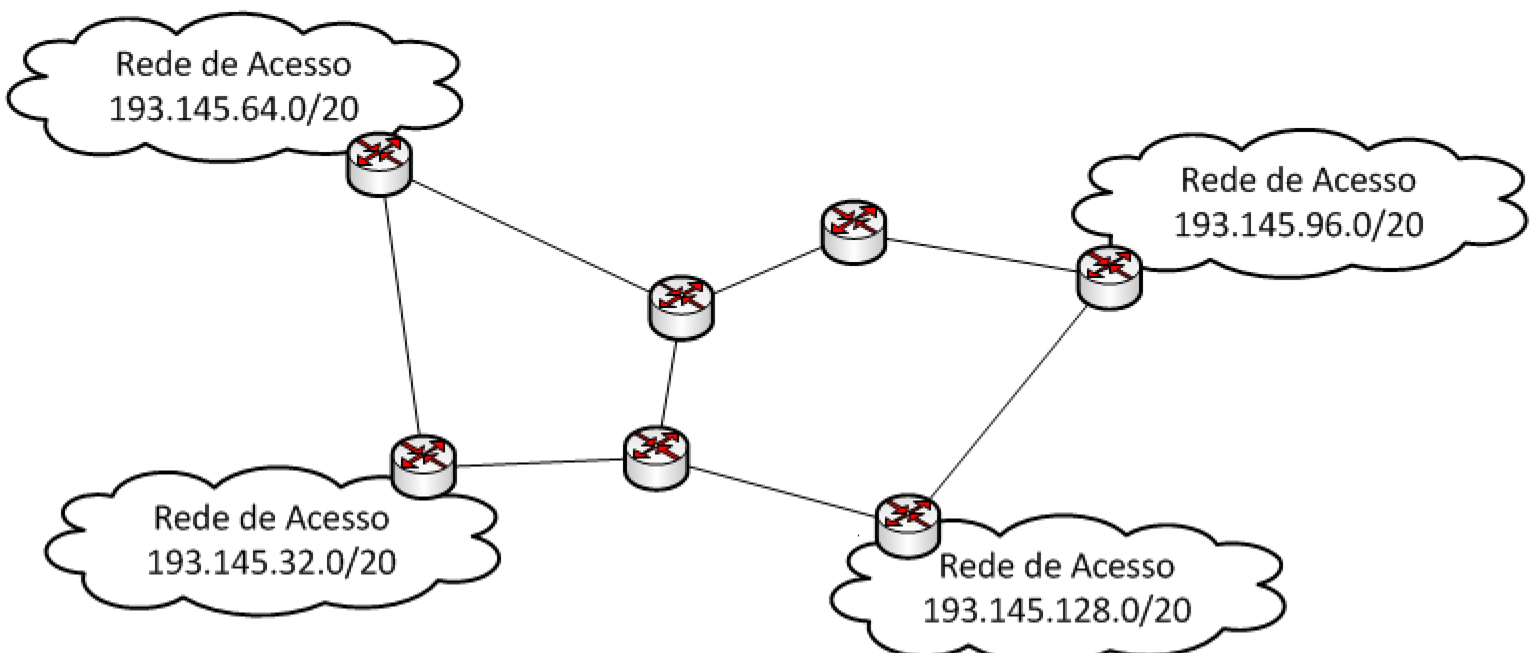
Routing in Packet-Switched Networks

Packet-switched networks are categorized into two main types:

- Connection-Oriented (Virtual Circuit) Packet Switching
- Connectionless (Datagram) Packet Switching

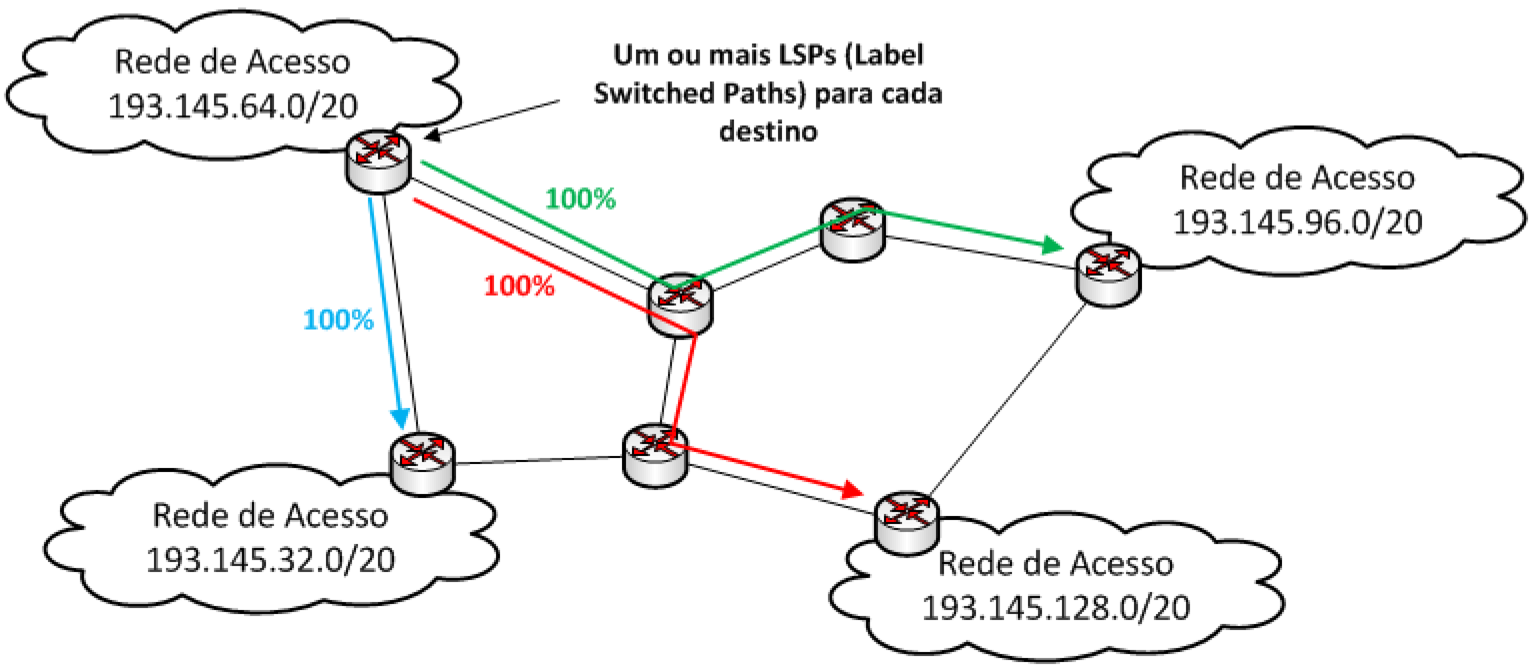
Consider the following example of an ISP (*Internet Service Provider*) core network connecting 4 access networks (networks with attached user clients):



Routing in
<u>connection-oriented packet switching networks</u>

- Each packet flow is assigned with at least one logical routing path (named virtual circuit).
- The virtual circuits are initially established.
- Packet transmission is only possible after the establishment of the virtual circuits.

Example: IP/MPLS networks, where virtual circuits are named LSPs (*Label Switched Paths*).



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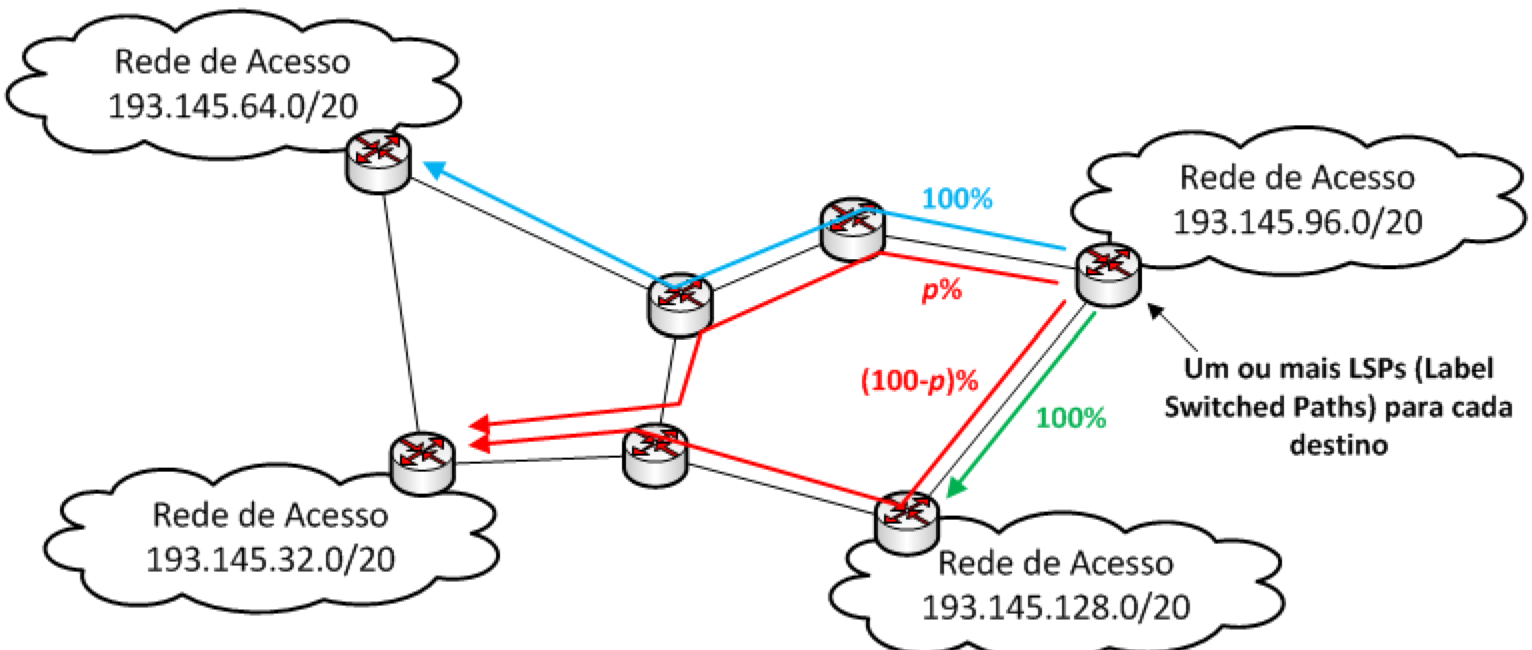


Routing in
<u>connectionless packet switching networks</u>

- The routing decisions on each router are done for each arriving packet.
- Different packets from the same source-destination packet flow can follow distinct routing paths towards the destination.

Examples: IP networks with dynamic routing protocols such as RIP or OSPF.

In IP networks, routing is based <u>on the minimum cost routing paths</u> from each router to the destination network of each IP packet

- In OSPF, the output port of each link is assigned with a positive value named <u>cost</u>.
- In RIP, the cost is 1 for each link.
- The cost of each routing path from a router to a destination network is the sum to the costs of the output ports used in the routing path.
- On each router, each IP packet is forward through a minimum cost routing path.

Routing in
<u>connectionless packet switching networks</u>

Each IP packet is routed through a minimum cost path towards the packet destination network:

<u>Static method</u>: the routing cost value of each output port is constant (the case of RIP and OSPF protocols).

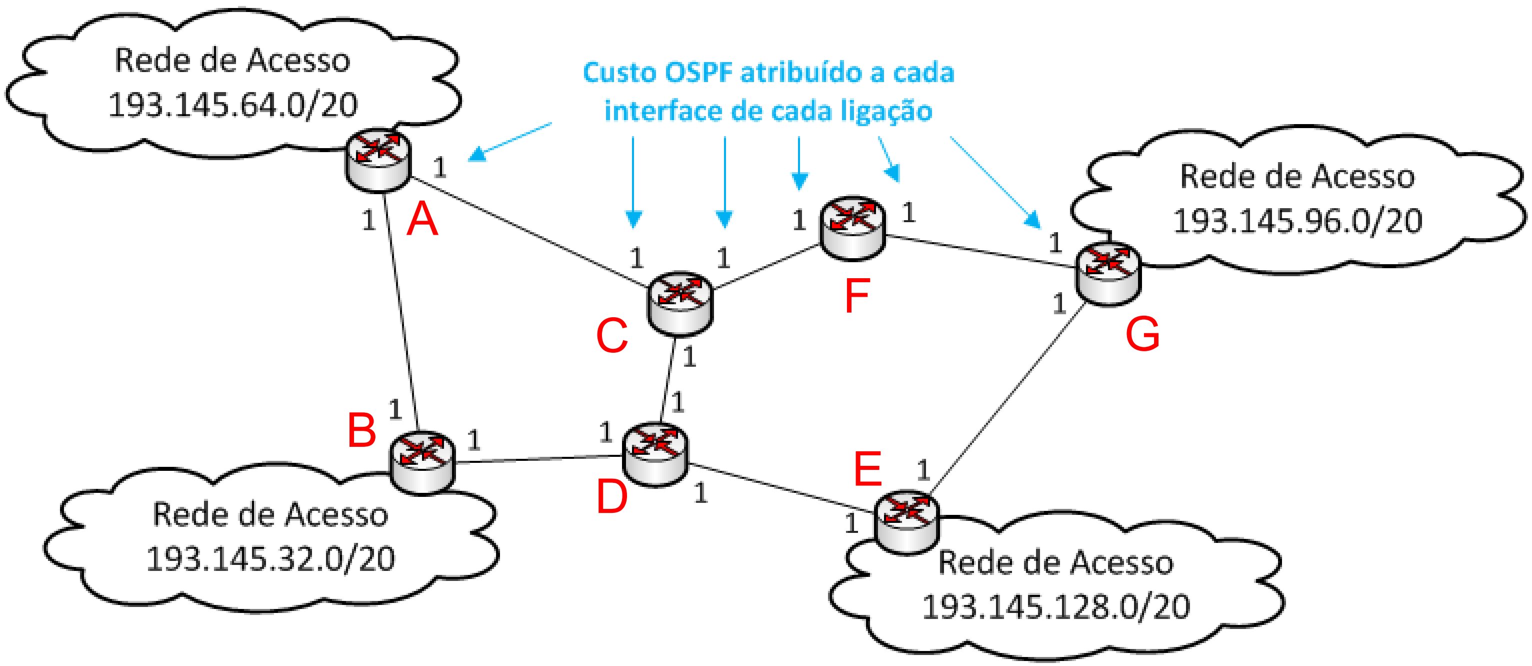
<u>Dynamic method</u>: the routing cost value of each output port is dynamically adjusted as a function of the link utilization (examples: IGRP and EIGRP protocols)

– when some links start becoming overloaded, the minimum cost routing paths dynamically adapt to avoid the overloaded links;
– in practice, these protocols are hardly used as they introduce a feedback effect that can lead to undesirable routing oscillations

When there are multiple minimum cost routing paths for a given destination, the ECMP (*Equal Cost Multi-Pathing*) technique is used:

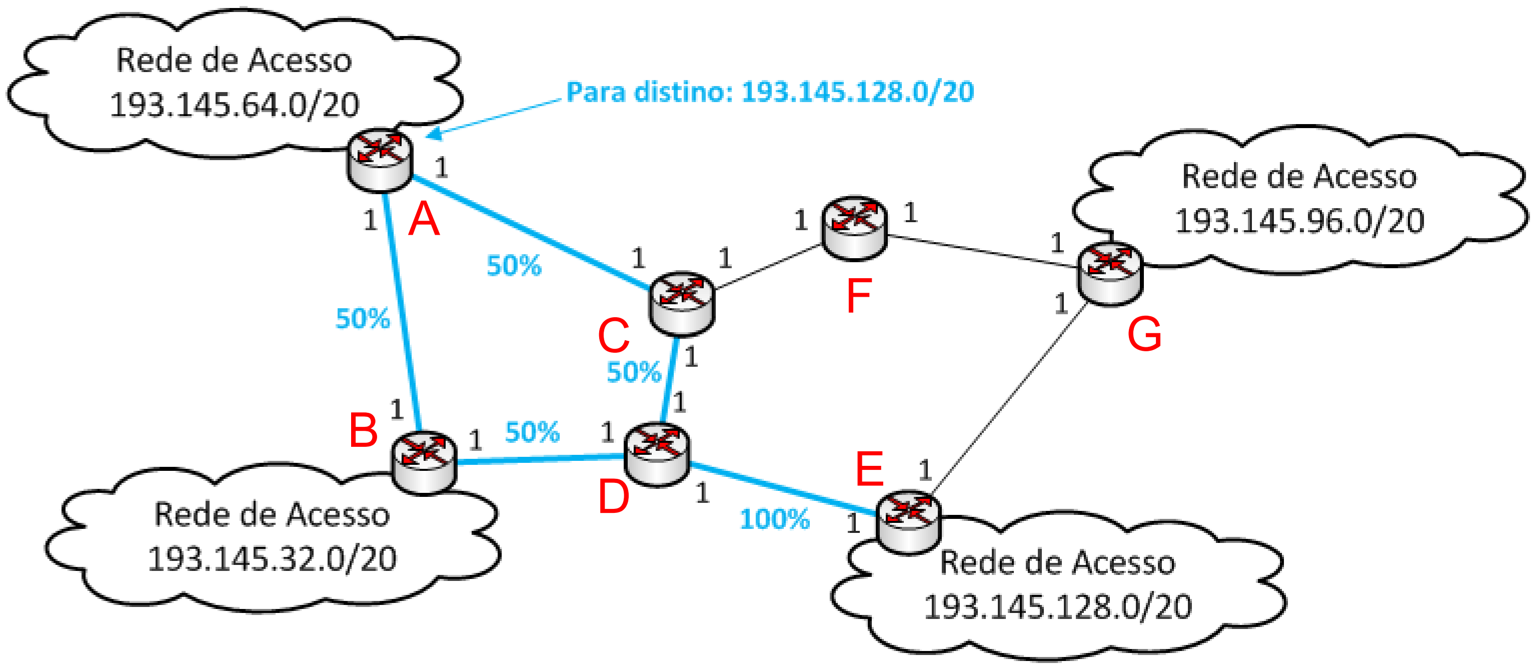
– on each router, the packet flow is split in equal percentage through all output links providing the different minimum cost routing paths

OSPF routing in IP networks (I)



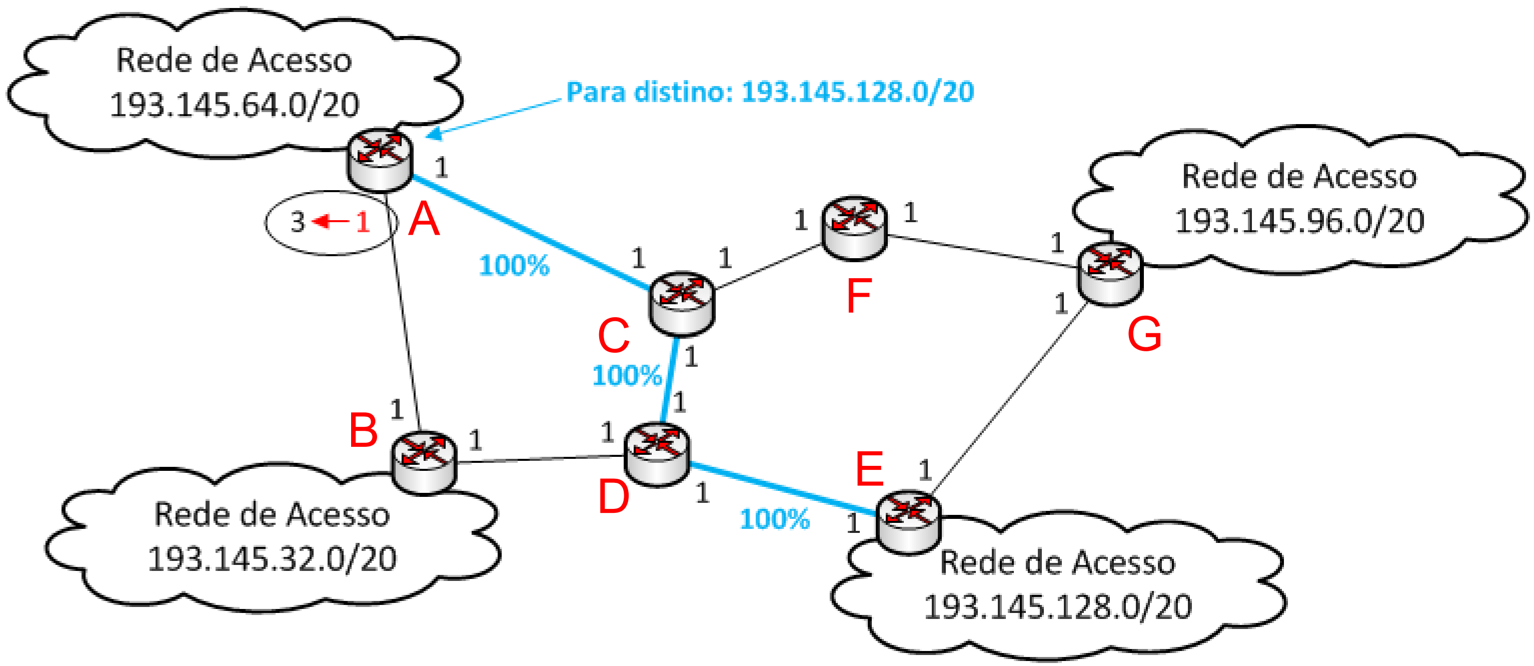
In this example, the OSPF cost value of all output ports is 1 (equivalent to RIP).

OSPF routing in IP networks (II)



By ECMP, router A forwards the IP packets for the IP addresses belonging to 193.145.128.0/20 in equal percentage towards router B and router C.

OSPF routing in IP networks (III)

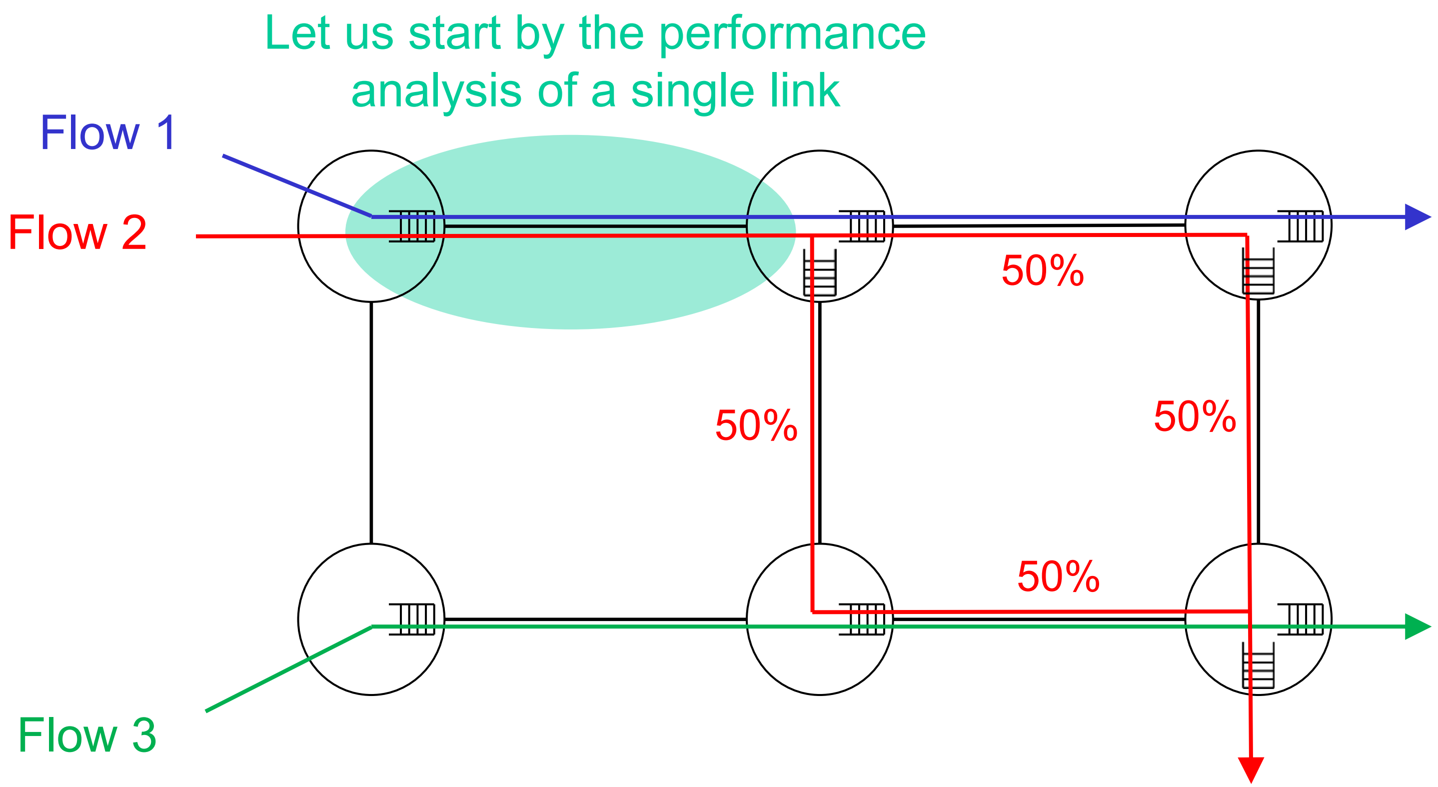


Changing administratively the cost of the output port of link A-B from 1 to 3, router A forwards the IP packets for the IP addresses belonging to 193.145.128.0/20 towards the unique minimum cost routing path.

Modelling the routing in packet-switched network

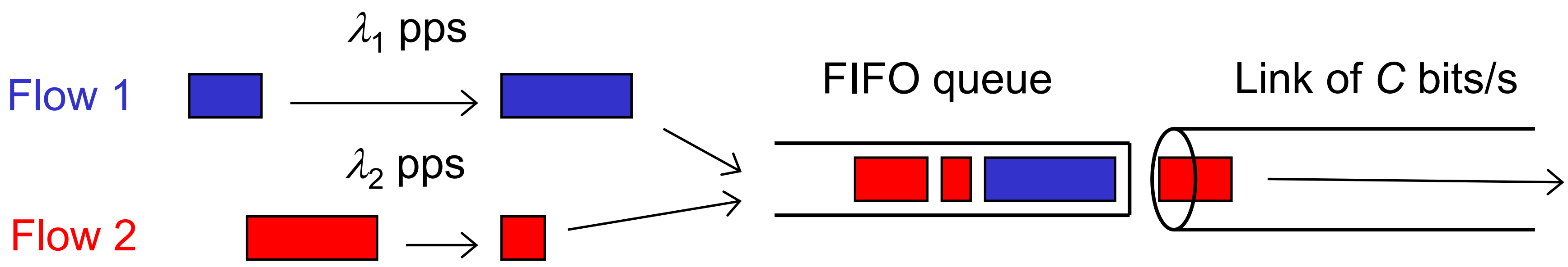
A network is modelled by a set of nodes (representing routers) and a set of existing links connecting nodes.

Routing defines the sequence of links through which the packets of each flow are forwarded from the source node to the destination node.



Statistical multiplexing of packet flows in a single queue

When the queuing of the packets of all flows is done in a single FIFO queue, we say that the flows are statistically multiplexed by the link.



Considering that:
(i) the packet arrivals of each flow is a Poisson process,
(ii) the queue has an infinite size,
then, the link can be modelled by a ***M*/*G*/1 queuing system**.

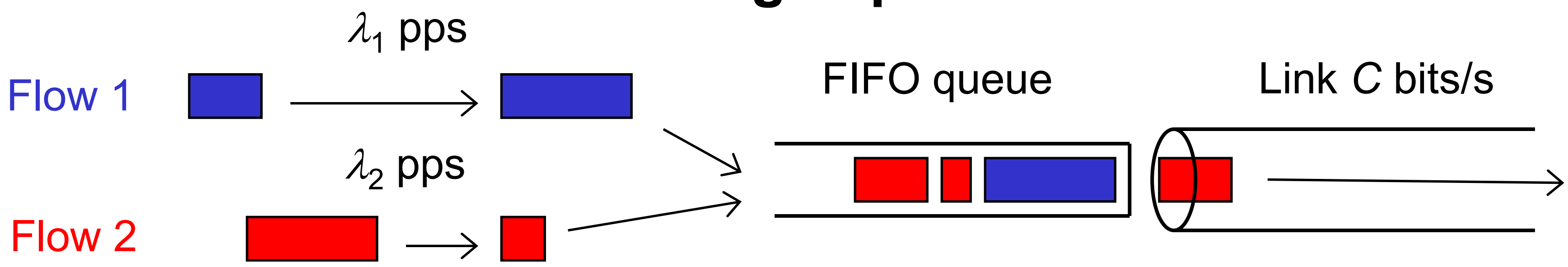
The packets of all flows suffer the same average queuing delay:

$$W_Q = \frac{\lambda E[S^2]}{2(1 - \lambda E[S])}$$

$\lambda = \lambda_1 + \lambda_2$ pps (packets/second)

$E[S]$ and $E[S^2]$ are the average transmission time and the average squared transmission time of the set of packets of all flows

Statistical multiplexing of packet flows in a single queue



Considering that:

(i) the packet arrivals of each flow is a Poisson process,

(ii) the queue has an infinite size,

(iii) <u>the packet size of all flows is exponentially distributed with average of B bits</u>,

then, the link can be modelled by a ***M*/*M*/1 queuing system**.

The average packet delay of the aggregate of flows is:

$$\lambda = \lambda_1 + \lambda_2 \text{ pps}$$

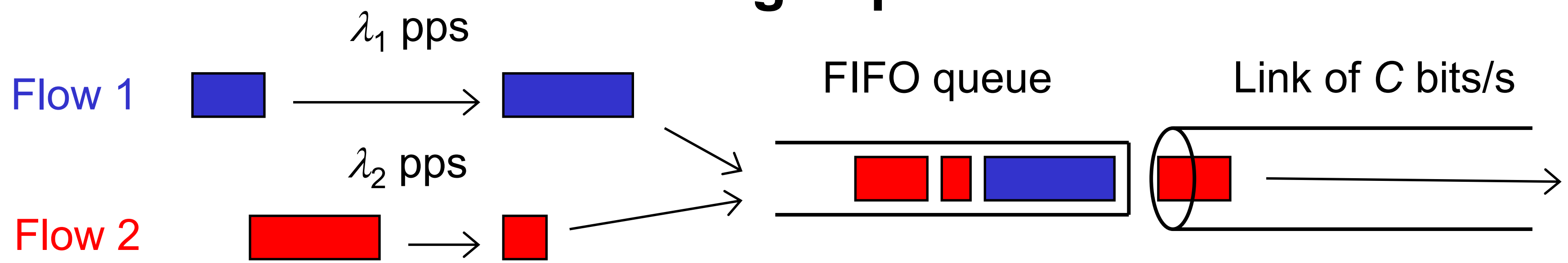
$$\mu = C / B \text{ pps}$$

$$W = \frac{1}{\mu - \lambda}$$

The packets of all flows suffer the same average queuing delay:

$$W_Q = W - \frac{1}{\mu} = \frac{\lambda}{\mu(\mu - \lambda)}$$

Statistical multiplexing of packet flows in a single queue



Considering that:

(i) the packet arrivals of each flow is a Poisson process,

(ii) the queue has a capacity of m – 1 packets,

(iii) the packet size of all flows is exponentially distributed with average of B bits,

Then, the link can be modelled by a ***M*/*M*/1/*m*** *queuing system*.

– Packet loss rate:

$$\theta_m = \frac{(\lambda/\mu)^m}{\sum_{j=0}^{m}(\lambda/\mu)^j}$$

PASTA property

– Average no. of packets in the system:

$$L = \sum_{i=0}^{m} i \times \pi_i = \frac{\sum_{i=0}^{m} i \times (\lambda/\mu)^i}{\sum_{j=0}^{m}(\lambda/\mu)^j}$$

– Average packet delay:

$$W = \frac{L}{\lambda(1-\theta_m)}$$

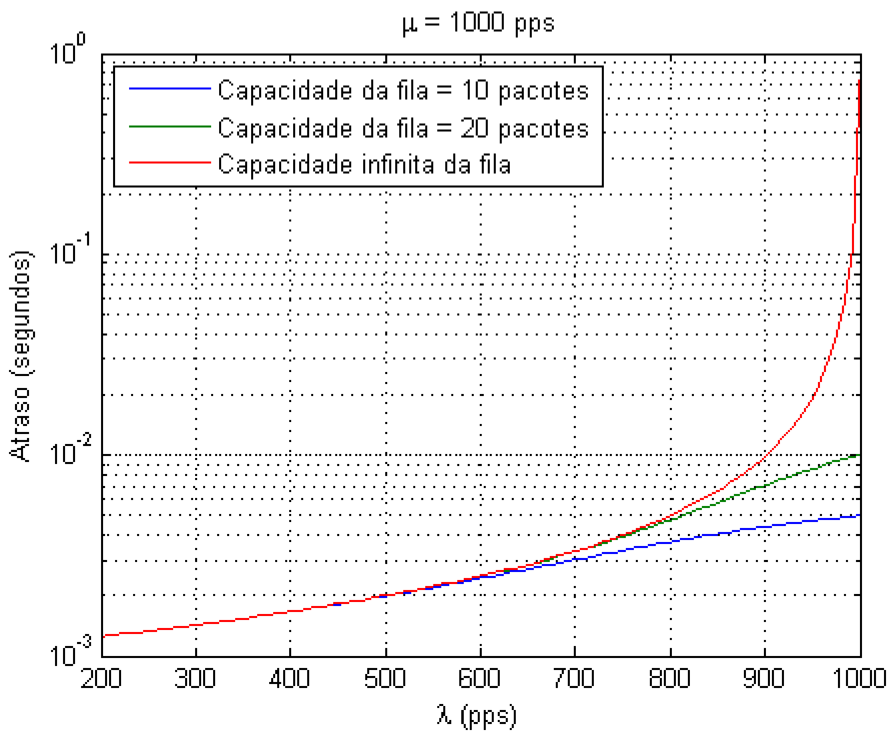
Little's theorem

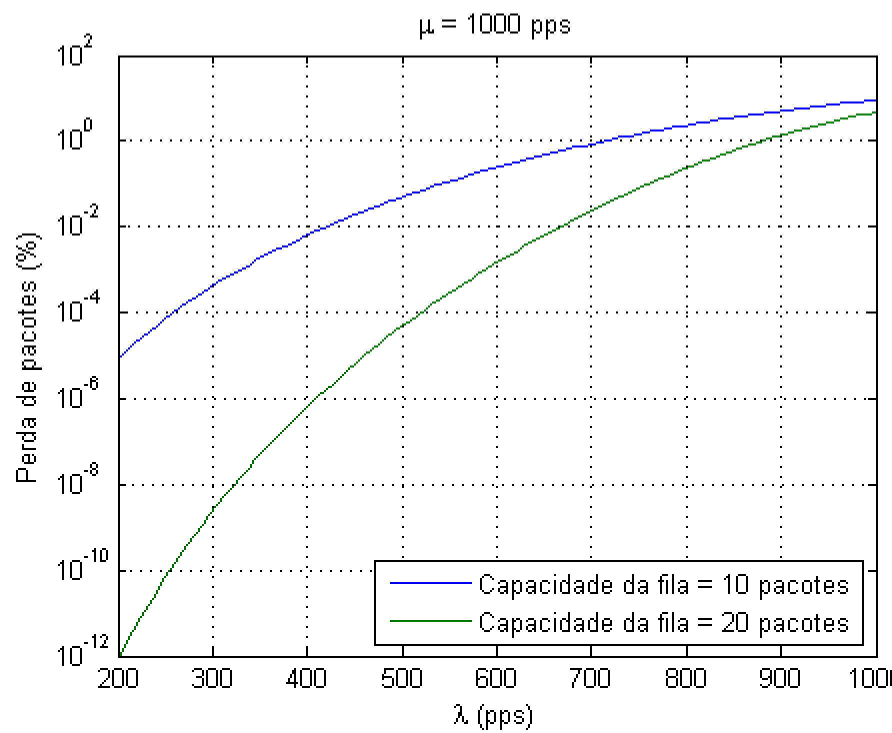
– The packets of all flows suffer the same average queuing delay:

$$W_Q = W - \frac{1}{\mu}$$

Statistical multiplexing of packet flows in a single queue

- If the queue has an infinite capacity, the system is modelled by an $M/M/1$
- In the queue has a capacity of m–1 packets, the system is modelled by an $M/M/1/m$
- Example:
  - Link of 10 Mbps and average packet size of 1250 Bytes
  - $\mu = 10^7/(1250\times8) = 1000$ pps





Queuing discipline with priorities

- In statistical multiplexing, the packets of all flows suffer the same average delay in their shared queue.
- A way of differentiating the average delay between different flows is to assign different priorities to the flows, i.e., the packets of a flow with a given priority are always transmitted before the packets of all flows with lower priority.

The *M*/*G*/1 system with priorities can be used to model this system provided that the packet arrivals are Poisson processes for all packet flows.

Consider a *M*/*G*/1 system with *n* priorities assuming that 1 corresponds to the highest priority and *n* corresponds to the lowest priority.

Consider the aggregate of packet flows of priority *k*, $1 \leq k \leq n$, defined by:

- packet arriving rate: λ_k
- average (or 1st moment) and 2nd moment of the packet transmission time: $E[S_k]$ e $E[S_k^2]$

M/G/1 system with priorities

The system always transmits first the packet of the highest priority that is in the queue.

The packets of the flows of the same priority are transmitted with a FIFO (first in first out) discipline.

The packet arrivals are independent between priorities and independent of their transmission time.

The transmission of a packet is not interrupted by the arrival of a higher priority packet (non-preemptive discipline).

The <u>average queuing delay of the packets of priority *k*</u> is given by:

$$W_{Qk} = \begin{cases} \dfrac{\sum_{i=1}^{n}\left(\lambda_i E\left[S_i^2\right]\right)}{2(1-\rho_1)} & ,k=1 \\ \dfrac{\sum_{i=1}^{n}\left(\lambda_i E\left[S_i^2\right]\right)}{2(1-\rho_1-\cdots-\rho_{k-1})(1-\rho_1-\cdots-\rho_k)} & ,k>1 \end{cases} \qquad \rho_k = \lambda_k E[S_k]$$

Validity condition: $\rho_1 + \cdots + \rho_n < 1$

Example 1

Consider a link of 10 Mbps with a very large queue supporting 2 packet flows: flow A of 1 Mbps and flow B of 6 Mbps. The packets of both flows are exponentially distributed with average 1000 bytes. Determine the average packet delay of each flow when:

(a) the 2 flows are statistically multiplexed,

(b) flow A has higher priority than flow B.

Example 1 – solution of (a)

Consider a link of 10 Mbps with a very large queue supporting 2 packet flows: flow A of 1 Mbps and flow B of 6 Mbps. The packets of both flows are exponentially distributed with average 1000 bytes. Determine the average packet delay of each flow when:

(a) the 2 flows are statistically multiplexed,

$$\mu = \frac{10 \times 10^6}{8 \times 1000} = 1250 \text{ pps} \qquad \lambda_A = \frac{1 \times 10^6}{8 \times 1000} = 125 \text{ pps} \qquad \lambda_B = \frac{6 \times 10^6}{8 \times 1000} = 750 \text{ pps}$$

$$W_A = W_B = \frac{1}{\mu - (\lambda_A + \lambda_B)} = \frac{1}{1250 - (125 + 750)} = 2.67 \times 10^{-3} = 2.67 \text{ ms}$$

Example 1 – solution of (b)

Consider a link of 10 Mbps with a very large queue supporting 2 packet flows: flow A of 1 Mbps and flow B of 6 Mbps. The packets of both flows are exponentially distributed with average 1000 bytes. Determine the average packet delay of each flow when:

(b) flow A has higher priority than flow B.

$$\lambda_A = \frac{1 \times 10^6}{8 \times 1000} = 125 \text{ pps}$$

$$\lambda_B = \frac{6 \times 10^6}{8 \times 1000} = 750 \text{ pps}$$

$$\mu_A = \mu_B = \mu = \frac{10 \times 10^6}{8 \times 1000} = 1250 \text{ pps}$$

$$E[S_A] = E[S_B] = \frac{1}{\mu} = \frac{1}{1250} \text{ seg.}$$

$$E[S_A^2] = E[S_B^2] = \frac{2}{\mu^2} = \frac{2}{1250^2} \text{ seg.}^2$$

Recall that: $E[S^2] = Var[S] + (E[S])^2$

$$W_{Qk} = \begin{cases} \dfrac{\sum_{i=1}^{n}\left(\lambda_i E\left[S_i^2\right]\right)}{2(1-\rho_1)} & ,k = 1 \\ \dfrac{\sum_{i=1}^{n}\left(\lambda_i E\left[S_i^2\right]\right)}{2(1-\rho_1-\cdots-\rho_{k-1})(1-\rho_1-\cdots-\rho_k)} & ,k > 1 \end{cases} \qquad \rho_k = \lambda_k E[S_k]$$

$$W_A = \frac{\lambda_A \times E[S_A^2] + \lambda_B \times E[S_B^2]}{2 \times (1-\rho_A)} + E[S_A] = 1.42 \text{ ms}$$

$$W_B = \frac{\lambda_A \times E[S_A^2] + \lambda_B \times E[S_B^2]}{2 \times (1-\rho_A) \times (1-\rho_A-\rho_B)} + E[S_B] = 2.87 \text{ ms}$$

Modelling the routing in packet-switched network

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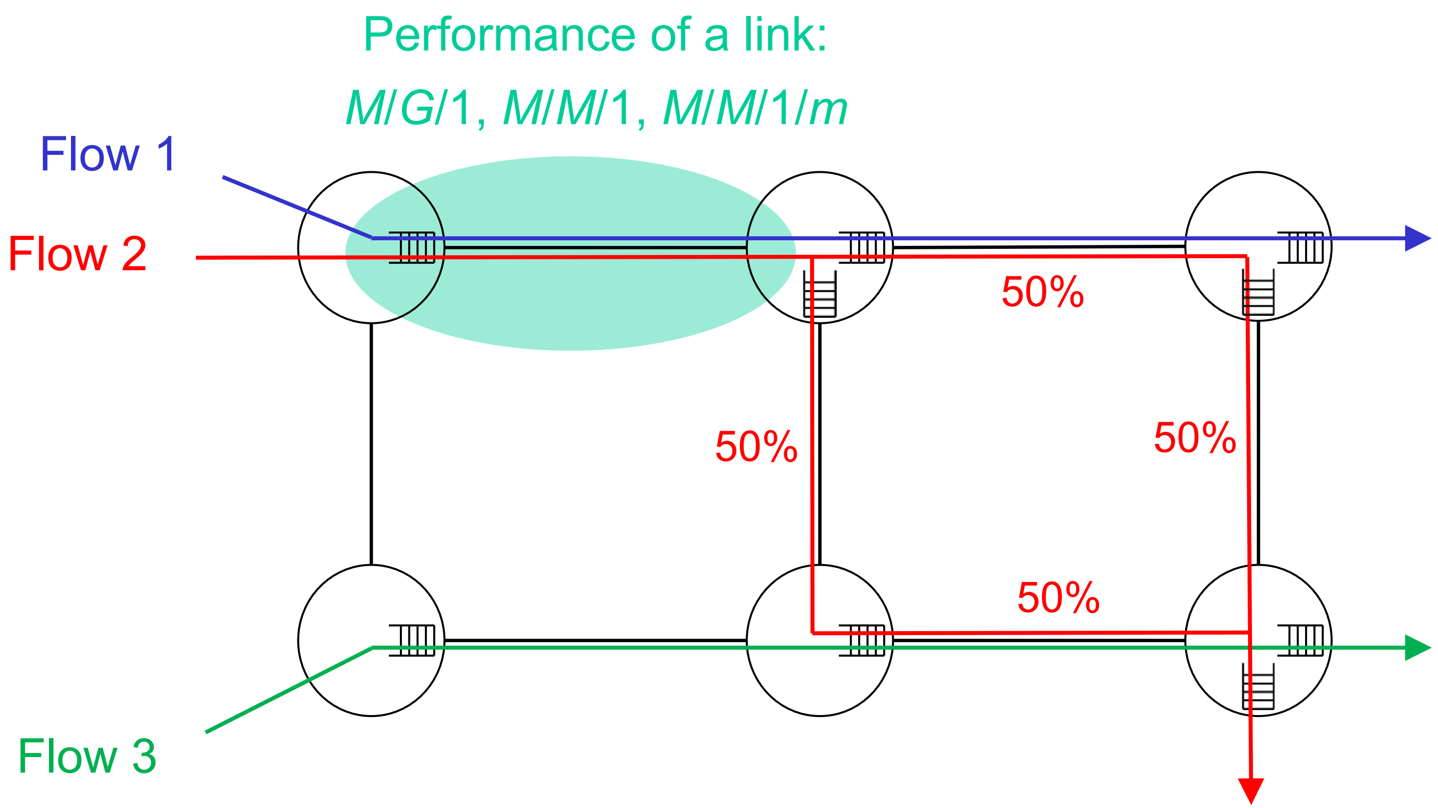
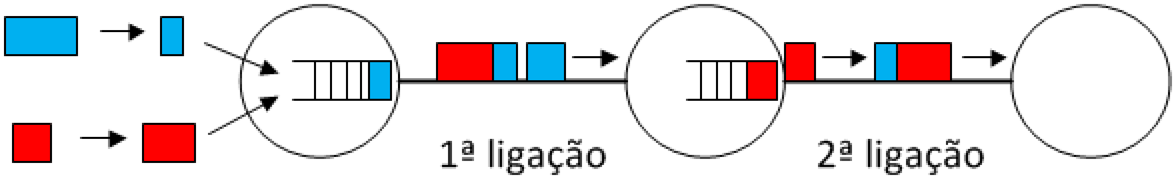
Routing defines the sequence of links through which the packets of each flow are forwarded from the source node to the destination node.



Network with multiple links

In a routing path with multiple links, the time intervals between consecutive packet arrivals are correlated with the size of the packets after their transmission in the first link. This fact makes it harder its modelling.



Example:

- Consider the above routing path with two links.
- Consider the aggregate of packet flows routed from the left node towards the right node.
- Consider that the packet arrivals of all flows are a Poisson process and the packet size of all flows is exponentially distributed with the same average size.

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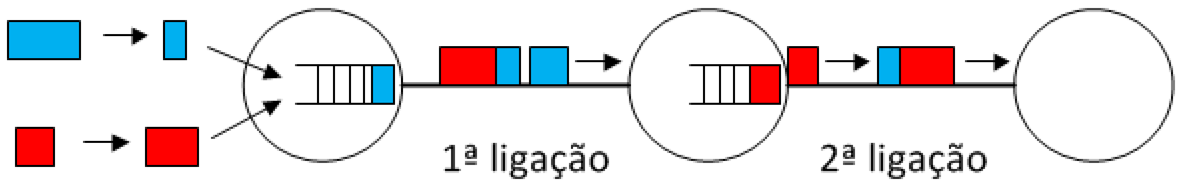
In a routing path with multiple links, the time intervals between consecutive packet arrivals are correlated with the size of the packets after their transmission in the first link. This fact makes it harder its modelling.



- In this case, the first (left) link is clearly a *M*/*M*/1 queuing system
- However, the second (right) link is not a *M*/*M*/1 queuing system:
  - The interarrival time between consecutive packets cannot be shorter than the transmission time of the second packet in the first link.
  - Typically, longer packets take more time to be transmitted in the first link and, therefore, wait less time on average in the queue of the second link.
  - So, the packet interarrival time it is not exponentially distributed and, therefore, packet arrivals at the second link are not Poisson processes.

Kleinrock approximation

The *Kleinrock approximation* consists in assuming that the packet arrivals of all flows are Poisson processes in all links of their routing paths

- i.e., it ignores the correlation between packet sizes and packet interarrival times

In links with long queues:

- when the packet size is exponentially distributed with the same average size for all flows – the link is modelled by $M/M/1$
- otherwise – the link is modelled by $M/G/1$

In links with short queues:

- the packet size is assumed to be exponentially distributed with the same average size for all flows – the link is modelled by $M/M/1/m$

Note that:

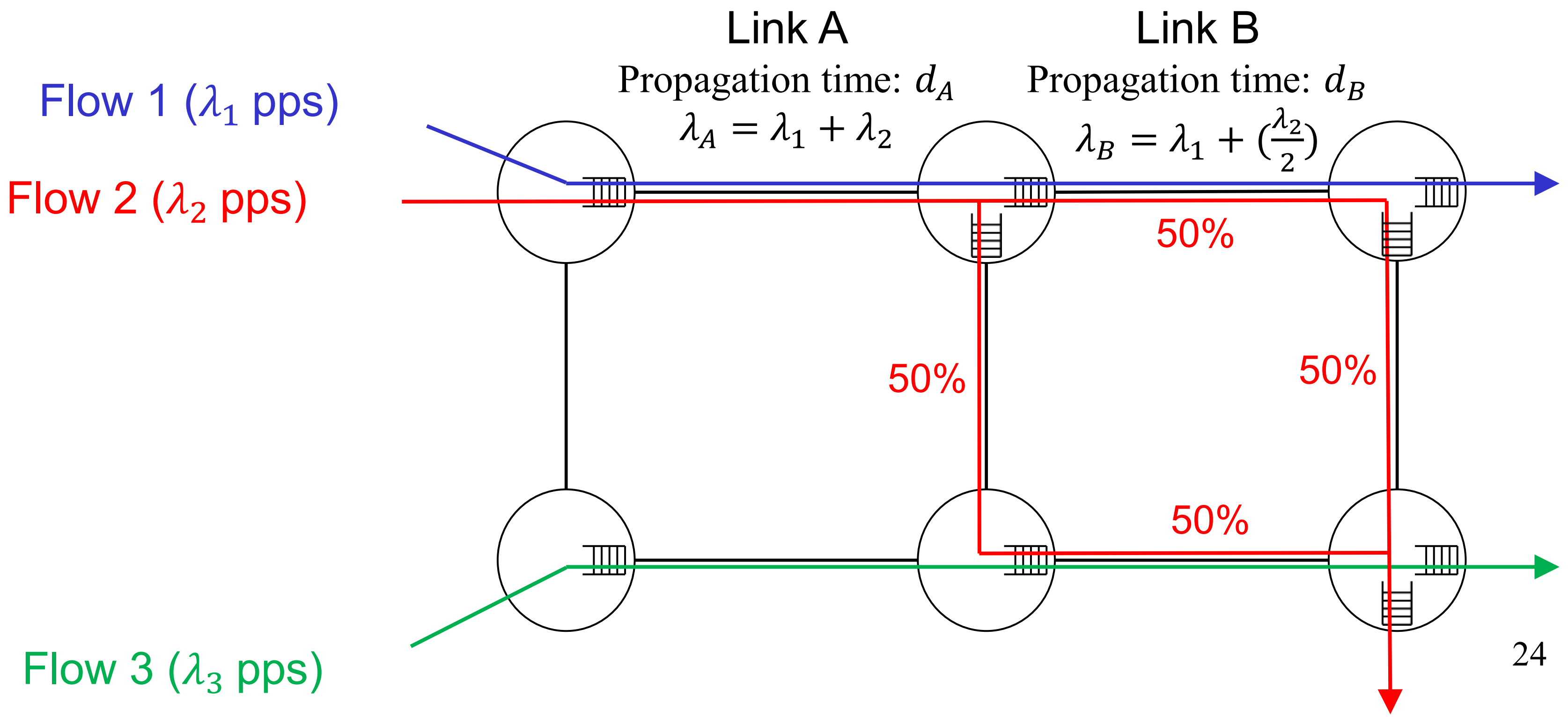
- the packet flows are unidirectional while the links in packet-switched networks are bidirectional
- so, a network link between nodes i and j is modelled by the ordered pairs (i,j) e (j,i) indicating each direction of the link

Average packet delay of each flow

For a flow with a single routing path (for example, Flow 1 in the figure), the average packet delay W_1 is the sum of the average delays on the links of the routing path.

$$\boxed{W_1 = W_{A1} + d_A + W_{B1} + d_B}$$

W_{A1} – average delay (average queuing delay + average transmission time) of flow 1 in link A

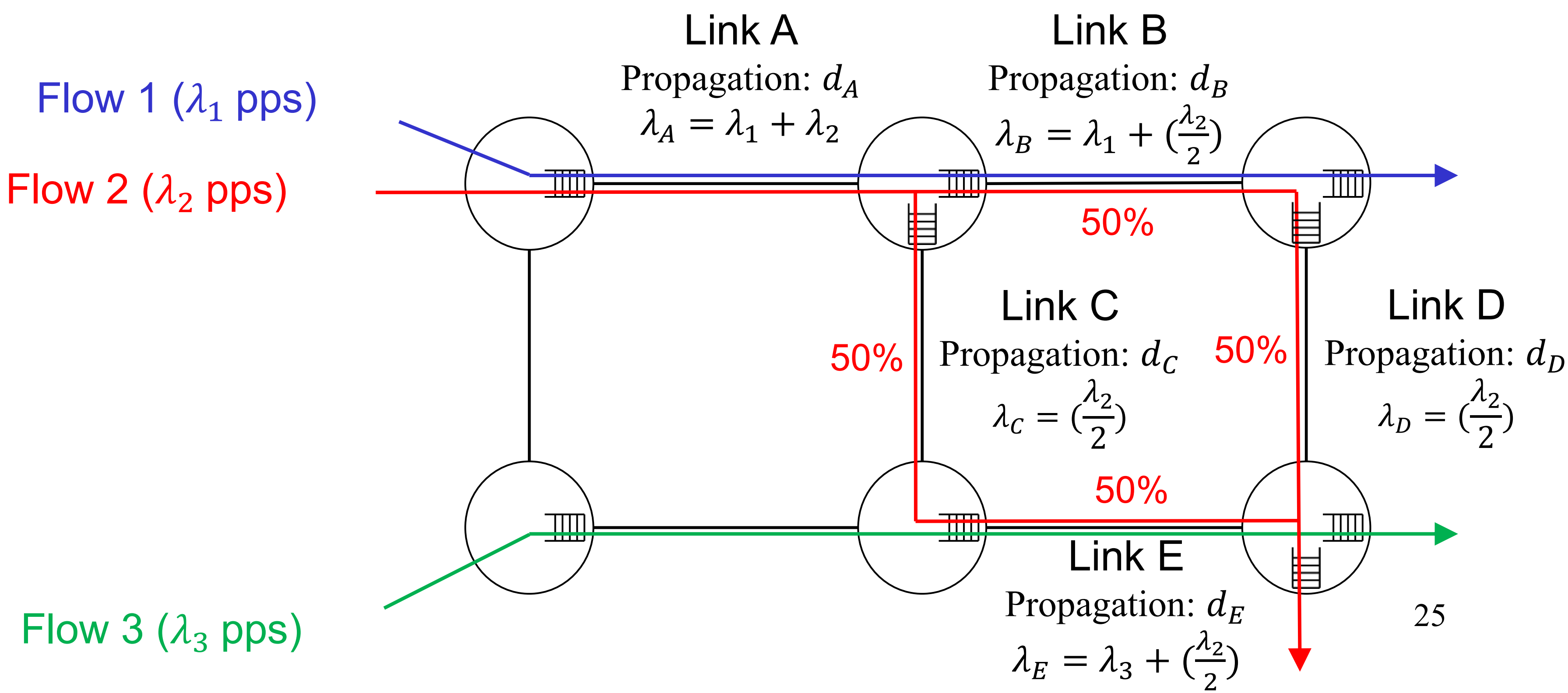


Average packet delay of each flow

For a flow with multiple routing paths (for example, Flow 2 in the figure), the average packet delay W_2 of the flow is:

- the weighted average of the average packet delay on each routing path,
- the weights are the percentages of the packets routed through each routing path.

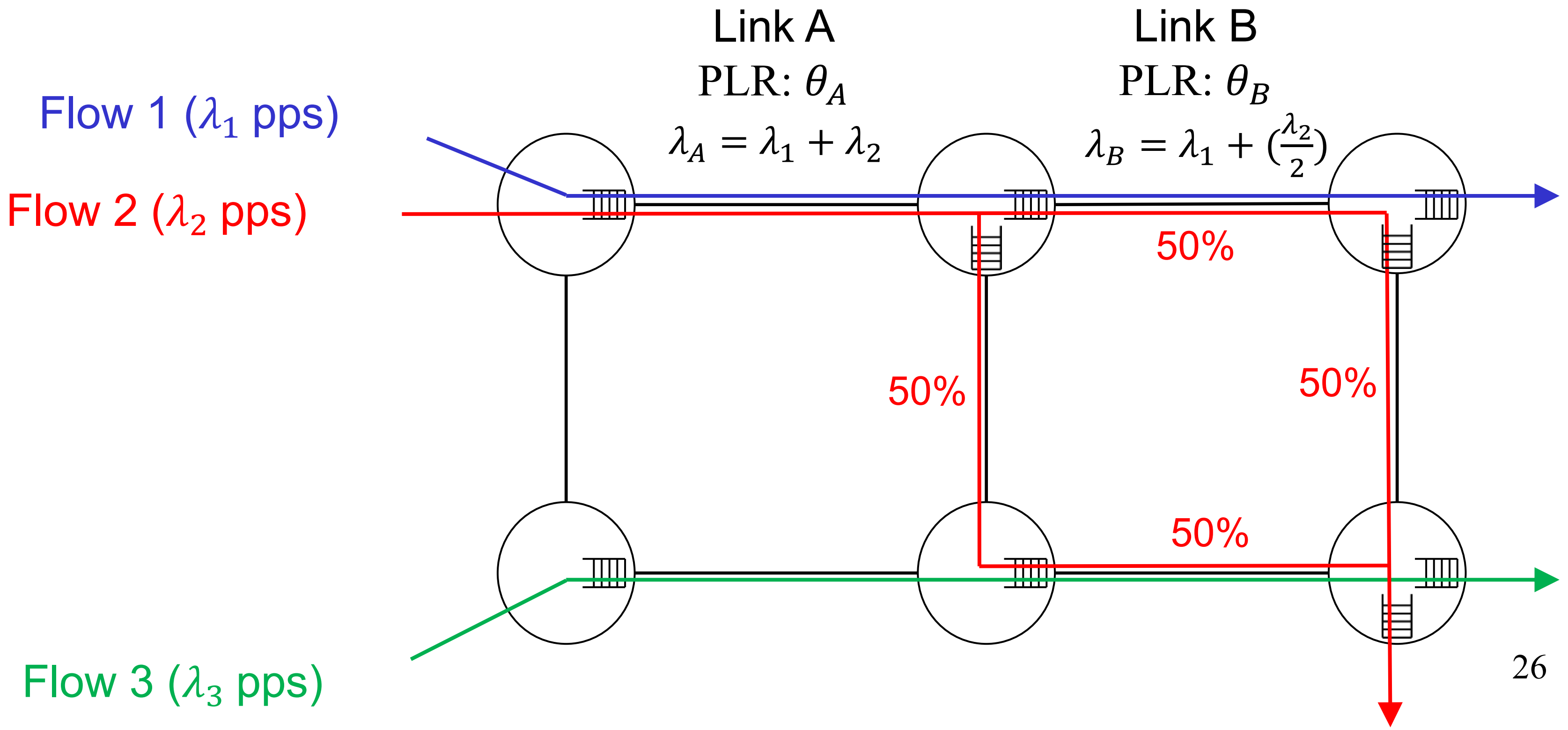
$$\boxed{\begin{aligned} W_2 = {} & 0.5 \times (W_{A2} + d_A + W_{B2} + d_B + W_{D2} + d_D) + \\ & + 0.5 \times (W_{A2} + d_A + W_{C2} + d_C + W_{E2} + d_D) \end{aligned}}$$



Packet loss rate (PLR) of each flow

For a flow with a single routing path (for example, Flow 1 in the figure), the packet loss rate θ_1 is given by the probability of each packet to be discarded in the 1st link, or in the 2nd link, etc.

$$\boxed{\theta_1 = \theta_A + (1 - \theta_A) \times \theta_B}$$

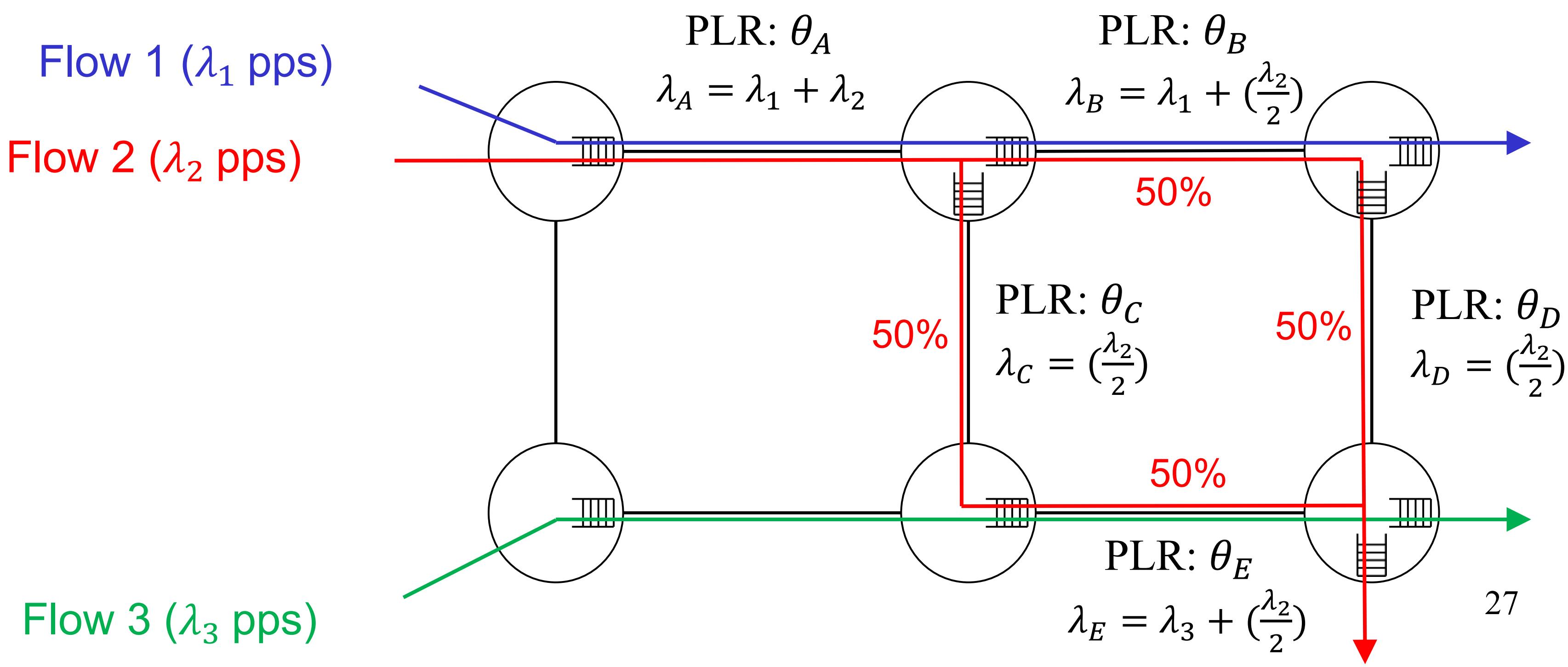


Packet loss rate (PLR) of each flow

For a flow with multiple routing paths (for example, Flow 2 in the figure), the packet loss rate θ_2 of the flow is:

- the weighted average of the packet loss rate on each routing path,
- the weights are the percentages of the packets routed through each routing path.

$$\boxed{\begin{aligned}\theta_2 = 0.5 \times [\theta_A + (1-\theta_A)\times\theta_B + (1-\theta_A)\times(1-\theta_B)\times\theta_D] + \\ + 0.5 \times [\theta_A + (1-\theta_A)\times\theta_C + (1-\theta_A)\times(1-\theta_C)\times\theta_E]\end{aligned}}$$



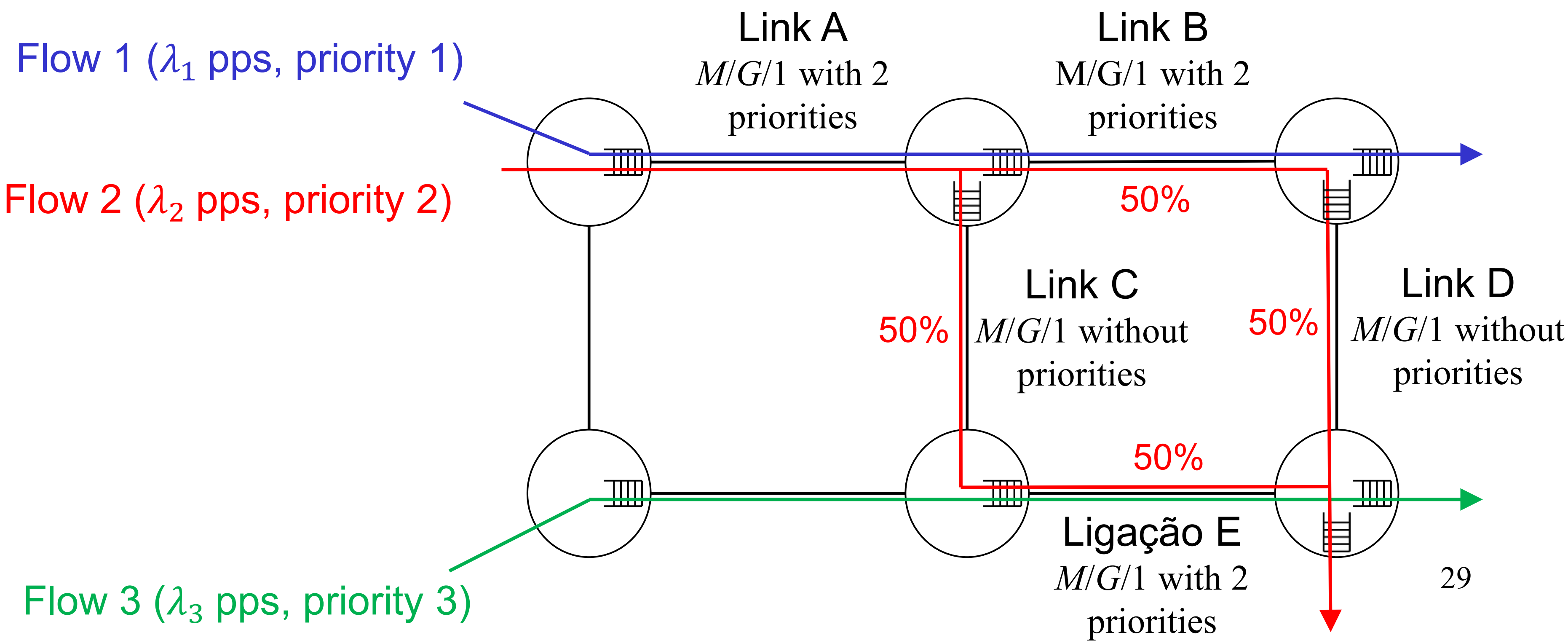
Impact of the packet loss rate in the average packet delay of each flow

- The packet loss rate (PLR) of a flow in one link reduces the packet arrival rate in the next links of the routing path towards the destination node.
- In practice, the packet loss rates are very small values (typically < 1%) since:
  - in data services, TCP protocol includes a flow control mechanism that reduces the packet sending rate in the source as soon it detects that a transmitted packet has not reached the receiver;
  - in real-time multimedia services, codecs can reconstruct the audio (and/or the video) for small packet loss rates; otherwise, services are halted when packet loss rates become prohibitively high.
- For small packet loss rate values, the impact in the reduction of the packet arrival rate is neglectable and, therefore, can be ignored in the determination of the average packet delays.

Global flow priorities and priorities on each link

Consider that each flow is assigned a global (i.e., network-wide) priority:

- Each link is modelled by a *M*/*G*/1 with the priorities considering only the priorities of the flows supported by the link
- In the example below, Flow 2 is the second priority flow in links A and B (Flow 2 has lower priority than Flow 1) but it is the first priority flow in link E (Flow 2 has higher priority than Flow 3)



Network of *M*/*M*/1 links (I)

Consider:

- a network of links such that the queues of all links are very large.
- the network supports a set of different flows $s = 1 \ldots S$ with the same priority, whose packet arriving rates are Poisson processes with rates λ_s (in packets/second)
- the packet size is exponentially distributed with the same average size for all flows.

In this case, all links are modelled by a *M*/*M*/1 queuing system.

Consider the particular case of each flow $s = 1 \ldots S$ being routed by a single routing path:

- Set R_s is the set of links (i,j) defining the routing path of flow s

Then, the total packet arriving rate to each link (i,j) is:

$$\lambda_{ij} = \sum_{s:(i,j)\in R_s} \lambda_s$$

Network of *M*/*M*/1 links (II)

Consider now the general case of each flow $s = 1 \dots S$ being routed by multiple routing paths:

- $f_{ij}(s)$ is defined as the fraction of the packets of flow s that are routed through link (i,j),
- Set R_s includes all links (i,j) such that $f_{ij}(s) > 0$.

In the general case, the total packet arriving rate to each link (i,j) is:

$$\lambda_{ij} = \sum_{s:(i,j)\in R_s} f_{ij}(s)\lambda_s$$

Considering μ_{ij} as the capacity of link (i,j) in average number of packets/second, the average number of packets in all links is (recall *M*/*M*/1 queuing model):

$$L = \sum_{(i,j)} \frac{\lambda_{ij}}{\mu_{ij} - \lambda_{ij}}$$

Network of *M*/*M*/1 links (III)

Using Little's theorem, the average packet delay suffered by all flows in the network is:

$$W = \frac{1}{\gamma}\sum_{(i,j)}\frac{\lambda_{ij}}{\mu_{ij}-\lambda_{ij}} \qquad \gamma = \sum_{s}\lambda_s$$

When propagation delay on links is not neglectable, the average packet delay suffered by all flows in the network becomes:

$$W = \frac{1}{\gamma}\sum_{(i,j)}\left(\frac{\lambda_{ij}}{\mu_{ij}-\lambda_{ij}}+\lambda_{ij}d_{ij}\right) \qquad \gamma = \sum_{s}\lambda_s$$

where d_{ij} is the propagation delay of link (*i*, *j*).

Network of *M*/*M*/1 links (IV)

For the flows *s* with a single routing path, the average packet delay of flow *s* is:

$$W_s = \sum_{(i,j)\in R_s} \left(\frac{1}{\mu_{ij} - \lambda_{ij}} + d_{ij} \right)$$

For the flows *s* with multiple routing paths (as previously stated), the average packet delay of flow *s* is:

- the weighted average of the average packet delay on each path (using the above formula),
- the weight of each path is the percentage of the arriving rate of flow *s*, λ_s, routed through each routing path.

- When all packet flows are routed by a single routing path, the main error source of the Kleinrock approximation is the correlation between packet size and interarrival time.
- When there are packet flows routed by multiple routing paths, another error source is the way how the packets of the flows are split on nodes between the different routing alternatives.

Example 2

Consider the IP network of the figure where all links are bidirectional with a capacity of 10 Mbps on each direction. The network is supporting 4 packet flows:

- from A to C with a Poisson rate of 1000 pps,
- from A to D with a Poisson rate of 250 pps,
- from B to D with a Poisson rate of 1000 pps,
- from B to E with a Poisson rate of 750 pps.

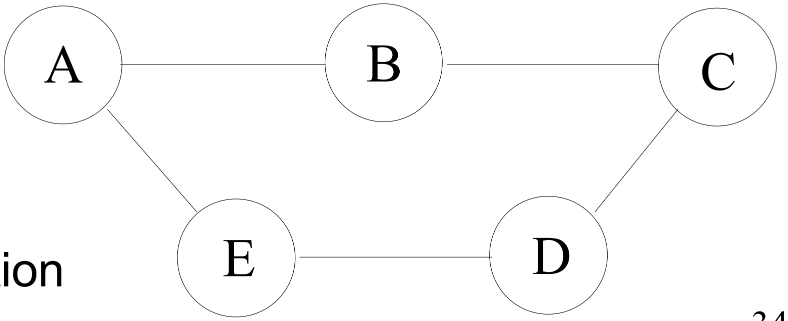
Packet sizes are exponentially distributed with average 500 bytes in all flows. The propagation delay of link B-C is 10 ms in each direction and is neglectable in all other links.

The routing protocol is RIP. Using the Kleinrock approximation, determine:

(a) the average packet delay of each flow,

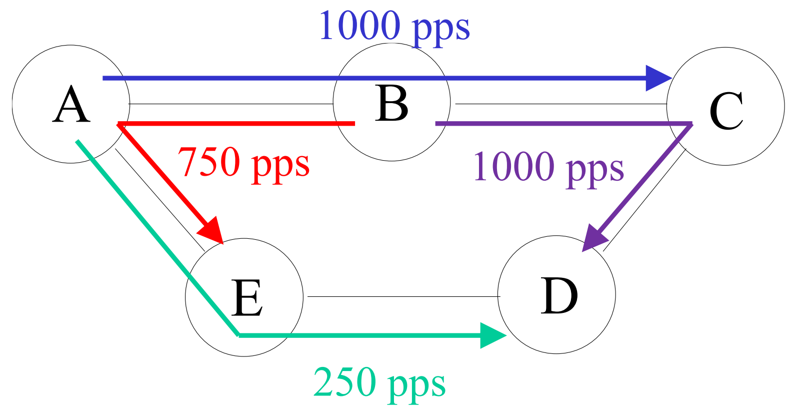
(b) the average packet delay of all flows,

(c) the utilization (in %) of each direction of each link.



Example 2

- Bidirectional links of 10 Mbps
- Average packet size = 500 bytes
- Propagation delay of link B-C: 10 ms in each direction
- Routing protocol: RIP



$$W_s = \sum_{(i,j)\in R_s} \left(\frac{1}{\mu_{ij} - \lambda_{ij}} + d_{ij} \right)$$

(a) the average packet delay of each flow,

$$\mu_{AB} = \mu_{BA} = \mu_{BC} = \ldots = \mu = \frac{10 \times 10^6 \text{ bps}}{500 \times 8 \text{ bpp}} = 2500 \text{ pps}$$

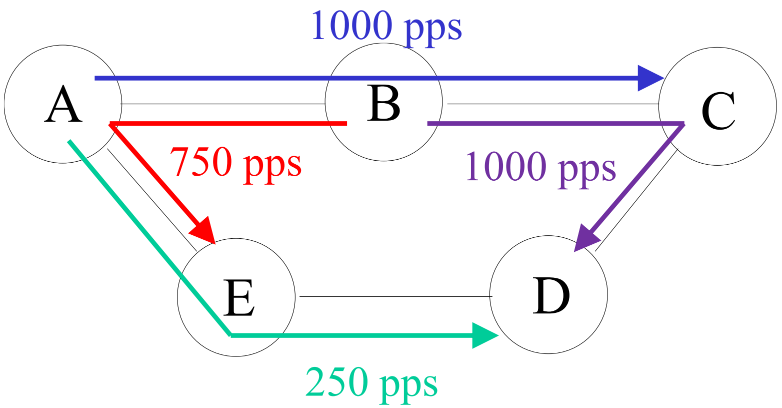
$$W_{A \to C} = \frac{1}{\mu_{AB} - \lambda_{AB}} + d_{AB} + \frac{1}{\mu_{BC} - \lambda_{BC}} + d_{BC} = \frac{1}{2500 - 1000} + 0 + \frac{1}{2500 - (1000 + 1000)} + 0.01 = 0.0127 \text{ seg.}$$

$$W_{A \to D} = \frac{1}{\mu_{AE} - \lambda_{AE}} + d_{AE} + \frac{1}{\mu_{ED} - \lambda_{ED}} + d_{ED} = \frac{1}{2500 - (750 + 250)} + 0 + \frac{1}{2500 - 250} + 0 = 0.0011 \text{ seg.}$$

$$W_{B \to D} = \frac{1}{\mu_{BC} - \lambda_{BC}} + d_{BC} + \frac{1}{\mu_{CD} - \lambda_{CD}} + d_{CD} = \frac{1}{2500 - (1000 + 1000)} + 0.01 + \frac{1}{2500 - 1000} + 0 = 0.0127 \text{ seg.}$$

$$W_{B \to E} = \frac{1}{\mu_{BA} - \lambda_{BA}} + d_{BA} + \frac{1}{\mu_{AE} - \lambda_{AE}} + d_{AE} = \frac{1}{2500 - 750} + 0 + \frac{1}{2500 - (750 + 250)} + 0 = 0.0012 \text{ seg.}$$

Example 2



- Bidirectional links of 10 Mbps
- Average packet size = 500 bytes
- Propagation delay of link B-C: 10 ms in each direction
- Routing protocol: RIP

$$W = \frac{1}{\gamma}\sum_{(i,j)}\left(\frac{\lambda_{ij}}{\mu_{ij}-\lambda_{ij}} + \lambda_{ij} d_{ij}\right)$$

$$\gamma = \sum_s \lambda_s$$

(b) the average packet delay of all flows,

$$\mu_{AB} = \mu_{BA} = \mu_{BC} = \ldots = \mu = \frac{10\times 10^6 \text{ bps}}{500\times 8 \text{ bpp}} = 2500 \text{ pps}$$

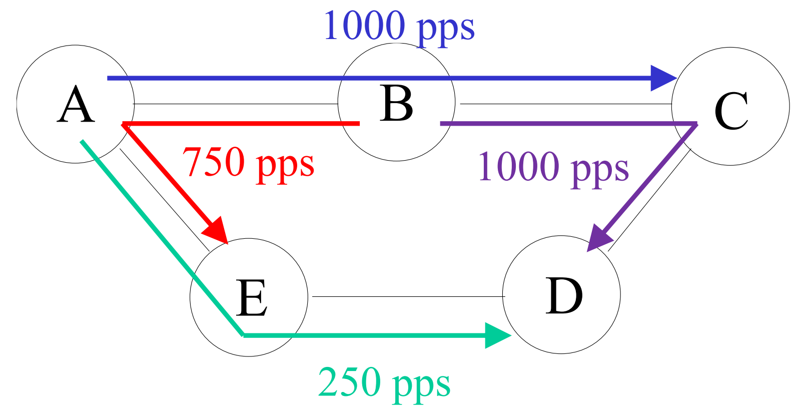
$$\gamma = \lambda_{A\to C} + \lambda_{A\to D} + \lambda_{B\to D} + \lambda_{B\to E} = 1000 + 250 + 1000 + 750 = 3000 \text{ pps}$$

$$W = \frac{1}{\gamma}\times\left(\frac{\lambda_{AB}}{\mu_{AB}-\lambda_{AB}} + \frac{\lambda_{BA}}{\mu_{BA}-\lambda_{BA}} + \frac{\lambda_{BC}}{\mu_{BC}-\lambda_{BC}} + \lambda_{BC} d_{BC} + \frac{\lambda_{CD}}{\mu_{CD}-\lambda_{CD}} + \frac{\lambda_{AE}}{\mu_{AE}-\lambda_{AE}} + \frac{\lambda_{ED}}{\mu_{ED}-\lambda_{ED}}\right)$$

$$W = \frac{1}{3000}\times\left(\frac{1000}{2500-1000} + \frac{750}{2500-750} + \frac{2000}{2500-2000} + 2000\times 0.01 + \frac{1000}{2500-1000} + \frac{1000}{2500-1000} + \frac{250}{2500-250}\right)$$

$$W = 0.00865 \text{ seg.}$$

Exemplo 2



- Bidirectional links of 10 Mbps
- Average packet size = 500 bytes
- Propagation delay of link B-C: 10 ms in each direction
- <u>Routing protocol: RIP</u>

(c) the utilization (in %) of each direction of each link.

$$\mu_{AB} = \mu_{BA} = \mu_{BC} = \ldots = \mu = \frac{10 \times 10^6 \text{ bps}}{500 \times 8 \text{ bpp}} = 2500 \text{ pps}$$

$$U_{AB} = \frac{\lambda_{AB}}{\mu_{AB}} = \frac{1000}{2500} = 0.4 = 40\% \qquad U_{BA} = \frac{\lambda_{BA}}{\mu_{BA}} = \frac{750}{2500} = 0.3 = 30\%$$

$$U_{BC} = \frac{\lambda_{BC}}{\mu_{BC}} = \frac{2000}{2500} = 0.8 = 80\% \qquad U_{CD} = \frac{\lambda_{CD}}{\mu_{CD}} = \frac{1000}{2500} = 0.4 = 40\%$$

$$U_{AE} = \frac{\lambda_{AE}}{\mu_{AE}} = \frac{1000}{2500} = 0.4 = 40\% \qquad U_{ED} = \frac{\lambda_{ED}}{\mu_{ED}} = \frac{250}{2500} = 0.1 = 10\%$$

Example 3

Consider the IP network of the figure where all links are bidirectional with a capacity of 10 Mbps on each direction. The network is supporting 4 packet flows:

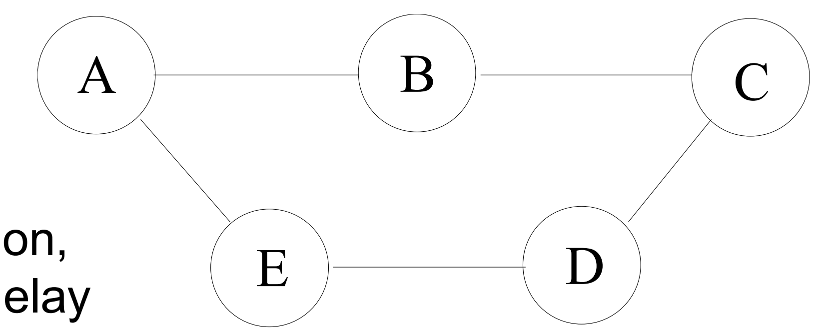
- from A to C with a Poisson rate of 1000 pps,
- from A to D with a Poisson rate of 250 pps,
- from B to D with a Poisson rate of 1000 pps,
- from B to E with a Poisson rate of 750 pps.

Packet sizes are exponentially distributed with average 500 bytes in all flows. The propagation delay of link B-C is 10 ms in each direction and is neglectable in all other links.

The routing protocol is OSPF.

(a) Determine the OSPF costs that minimize the highest utilization among all links.

(b) Using the Kleinrock approximation, determine the average packet delay of all flows in the previous solution.



Example 3

- Bidirectional links of 10 Mbps
- Average packet size = 500 bytes
- Propagation delay of link B-C: 10 ms in each direction
- <u>Routing protocol: OSPF</u>

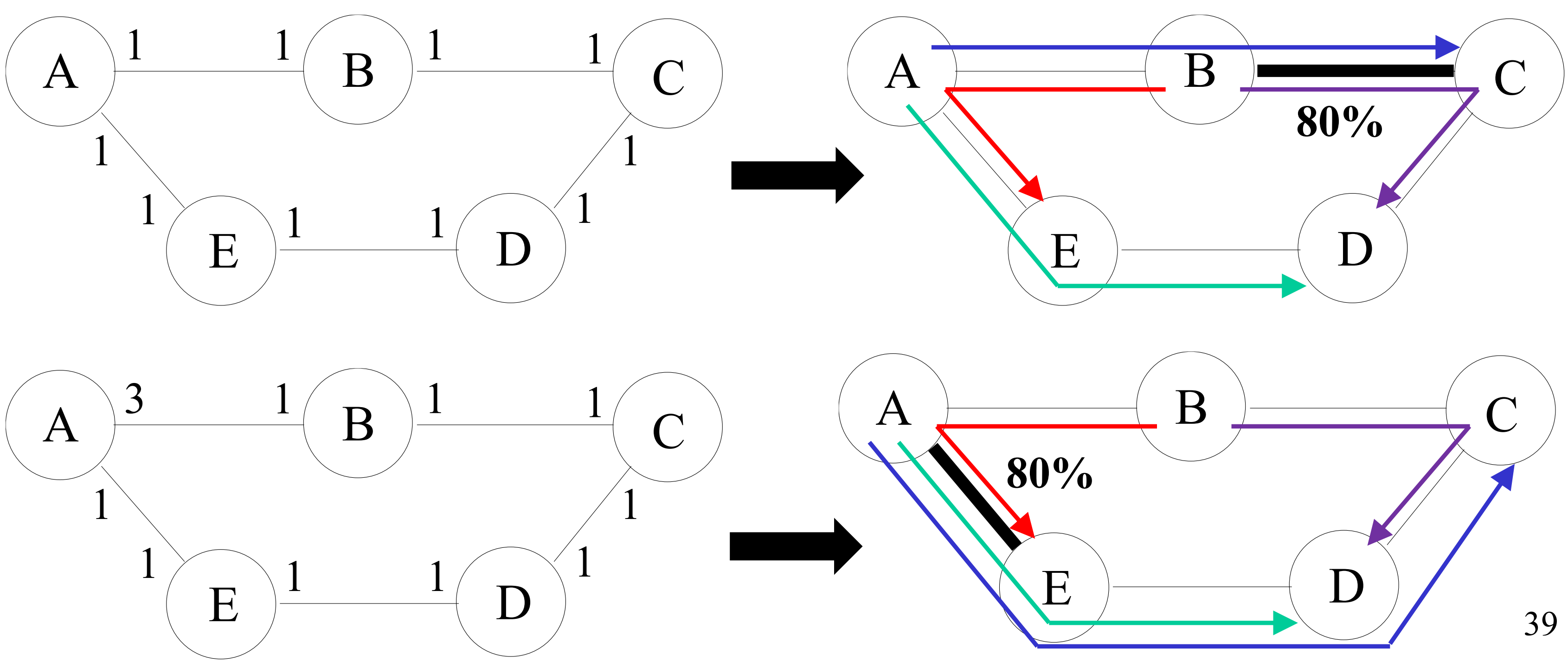
$\lambda_{A\to C} = 1000$ pps

$\lambda_{A\to D} = 250$ pps

$\lambda_{B\to D} = 1000$ pps

$\lambda_{B\to E} = 750$ pps

(a) Determine the OSPF costs that minimize the highest utilization among all links.



Exemplo 3

- Bidirectional links of 10 Mbps
- Average packet size = 500 bytes
- Propagation delay of link B-C: 10 ms in each direction
- <u>Routing protocol: OSPF</u>

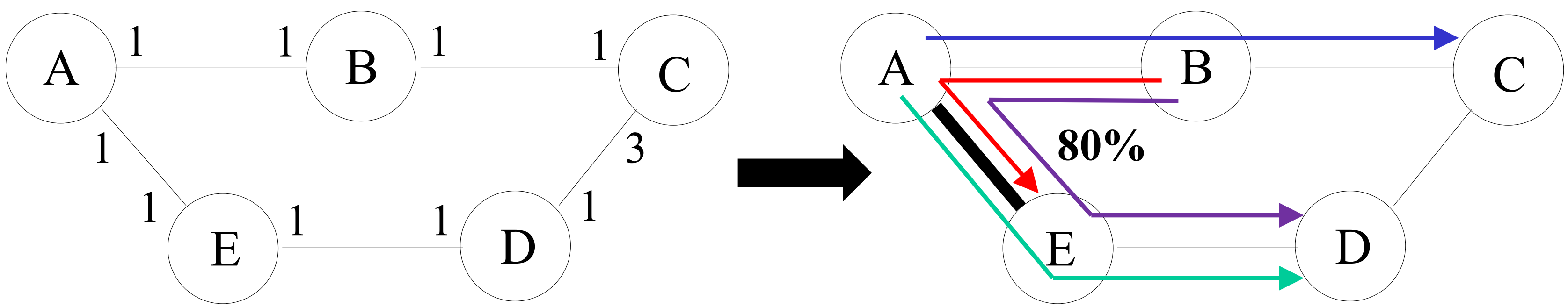
$\lambda_{A \to C} = 1000$ pps

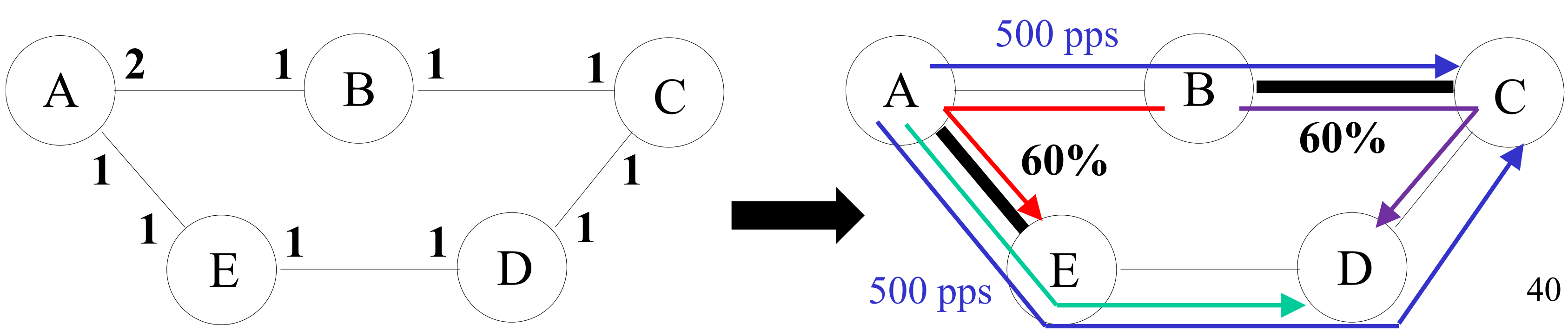
$\lambda_{A \to D} = 250$ pps

$\lambda_{B \to D} = 1000$ pps

$\lambda_{B \to E} = 750$ pps

(a) Determine the OSPF costs that minimize the highest utilization among all links.





Example 3

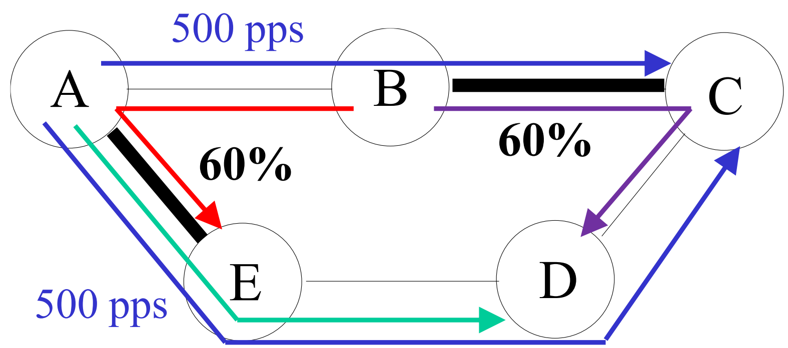
- Bidirectional links of 10 Mbps
- Average packet size = 500 bytes
- Propagation delay of link B-C: 10 ms in each direction
- Routing protocol: OSPF

$\lambda_{A\to C} = 1000 \text{ pps}$

$\lambda_{A\to D} = 250 \text{ pps}$

$\lambda_{B\to D} = 1000 \text{ pps}$

$\lambda_{B\to E} = 750 \text{ pps}$



(b) Using the Kleinrock approximation, determine the average packet delay of all flows in the previous solution.

$$\mu_{AB} = \mu_{BA} = \mu_{BC} = \ldots = \mu = \frac{10\times 10^6 \text{ bps}}{500\times 8 \text{ bpp}} = 2500 \text{ pps}$$

$$\gamma = \lambda_{A\to C} + \lambda_{A\to D} + \lambda_{B\to D} + \lambda_{B\to E} = 1000 + 250 + 1000 + 750 = 3000 \text{ pps}$$

$$W = \frac{1}{\gamma}\times\left(\frac{\lambda_{AB}}{\mu_{AB}-\lambda_{AB}} + \frac{\lambda_{BA}}{\mu_{BA}-\lambda_{BA}} + \frac{\lambda_{BC}}{\mu_{BC}-\lambda_{BC}} + \lambda_{BC}d_{BC} + \frac{\lambda_{CD}}{\mu_{CD}-\lambda_{CD}} + \frac{\lambda_{DC}}{\mu_{DC}-\lambda_{DC}} + \frac{\lambda_{AE}}{\mu_{AE}-\lambda_{AE}} + \frac{\lambda_{ED}}{\mu_{ED}-\lambda_{ED}}\right)$$

$$W = \frac{1}{3000}\times\left(\frac{500}{2500-500} + \frac{750}{2500-750} + \frac{1500}{2500-1500} + 1500\times 0.01 + \frac{1000}{2500-1000} + \frac{500}{2500-500} + \frac{1500}{2500-1500} + \frac{750}{2500-750}\right)$$

$W = 0.00667$ seg. (Example 2: $W = 0.00865$ seg.)