Link state routing and OSPF

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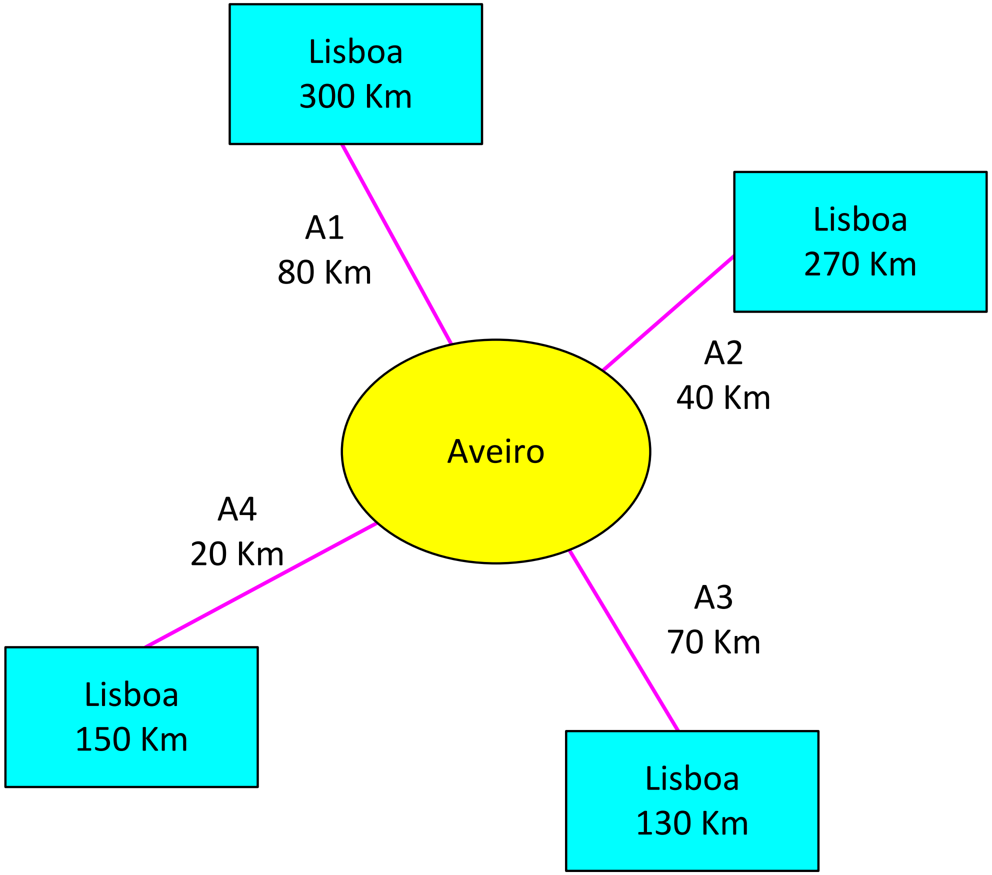
IP routing protocols

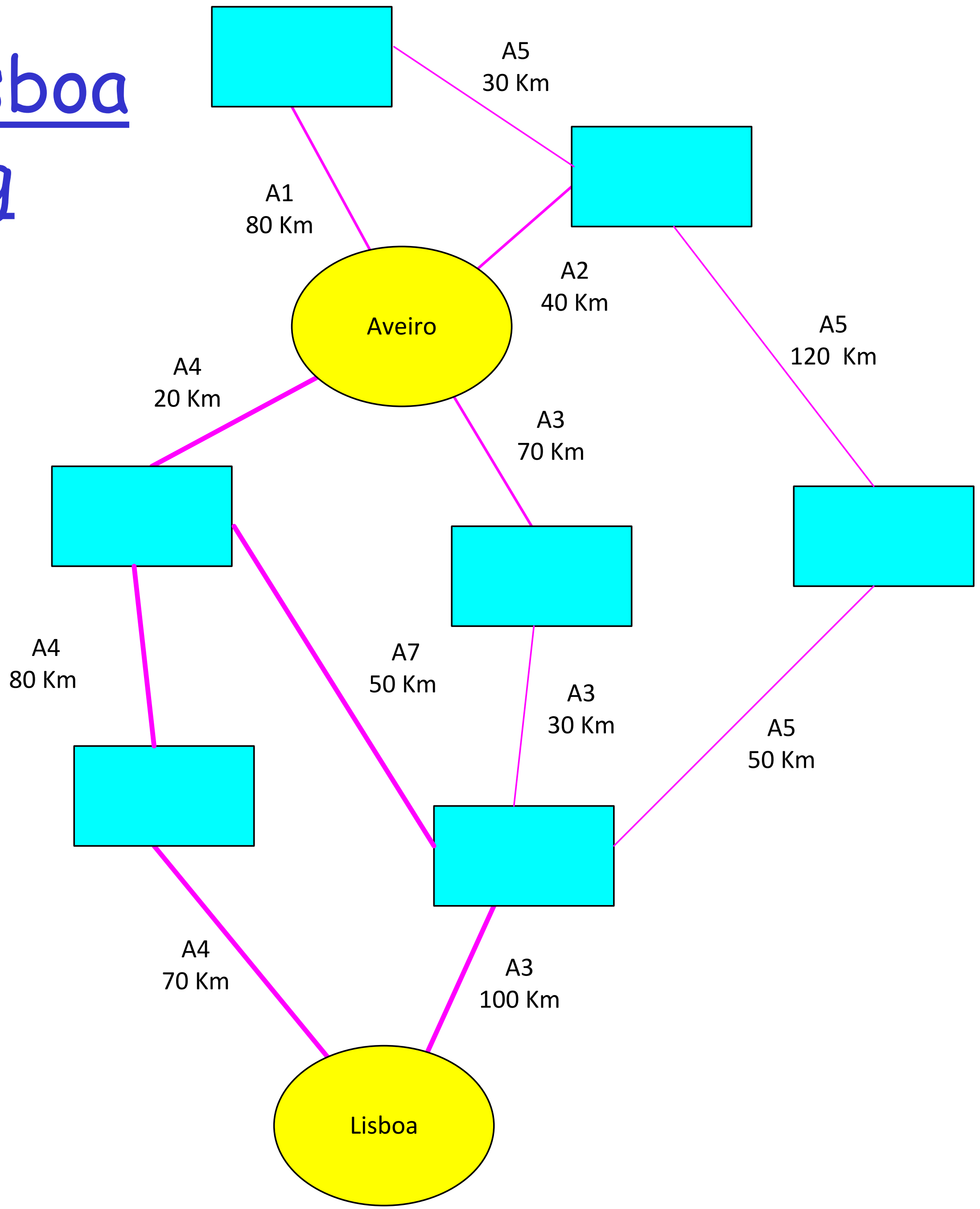
- IP routing is based on shortest paths
  - But there are different ways to compute them in a distributed way…
- Distance vector protocols
  - Use the distributed and asynchronous version of the Bellman-Ford algorithm
  - Examples: RIP, IGRP, EIGRP
- Link state protocols
  - Routers broadcast information about their links with neighbors; in this way, they get to know the complete network topology (which is stored in a database)
  - Each router runs a centralized shortest path algorithm (usually the Dijkstra algorithm) to build the routing table
  - Examples: OSPF, IS-IS, NLSP

From Aveiro to Lisboa - distance vector routing

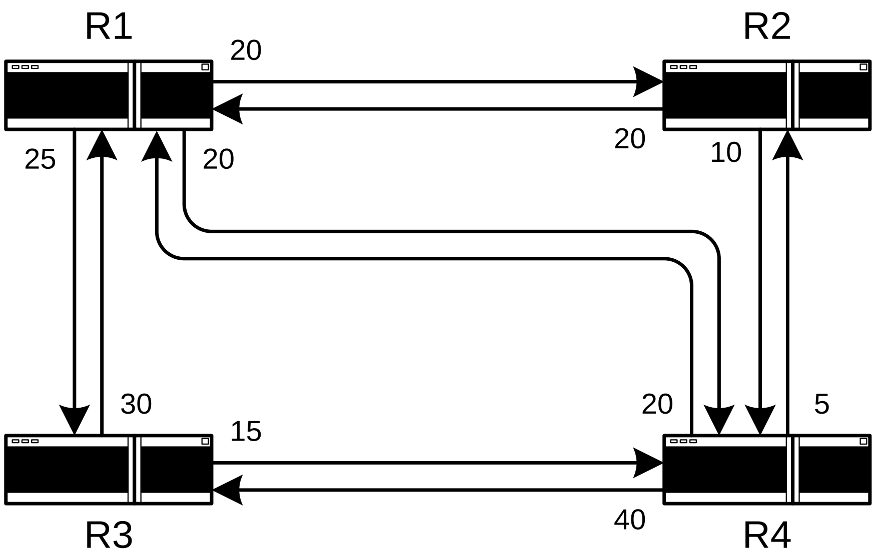


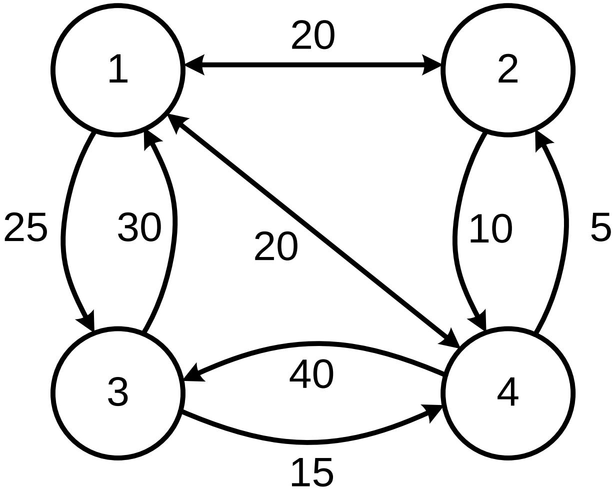
The shortest path is through A4!

From Aveiro to Lisboa - link state routing



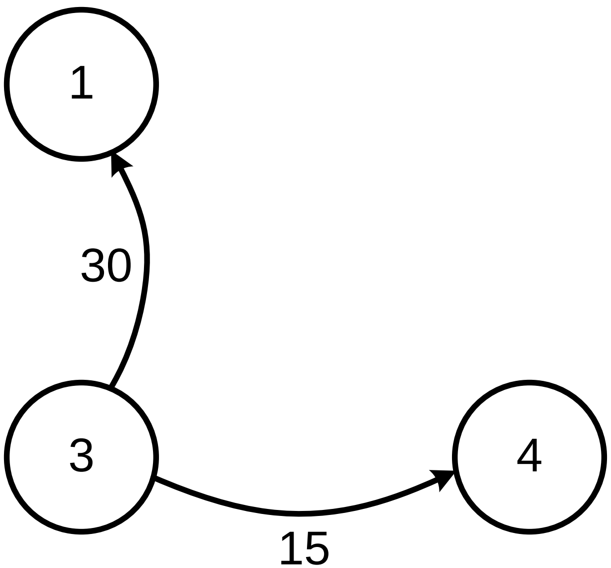
Building the network graph



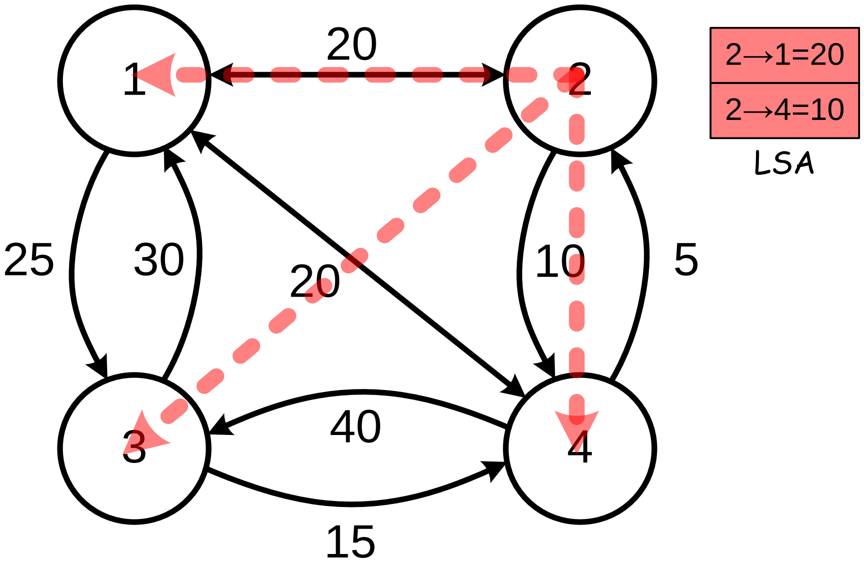


Network of routers connected by point-to-point links and its directed graph

Building the network graph

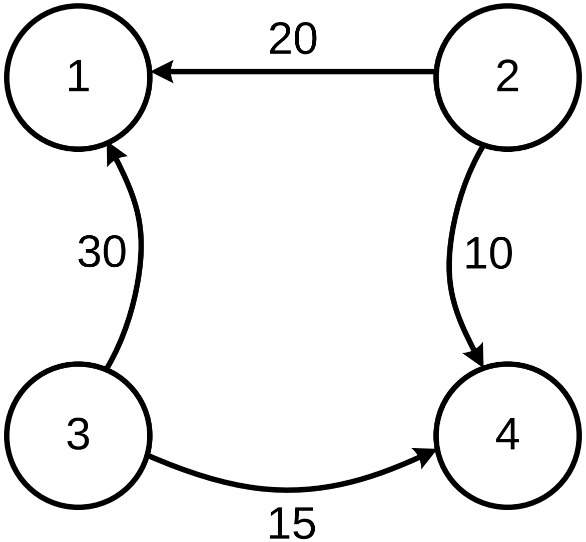


Initial graph of R3

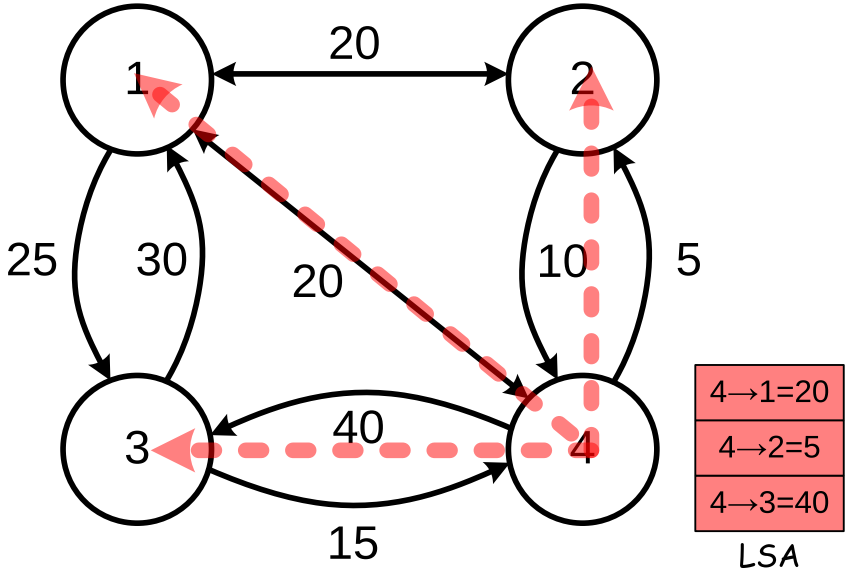


R2 broadcasts its LSA

Building the network graph

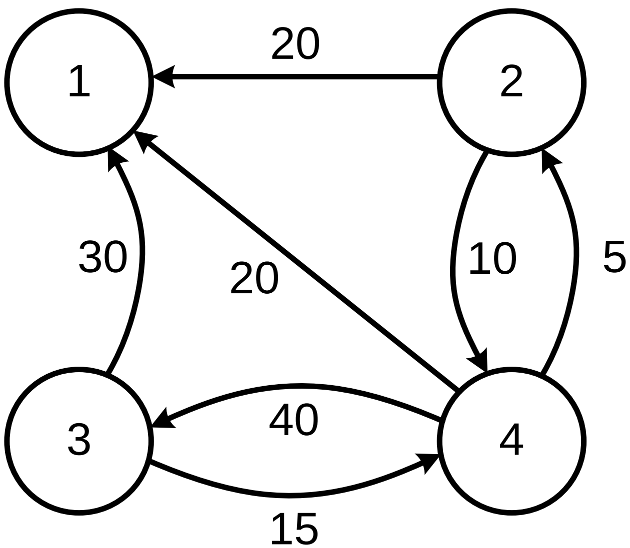


Graph of R3 after receiving LSA from R2

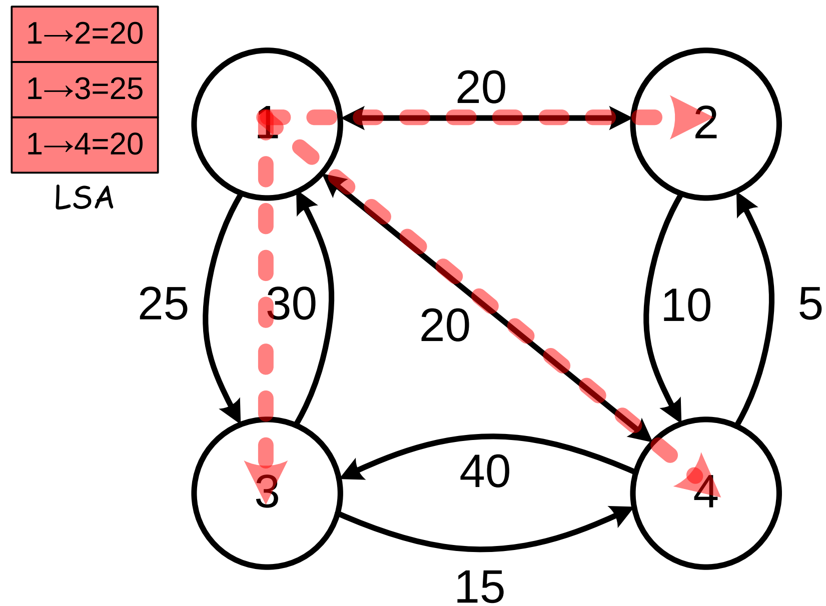


R4 broadcasts its LSA

Building the network graph

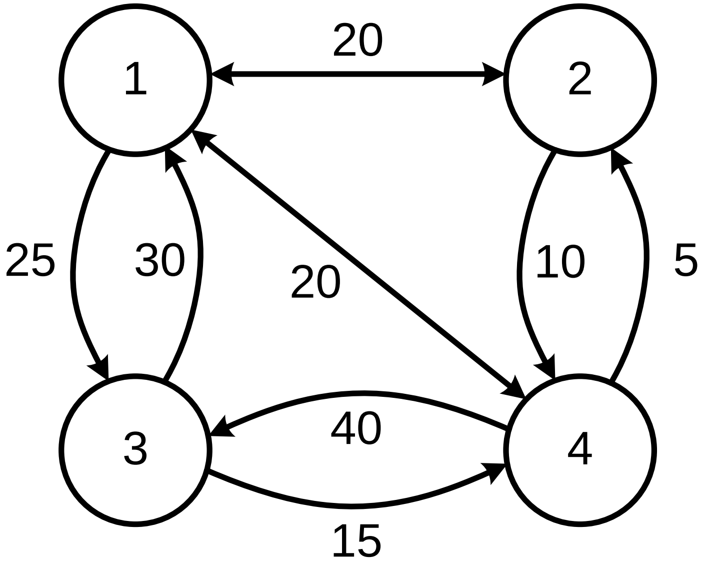


Graph of R3 after receiving LSA from R4



R1 broadcasts its LSA

Building the network graph



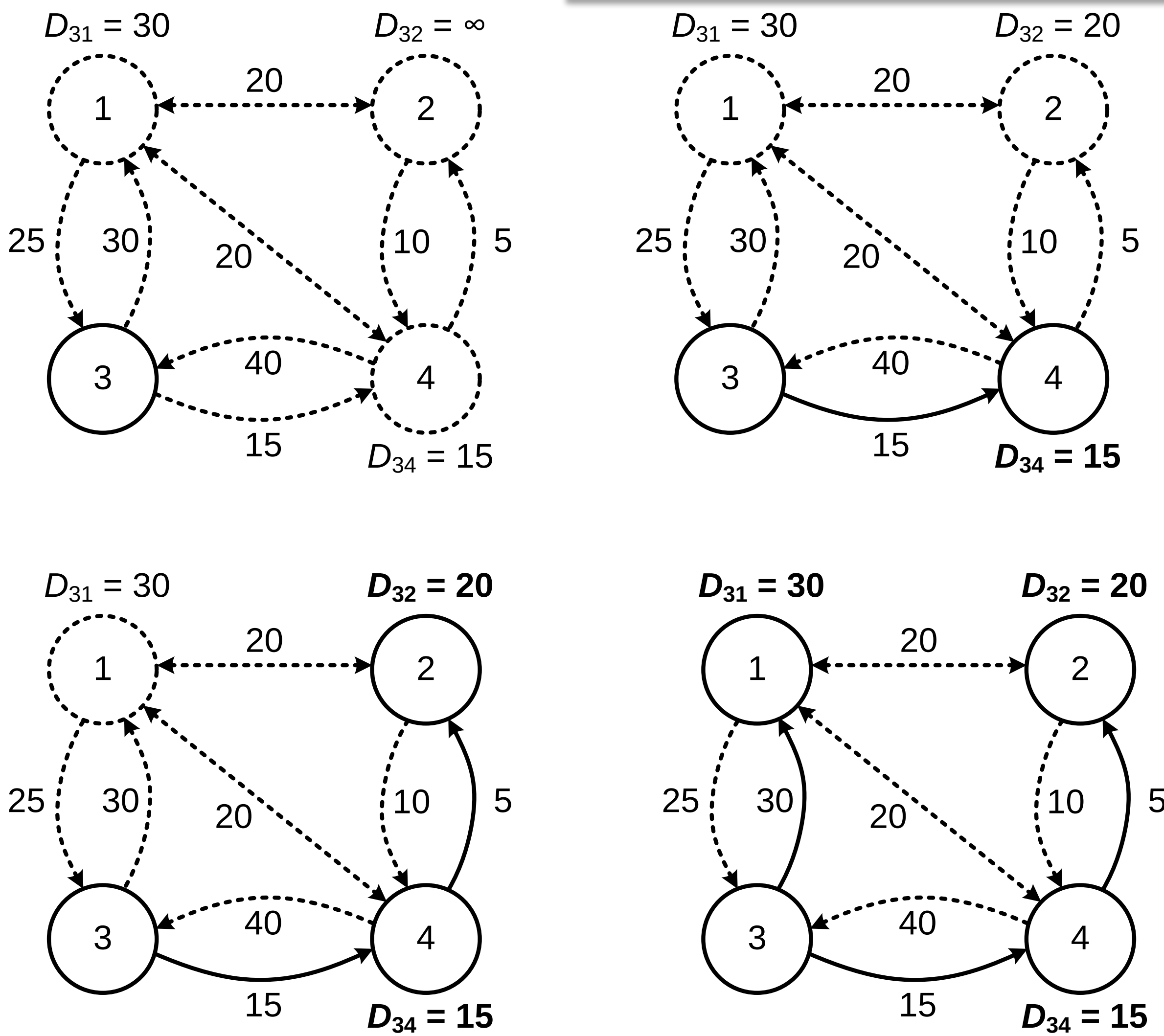
Final graph of R3, after receiving LSAs from all routers

IMPORTANT NOTE: all nodes must have the same network graph!

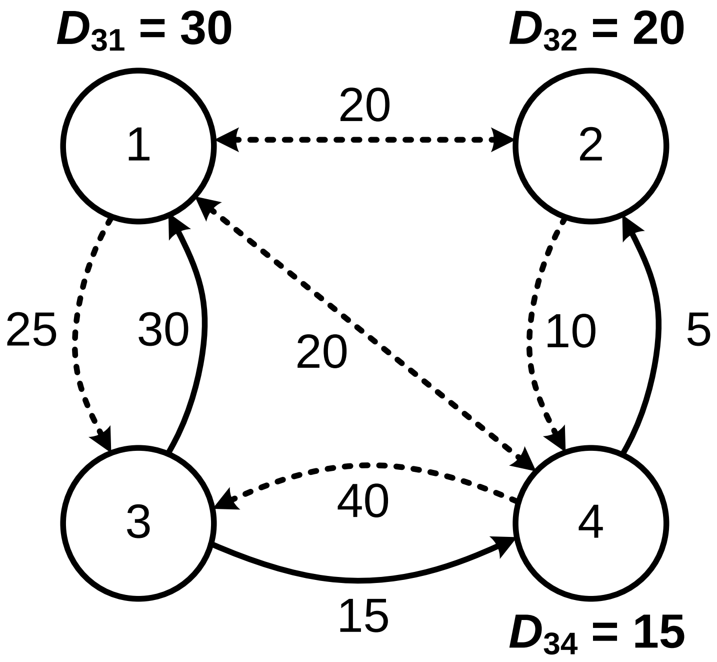
Building the routing table

0. Initially, set $S = \{i\}$, $D_{ij} = d_{ij}$, for all $j \notin S$.
1. Find the next closest node, i.e., find $k \notin S$ such that
$$D_{ik} = \min_{m \notin S} D_{im}$$
   Set $S \coloneqq S \cup \{k\}$. If S contains all nodes, stop.
2. Update the labels, i.e., for all $j \notin S$ set
$$D_{ij} = \min[D_{ij}, D_{ik} + d_{kj}]$$
   Go to step 1.

Dijkstra algorithm



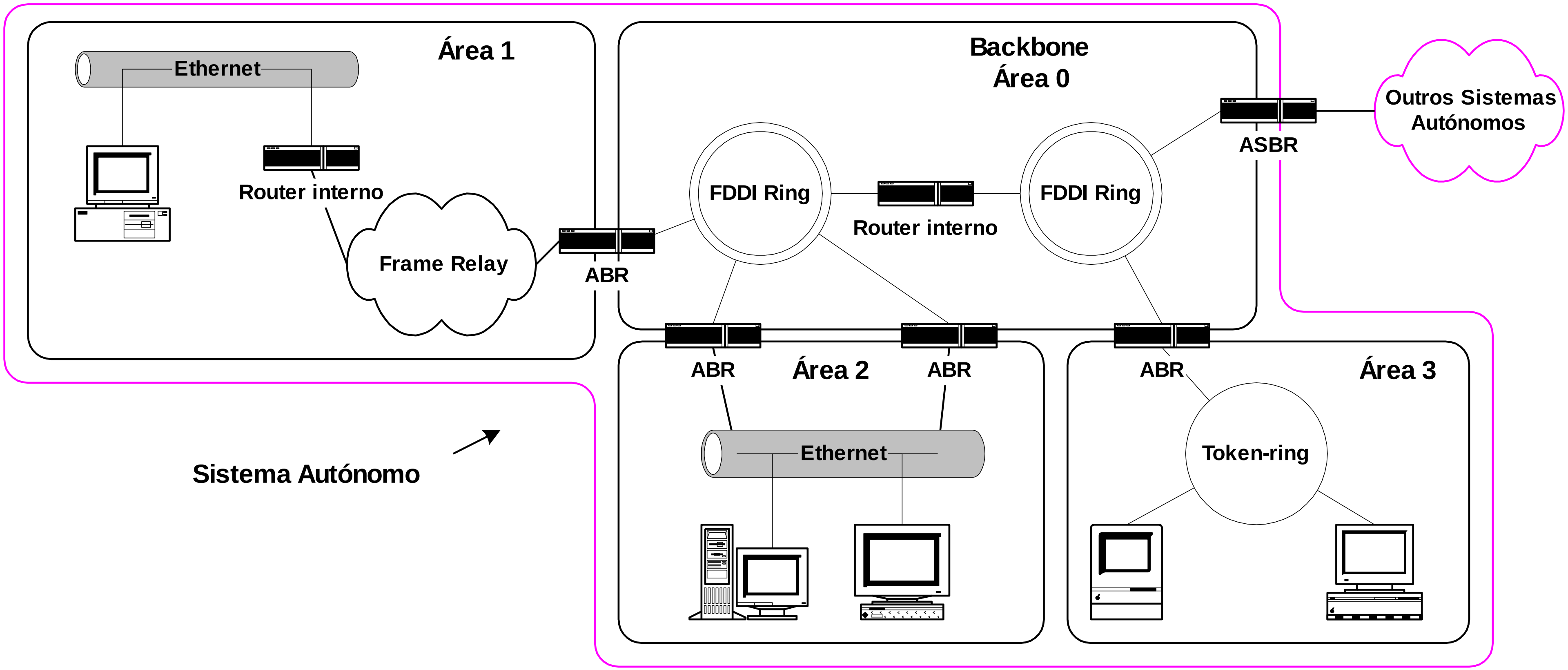
Building the routing table



destination	next hop	cost
R1	R1	30
R2	R4	20
R4	R4	15

Routing table of R3

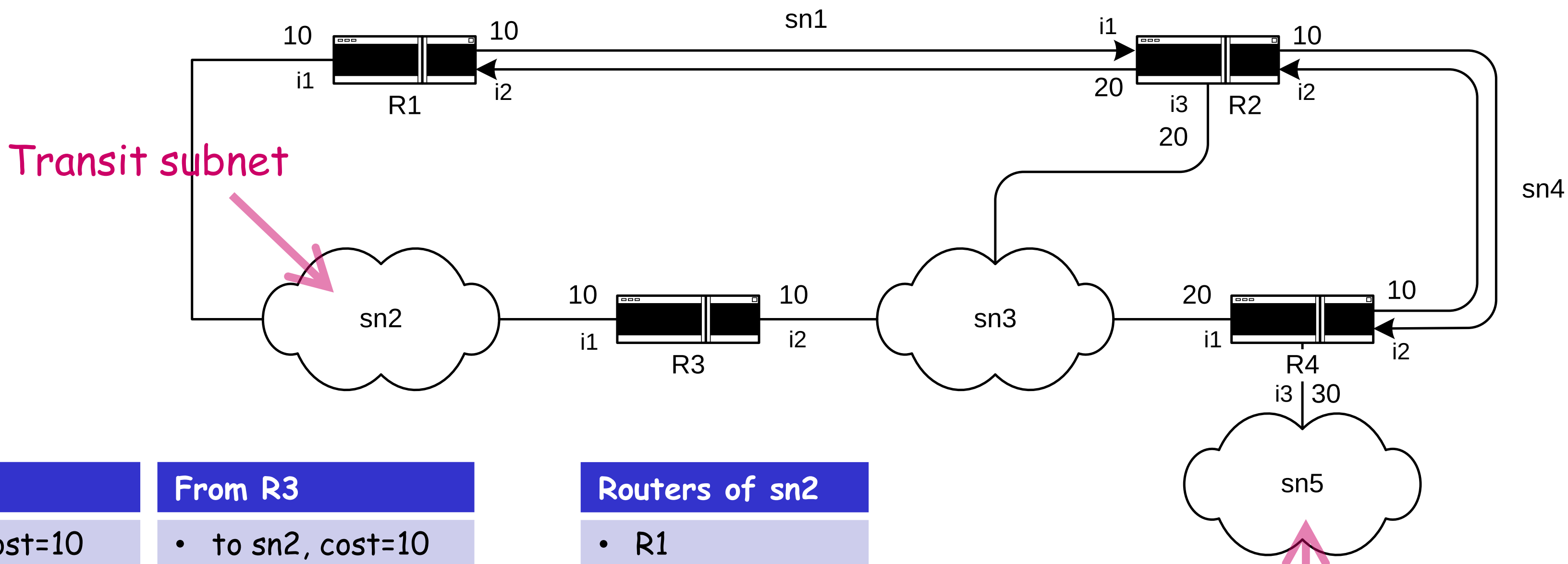
Structure of OSPF network



The Link State Database (LSDB)

- Database that stores the network topology (the network graph)
- A collection of LSAs each describing a piece of the network
- LSA Types:
  - Router-LSA: describes one router and its outgoing links
  - Network-LSA: describes one broadcast subnet and the routers attached to it
  - Summary-LSA and AS-external-LSA: used in hierarchical routing
  - … and a few more

The Link State Database



Stub subnet

From R1
• to R2, cost=10
• to sn2, cost=10

From R2
• to R1, cost=20
• to sn3, cost=20
• to R4, cost=10

From R3
• to sn2, cost=10
• to sn3, cost=10

From R4
• to R2, cost=10
• to sn3, cost=20
• to sn5, cost=30

Router-LSAs

(describes one router and its outgoing links)

Routers of sn2
• R1
• R3

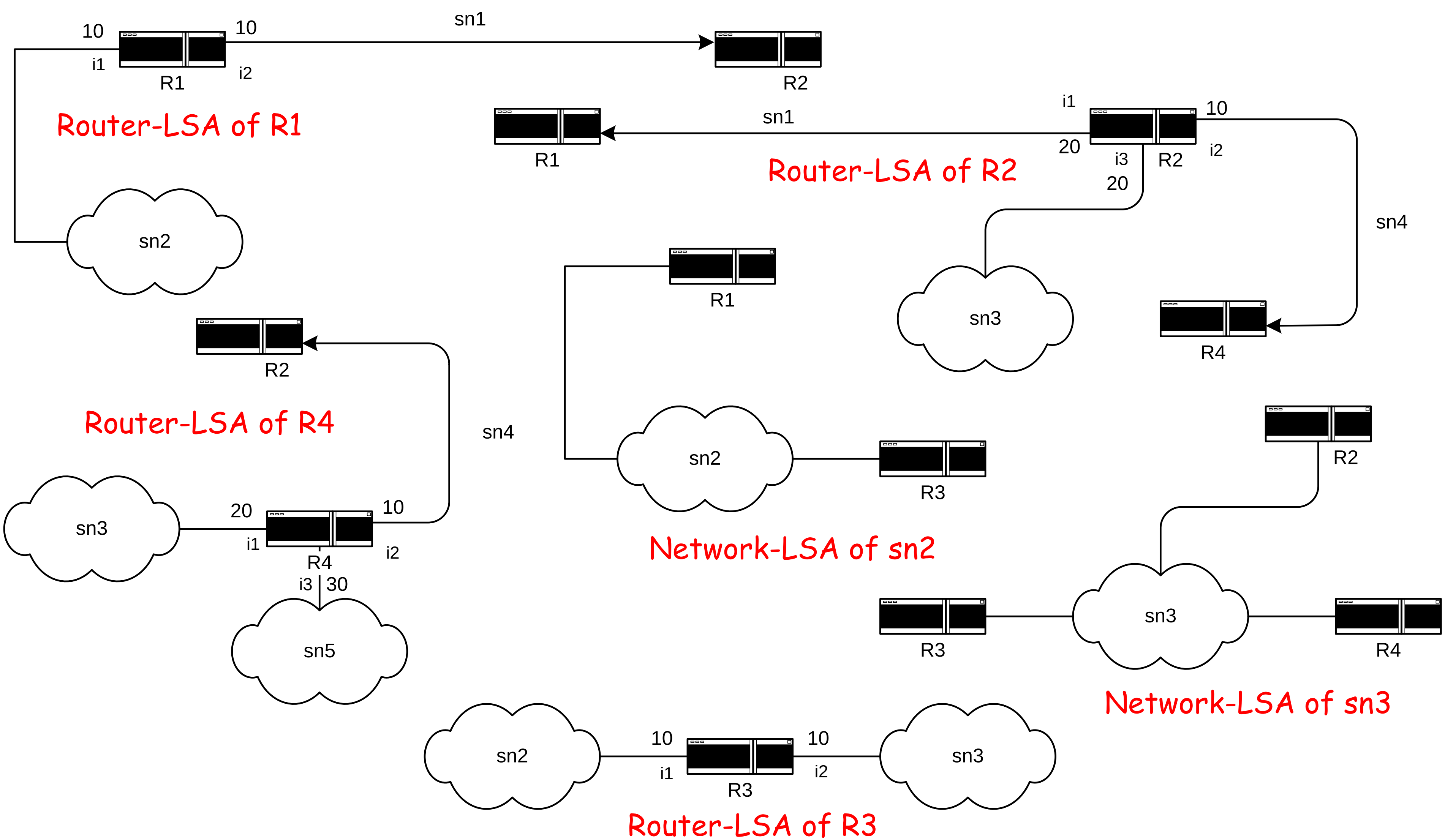
Routers of sn3
• R2
• R3
• R4

Network-LSAs

(describes one broadcast subnet and its attached routers)

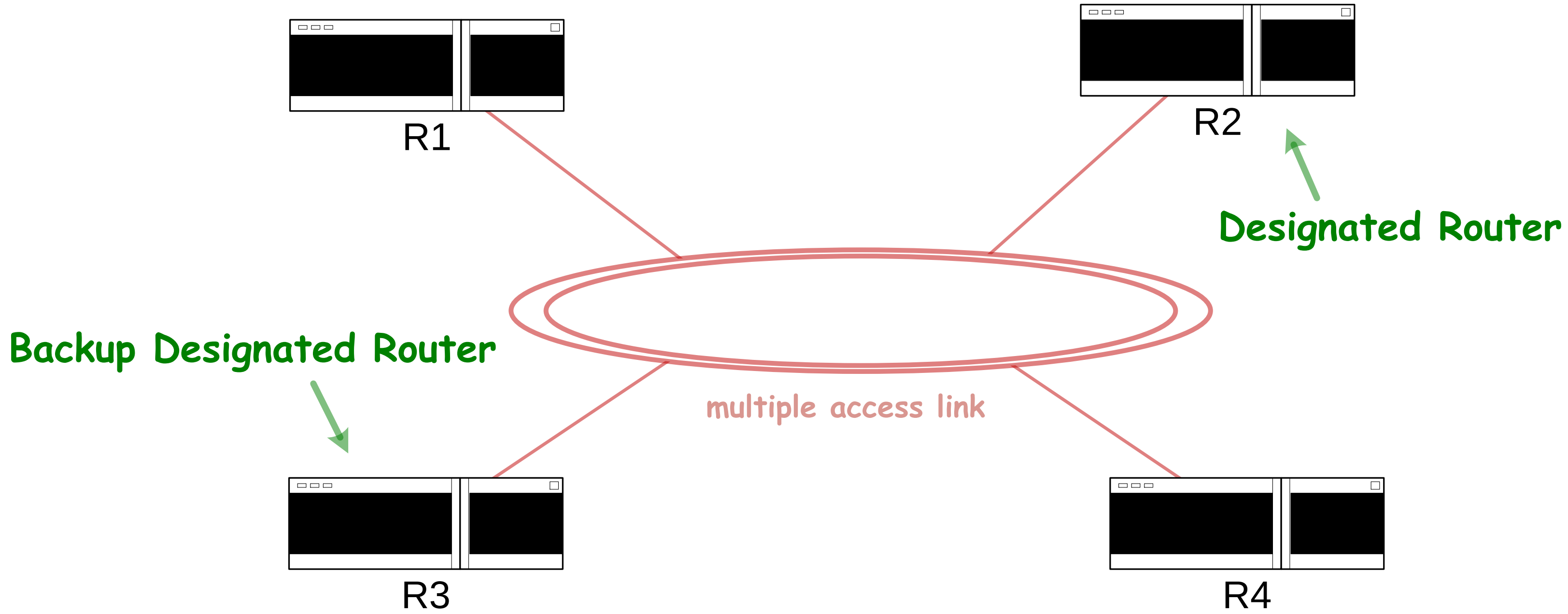
- Routers are identified by RID (Router ID)
- Transit subnets are identified by address of Designated Router (DR)
- Stub subnet represented in router-LSA by subnet address

LSDB - The OSPF network broken in pieces

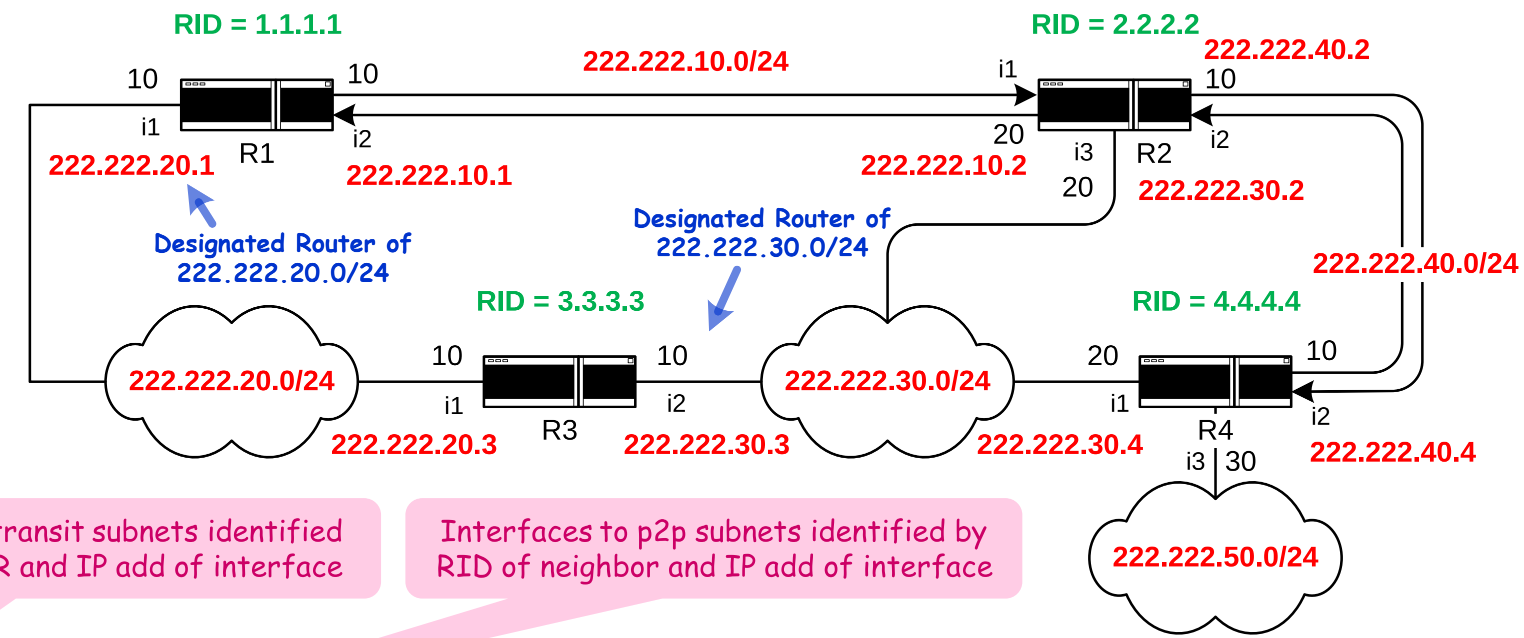


Designated and Backup Designated Routers

- Every broadcast subnet has a Designated Router and Backup Designated Router
- DR plays special role in flooding process and identifies subnet in the LSDB
- BDR replaces the DR in case of failure



The Link State Database



Interfaces to transit subnets identified by IP add of DR and IP add of interface

Interfaces to p2p subnets identified by RID of neighbor and IP add of interface

1.1.1.1	3.3.3.3
2.2.2.2, 222.222.10.1, c=10	222.222.20.1, 222.222.20.3, c=10
222.222.20.1, 222.222.20.1, c=10	222.222.30.3, 222.222.30.3, c=10

2.2.2.2	4.4.4.4
1.1.1.1, 222.222.10.2, c=20	2.2.2.2, 222.222.40.4, c=10
222.222.30.3, 222.222.30.2, c=20	222.222.30.3, 222.222.30.4, c=20
4.4.4.4, 222.222.40.2, c=10	222.222.50.0/24, c=30

222.222.20.1/24
1.1.1.1
3.3.3.3

222.222.30.3/24
2.2.2.2
3.3.3.3
4.4.4.4

Broadcast subnets identified by IP address of DR

Routers identified by RID

Router-LSAs

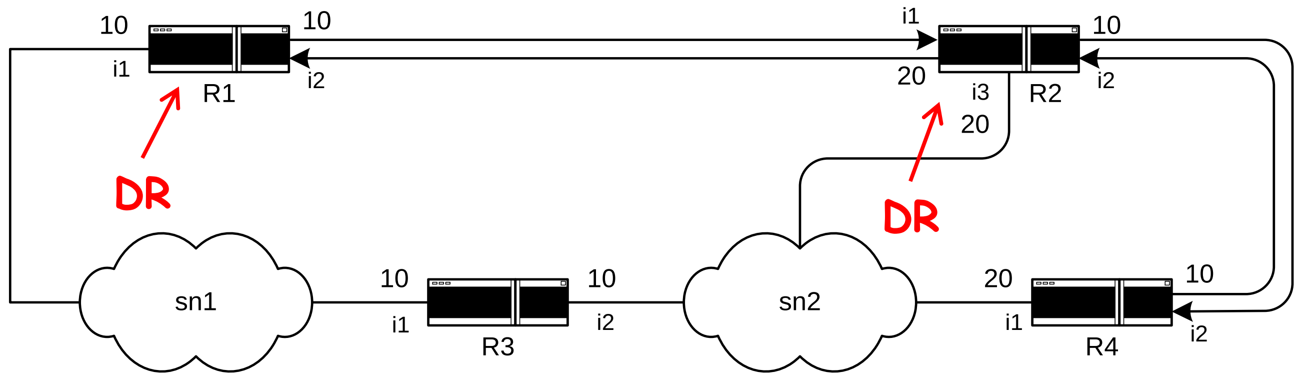
(describes one router and its outgoing links)

Network-LSAs

(describes one broadcast subnet and its attached routers)

Interfaces to stub subnets identified by subnet address

Advertising Routers



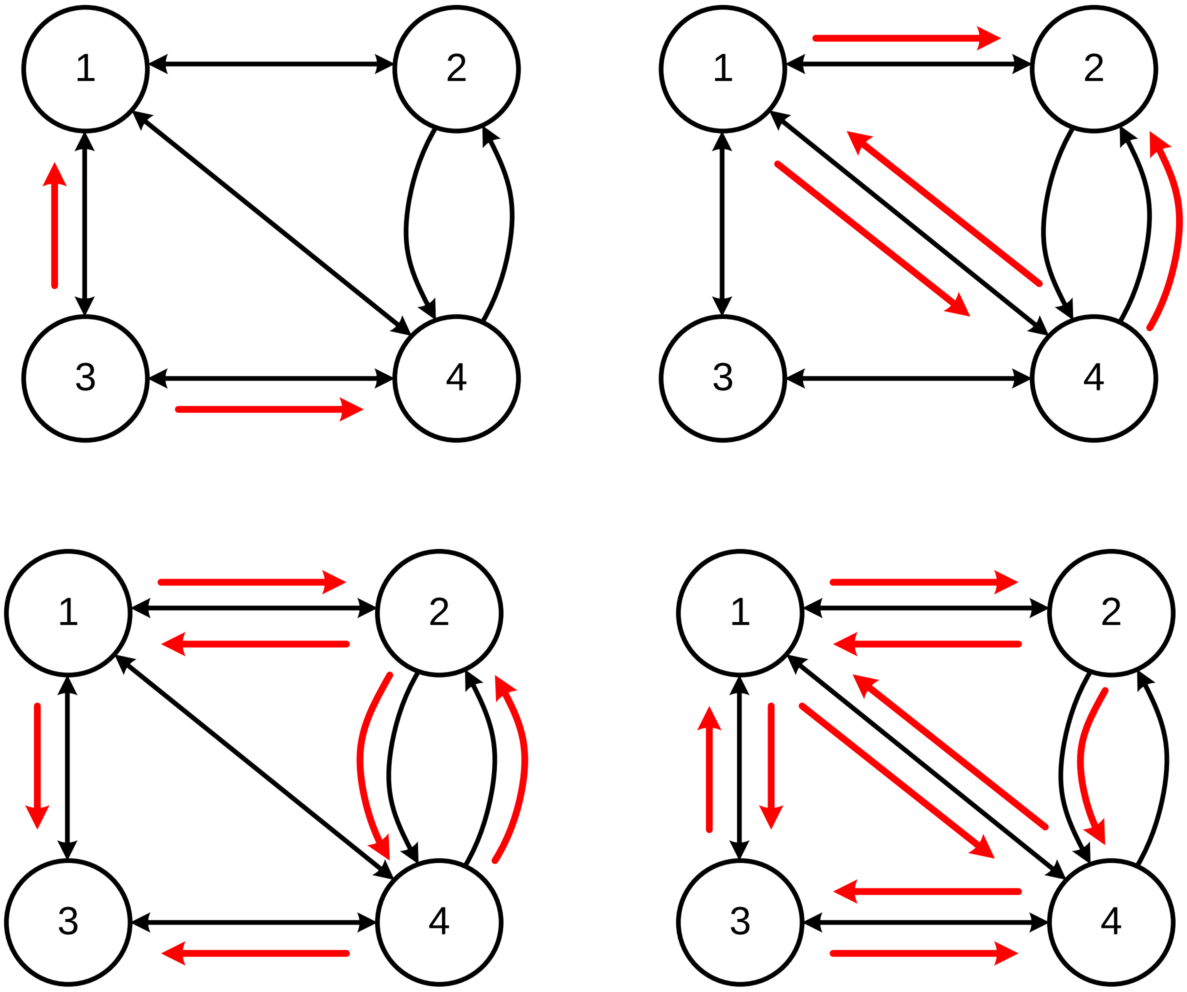
Link State DataBase

Router-LSA of R1 Adv Router = R1	Router-LSA of R3 Adv Router = R3
Router-LSA of R2 Adv Router = R2	Router-LSA of R4 Adv Router = R4
Network-LSA of sn1 Adv Router = R1	Network-LSA of sn2 Adv Router = R2

- The LSDB <u>is the same</u> in all routers, but each LSA has a responsible: the Advertising Router
- <u>Only the AR</u> can create, update, delete, and flood its LSAs

Broadcast routing

RULE: receive on one interface, retransmit on all others



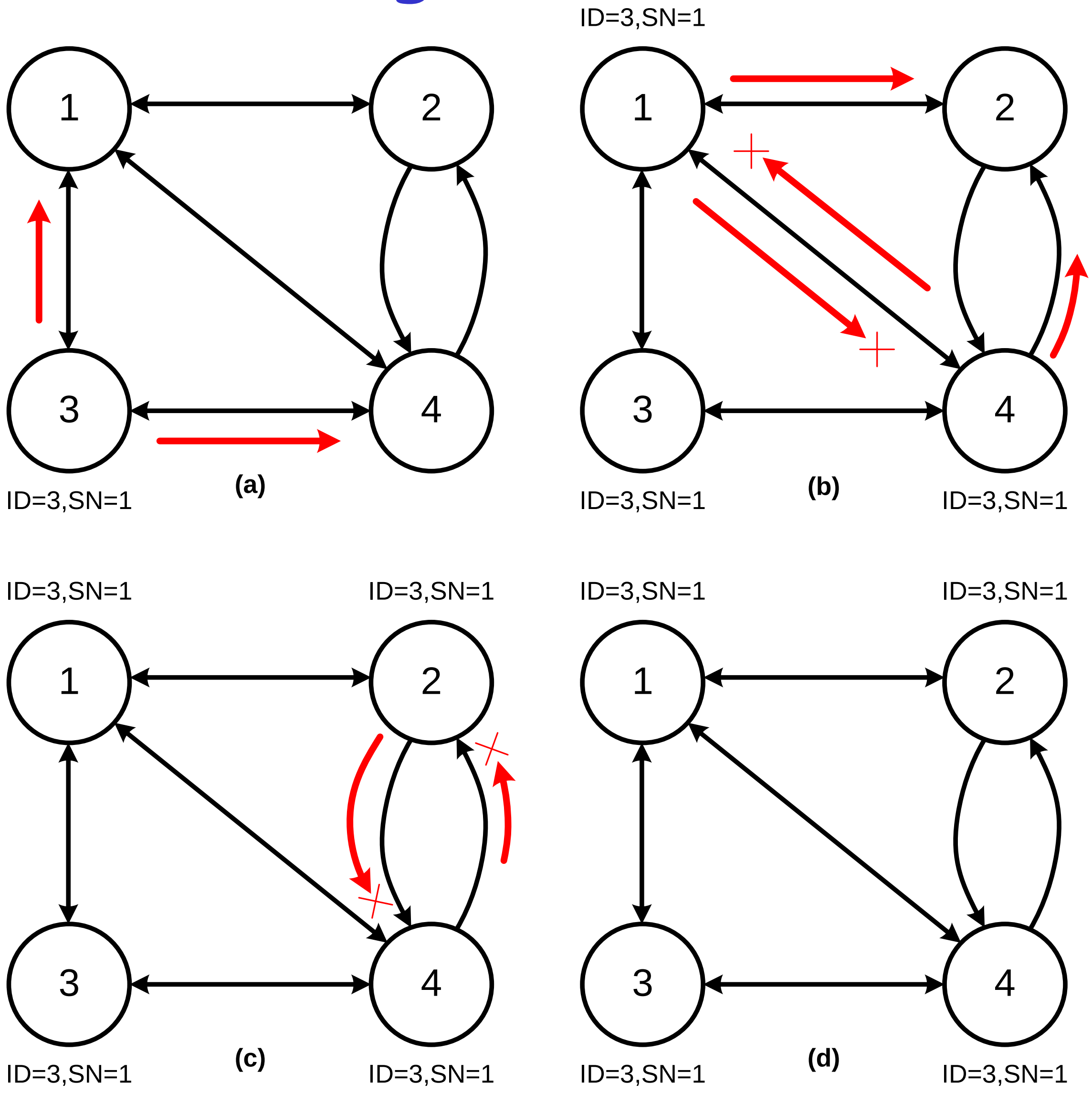
From node 3 to all others: uncontrolled flooding

Uncontrolled flooding

- Flooding rules:
  - Nodes retransmit message on all interfaces except the one where the message was received
- Message is delivered to all destinations… but the flooding of messages never stops
  - Unless network is a tree

Broadcast routing

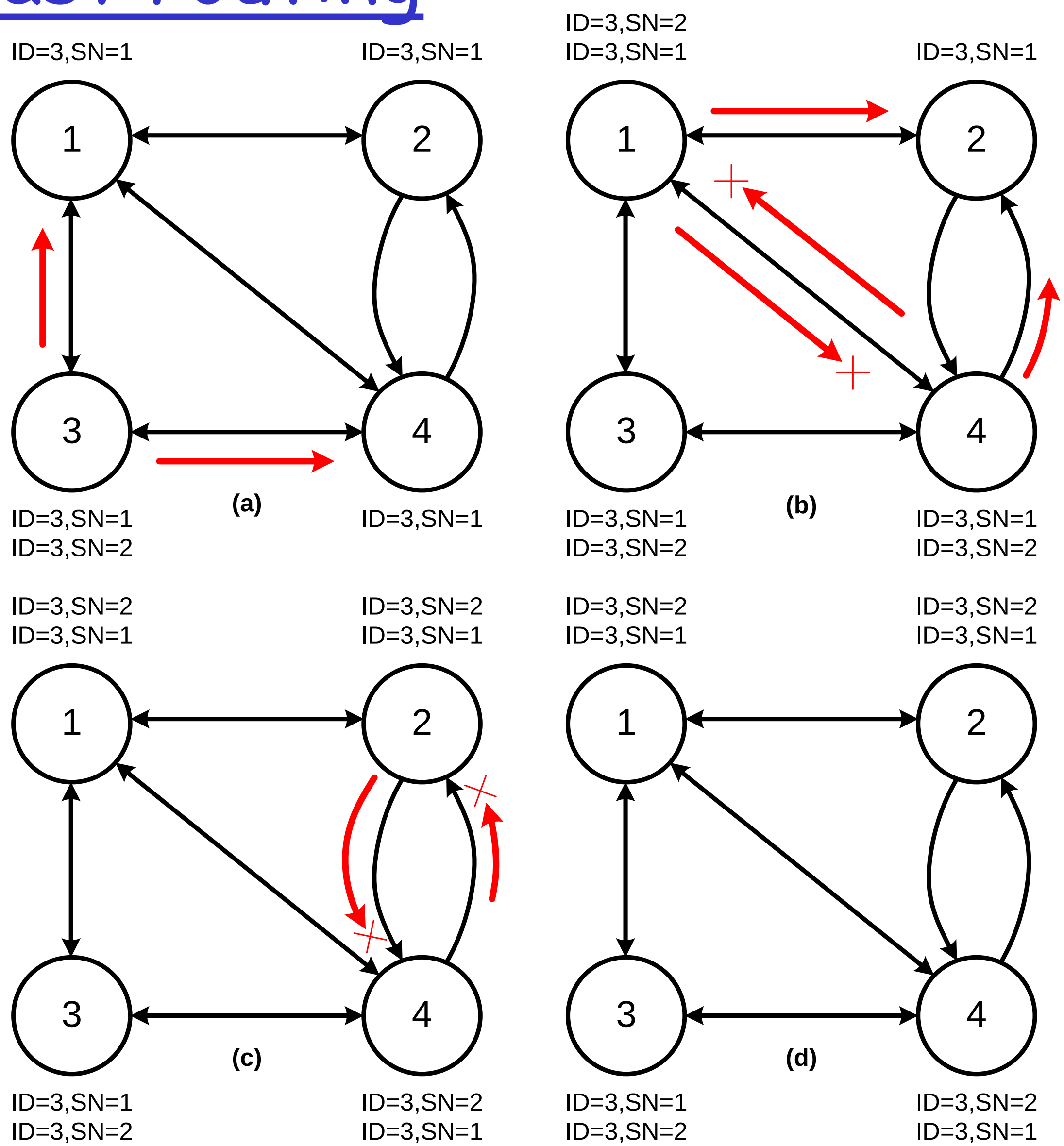
Link 4→2 much slower than others



Controlled flooding, broadcast of first message.

Broadcast routing

Link 4→2 much slower than others



Controlled flooding, broadcast of second message

Controlled flooding

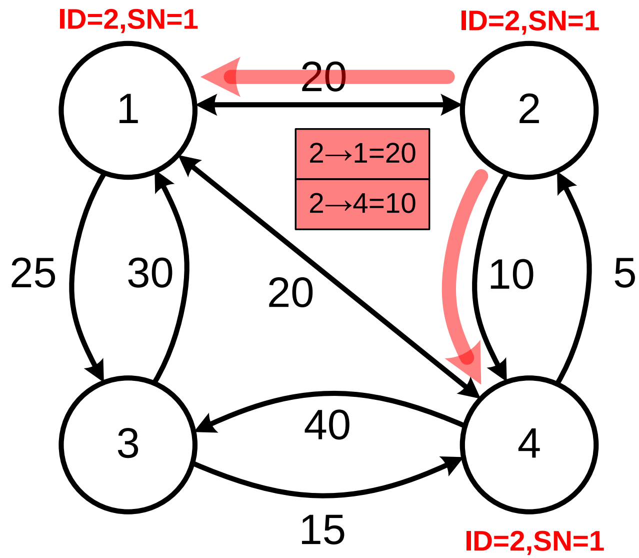
- Flooding rules:
  1. Origin nodes assign each message to be broadcasted (i) an identifier (ID) of the node and (ii) a number that is unique for every new message sent, called sequence number (SN).
  2. When a message is received at a node, the node verifies if the received pair (ID,SN) is already stored in memory. If yes, the message is discarded; if not the pair is stored, and the message is flooded to the neighbor nodes (except the one that sent the message).
- The flooding of messages stops at some point. Great!

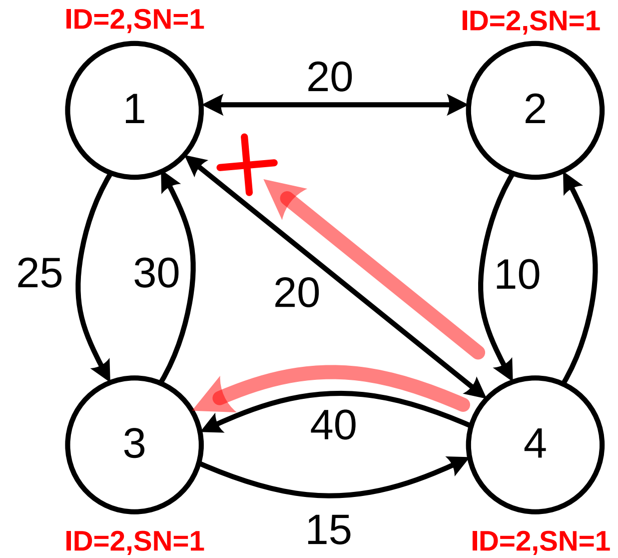
Building the network graph

How R2 broadcasts LSA to all other routers?

Step 1

- 2 sends to 1 and 4
- 1 saves (ID,SN) and schedules tx to 3 and 4;
- 4 saves (ID,SN) and schedules tx to 1 and 3



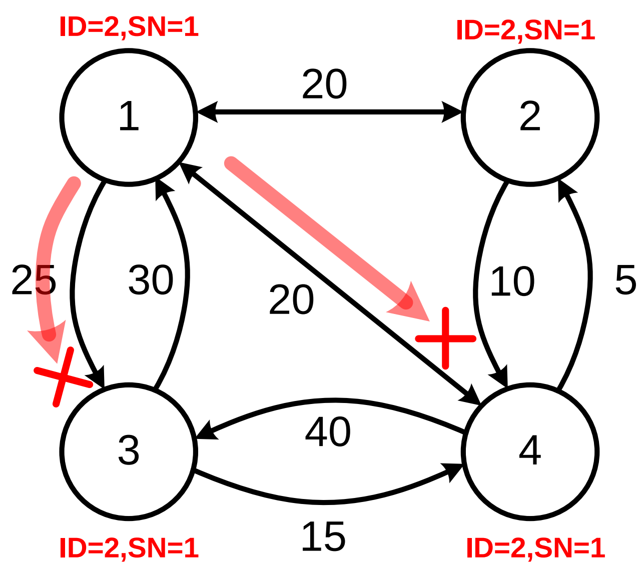


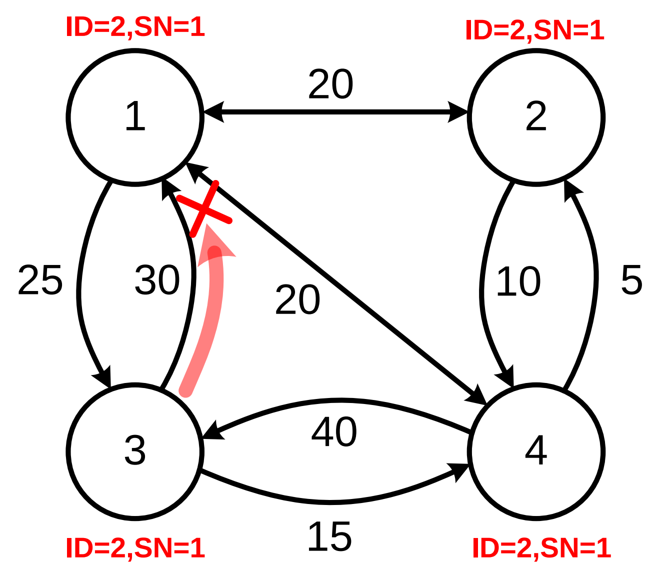
Step 2

- 4 sends to 1 and 3
- 3 saves (ID,SN) and schedules tx to 1;
- message to 1 discarded since (ID,SN) already in memory

Step 3

- 1 sends to 3 and 4
- both messages discarded since (ID,SN) already in memory





Step 4

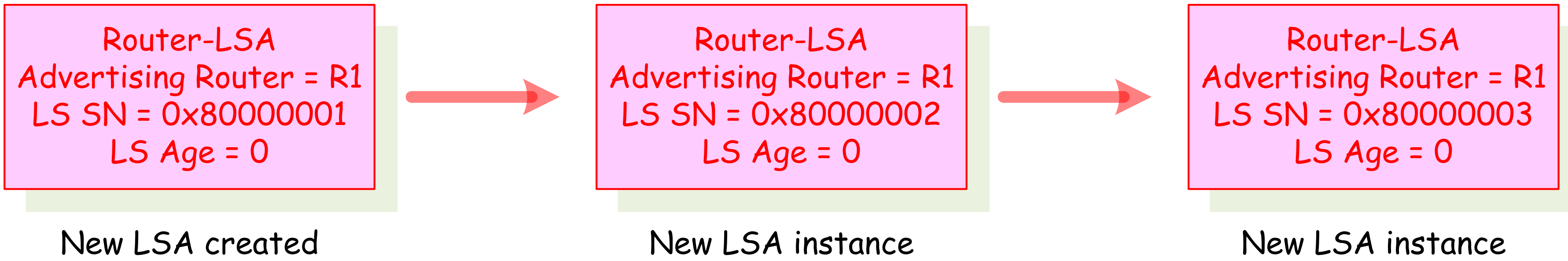
- 3 sends to 1
- message discarded since (ID,SN) already in memory

NOTE: This is not the only possible sequence of events!

Management of LSAs

- Every LSA has an Advertising Router
  - The single responsible for creating, updating, deleting and flooding it
- Every LSA instance has an age (LS Age) and a lifetime
  - Lifetime is 1 hour
  - LSA is deleted from the LSDB if its LS Age reaches the lifetime
- Every LSA instance has a sequence number
  - Starts at 0x80000001 and stops at 0x7FFFFFFF (uses 32-bit signed integer, MSB=1 means negative number; MSB=0 means positive)
- A new LSA instance is created and flooded every 30 minutes or when the Advertising Router senses a change in its link states
  - A new LSA instance has LS Age = 0 and the LS Sequence Number incremented by one
- The Advertising Router can delete one of its LSAs using the premature aging mechanism
  - Broadcast the LSA instance with an LS age = 3600 seconds

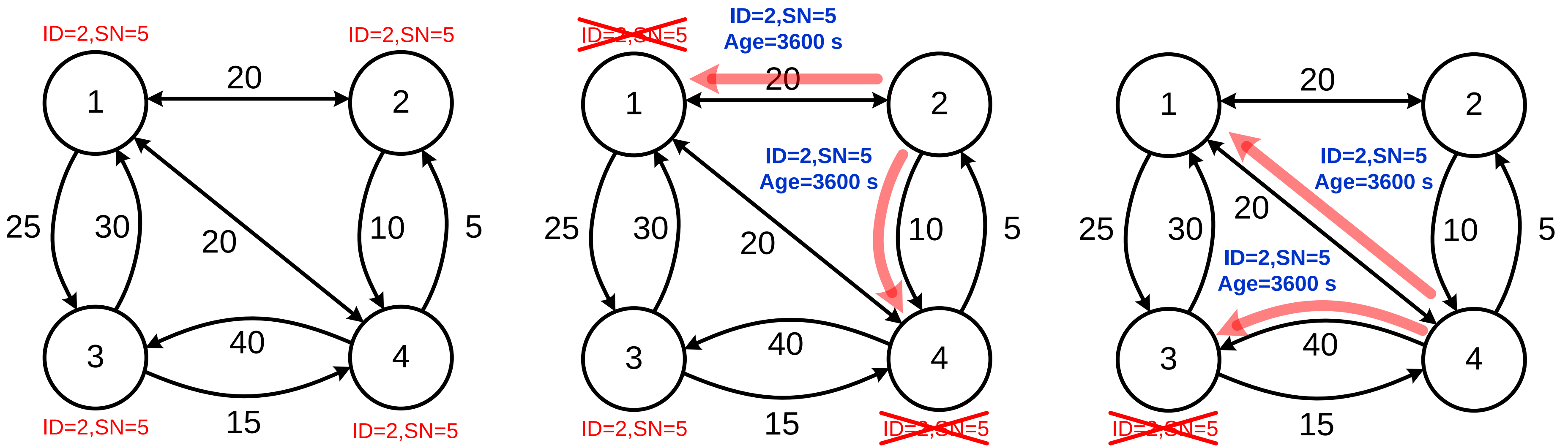
Creating LSAs and LSA instances



- Each LSA has a responsible: the Advertising Router (AR)
- The AR creates the LSA first, and then creates new LSA instances (LS Sequence Number incremented by one and LS Age = 0) to update the LSA

Premature aging

- Process used by Advertising Routers to delete their LSAs from the LSDB
- Just flood the LSA to be deleted with LS Age = 3600 seconds

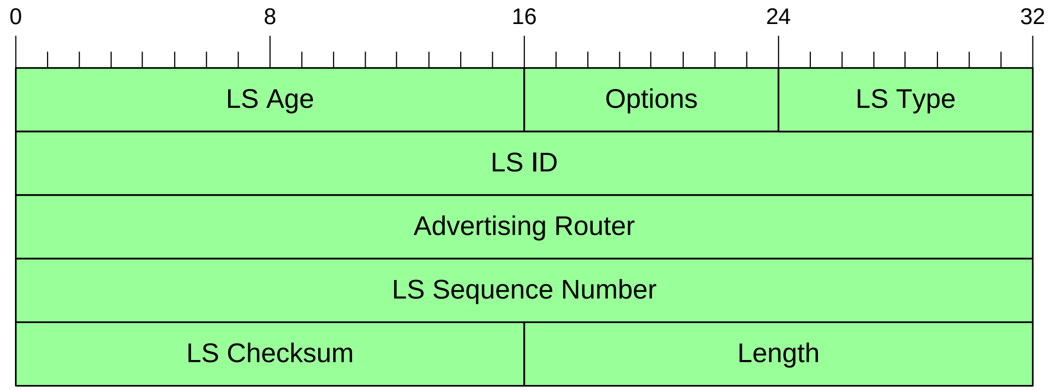


LSA Header format

0–15	16–23	24–31
LS Age	Options	LS Type
LS ID		
Advertising Router		
LS Sequence Number		
LS Checksum	Length	

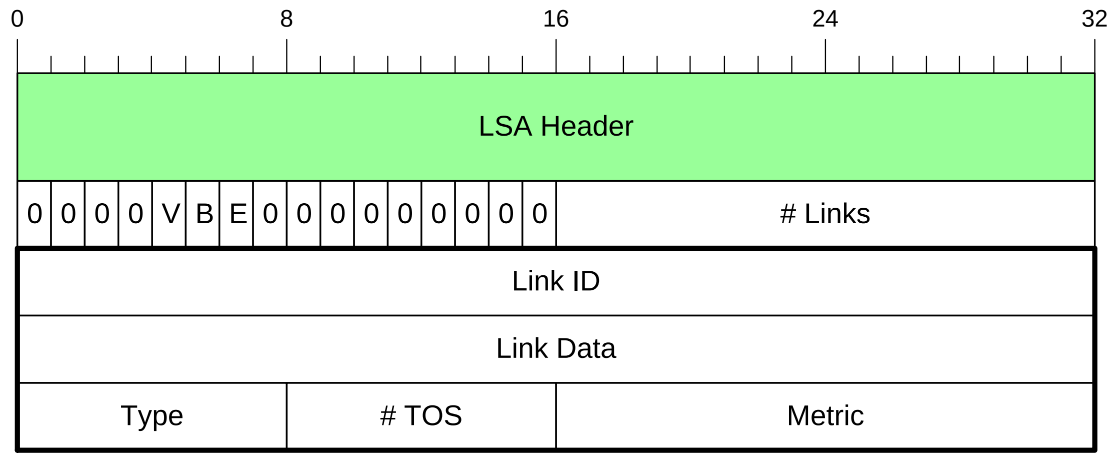
- **Advertising Router**
  - RID of router responsible for creating, updating, deleting and flooding the LSA
- **LS Type**
  - Type of LSA: 1 for router-LSA, 2 for network-LSA, 3 for summary-LSA, …
- **LS ID**
  - Distinguishes among LSAs of the same type originated by the same router
  - Interpretation depends on LS Type
- LSAs are uniquely identified by 3-tuple (Advertising Router, LS Type, and LS ID), called the LSA Identifier

LSA Header format



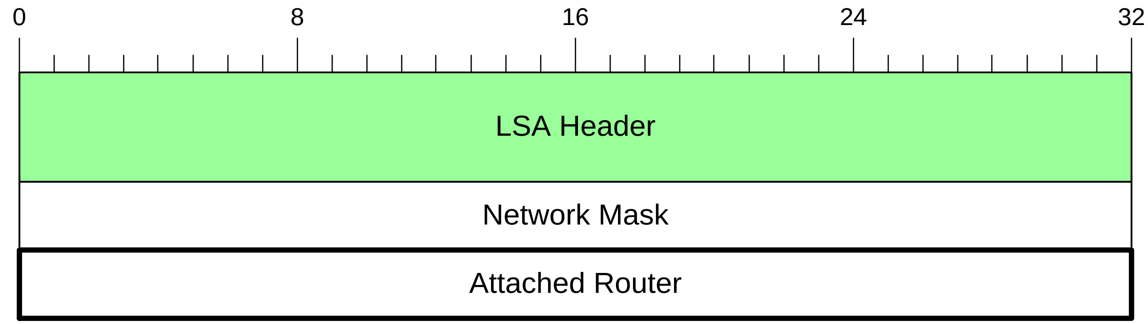
- LS Sequence Number
  - Distinguishes among different LSA instances
  - Starts at 0x80000001 and stops at 0x7FFFFFFF (uses 32-bit signed integer, MSB=1 means negative number; MSB=0 means positive)
  - LS Identifier + LS Sequence Number is used to control the flooding process
- LS Age
  - Number of seconds since LSA instance was created
  - LSA instances have a lifetime, called **MaxAge** (1 hour)
  - Advertising Router floods a new LSA instance (LS Sequence Number incremented by one and LS Age = 0) every **LSRefreshTime** (30 minutes)

Router-LSA format



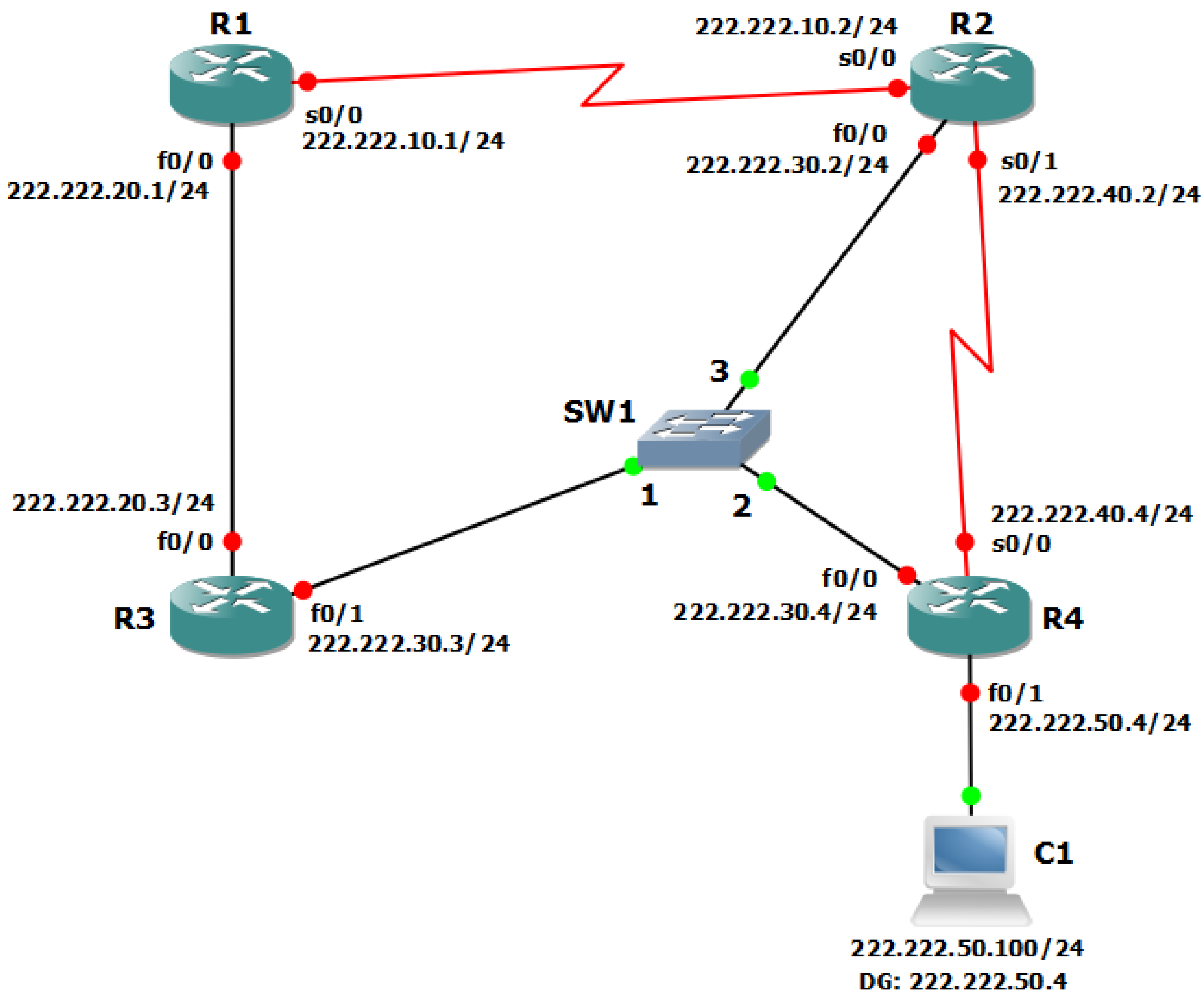
- Type
  - Identifies type of subnet: 1 for point-to-point, 2 for transit, 3 for stub
- Link ID
  - Identifies the neighbor, depends on Type
    - Point-to-point subnets: RID of neighbor
    - Transit subnets: IP address of DR
    - Stub subnets: IP address of subnet
- Link Data
  - Additional link information, depends on Type
    - Unnumbered point-to-point links: identifier of interface
    - Stub subnets: subnet mask
    - Other link types: IP address of interface
- Metric
  - Link cost
- # Links
  - Number of links represented in the LSA

Network-LSA format



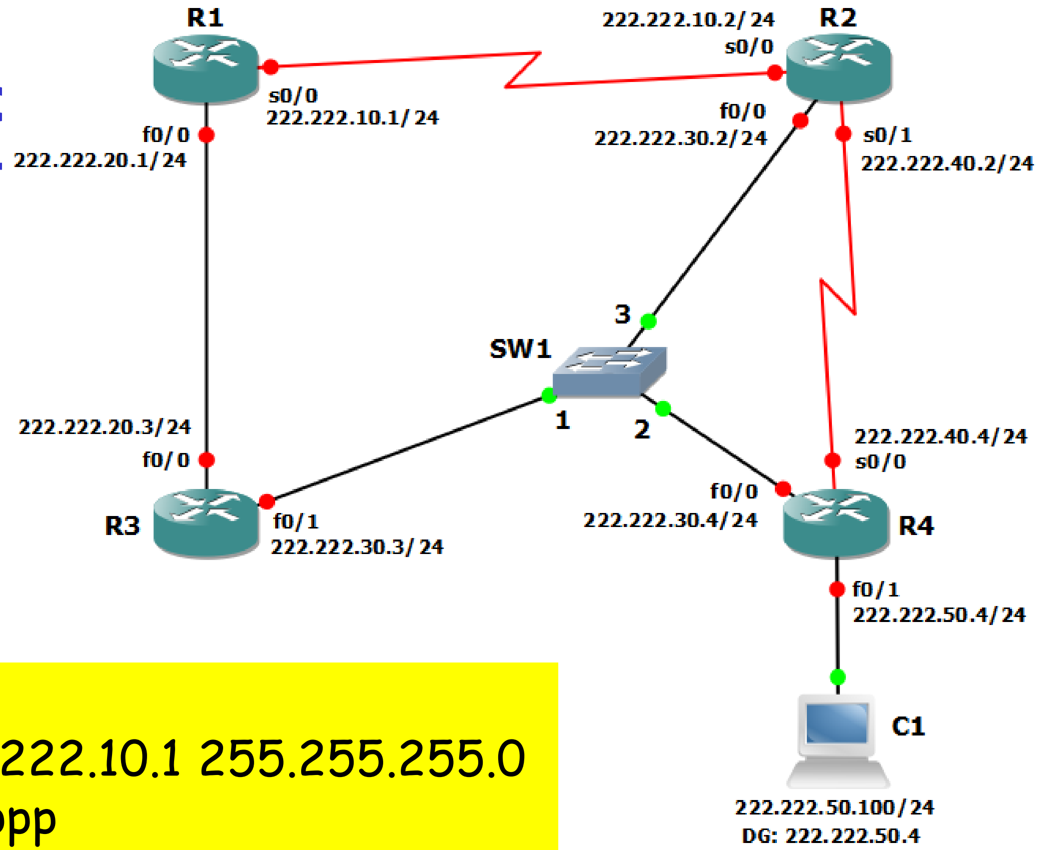
- **Network Mask**
  - Subnet mask of network represented by LSA
- **Attached Router**
  - RID of an attached router

Case study



R1
222.222.10.2/24
R2
s0/0
s0/0
222.222.10.1/24
f0/0
222.222.30.2/24
f0/0
222.222.20.1/24
s0/1
222.222.40.2/24
3
SW1
1
2
222.222.20.3/24
f0/0
222.222.40.4/24
s0/0
f0/0
222.222.30.4/24
R3
f0/1
222.222.30.3/24
R4
f0/1
222.222.50.4/24
C1
222.222.50.100/24
DG: 222.222.50.4

Case study - OSPF configuration



First install slot NM-4T

```
R1(config)#int s0/0
R1(config-if)#ip address 222.222.10.1 255.255.255.0
R1(config-if)# encapsulation ppp
R1(config-if)#no shutdown
```

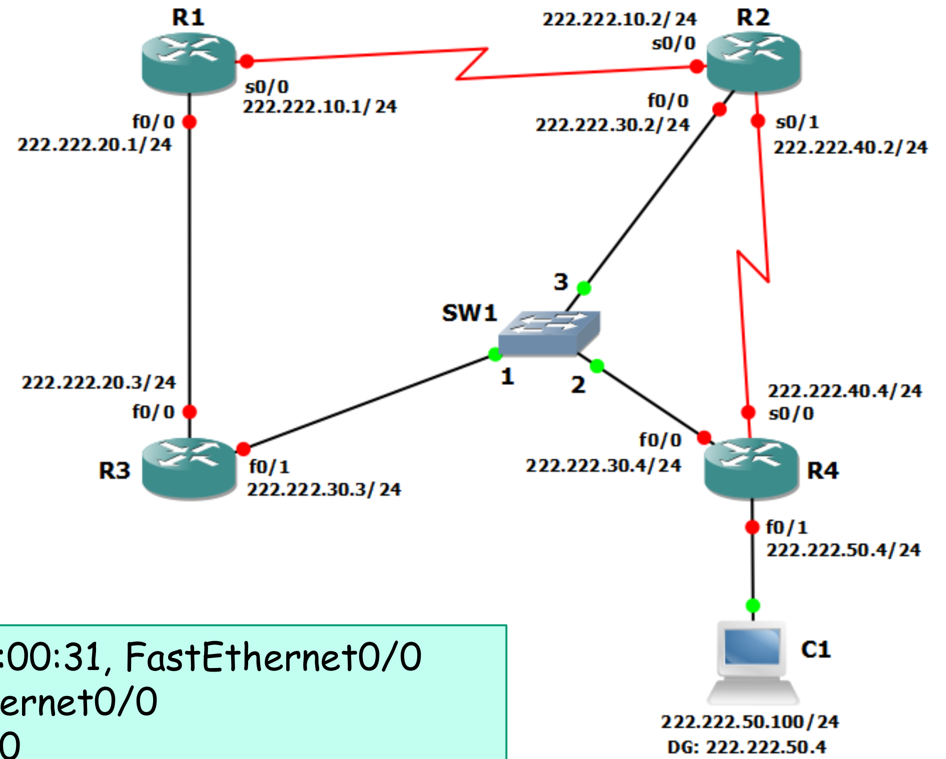
Configuration of serial interface of R1

```
R3(config)#router ospf 1
R3(config-router)# router-id 3.3.3.3
R3(config-router)# network 222.222.20.0 0.0.0.255 area 0
R3(config-router)# network 222.222.30.0 0.0.0.255 area 0
```

Configuration of OSPF at R3

Case study – Analyzing routing tables

Default interface costs:
- Fast Ethernet = 10
- Serial = 64



R1#show ip route

```
O   222.222.50.0/24 [110/30] via 222.222.20.3, 00:00:31, FastEthernet0/0
C   222.222.20.0/24 is directly connected, FastEthernet0/0
C   222.222.10.0/24 is directly connected, Serial0/0
O   222.222.40.0/24 [110/84] via 222.222.20.3, 00:00:31, FastEthernet0/0
O   222.222.30.0/24 [110/20] via 222.222.20.3, 00:00:31, FastEthernet0/0
```

Routing table of R1

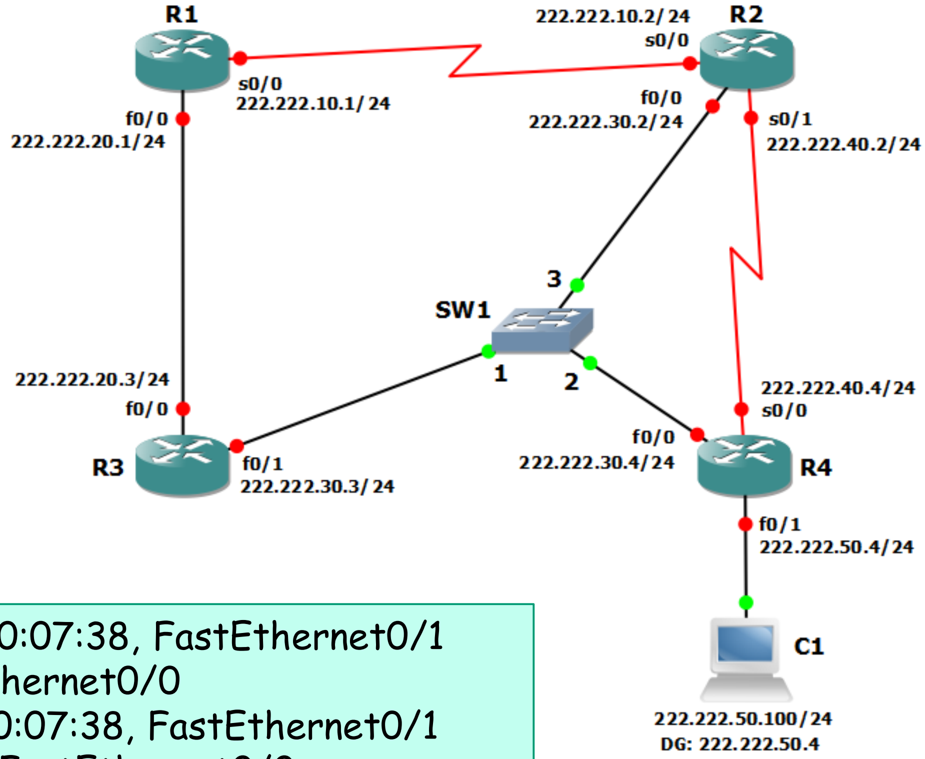
```
O   222.222.50.0/24 [110/20] via 222.222.30.4, 00:07:38, FastEthernet0/1
C   222.222.20.0/24 is directly connected, FastEthernet0/0
O   222.222.10.0/24 [110/74] via 222.222.30.2, 00:07:38, FastEthernet0/1
                    [110/74] via 222.222.20.1, 00:07:38, FastEthernet0/0
O   222.222.40.0/24 [110/74] via 222.222.30.4, 00:07:38, FastEthernet0/1
                    [110/74] via 222.222.30.2, 00:07:38, FastEthernet0/1
C   222.222.30.0/24 is directly connected, FastEthernet0/1
```

Routing table of R3

Case study – Changing interface costs

Default interface costs:
- Fast Ethernet = 10
- Serial = 64

```
R3(config)#int f0/1
R3(config-if)#ip ospf cost 15
```



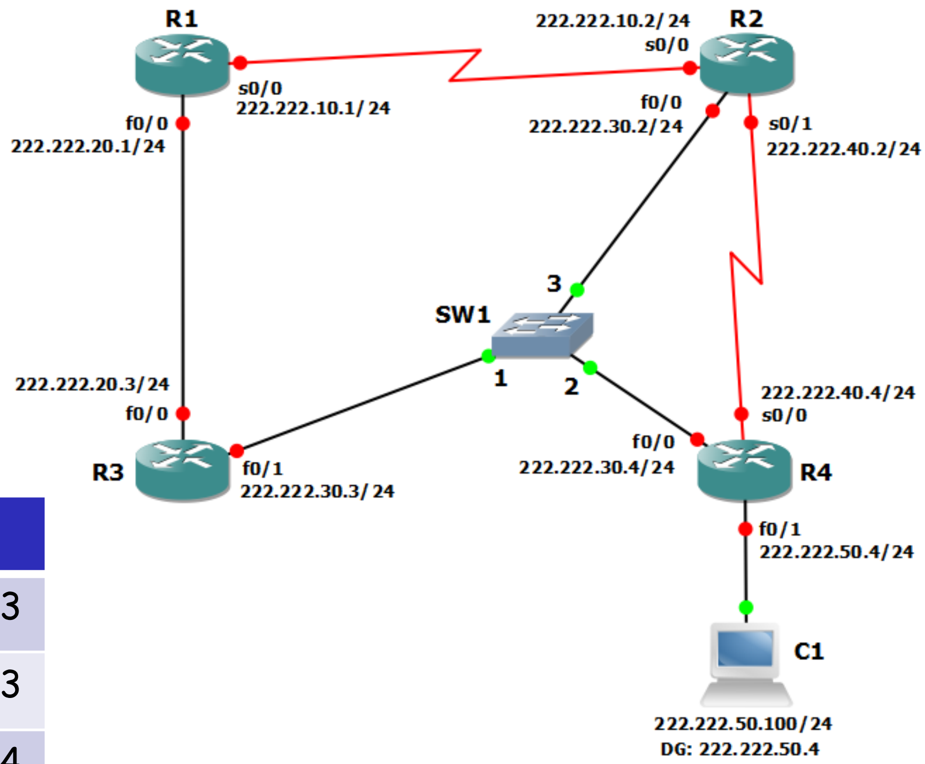

```
O    222.222.50.0/24 [110/20] via 222.222.30.4, 00:07:38, FastEthernet0/1
C    222.222.20.0/24 is directly connected, FastEthernet0/0
O    222.222.10.0/24 [110/74] via 222.222.30.2, 00:07:38, FastEthernet0/1
                     [110/74] via 222.222.20.1, 00:07:38, FastEthernet0/0
O    222.222.40.0/24 [110/74] via 222.222.30.4, 00:07:38, FastEthernet0/1
                     [110/74] via 222.222.30.2, 00:07:38, FastEthernet0/1
C    222.222.30.0/24 is directly connected, FastEthernet0/1
```

Routing table of R3, before changing cost of f0/1-R3

```
O    222.222.50.0/24 [110/25] via 222.222.30.4, 00:00:41, FastEthernet0/1
C    222.222.20.0/24 is directly connected, FastEthernet0/0
O    222.222.10.0/24 [110/74] via 222.222.20.1, 00:00:41, FastEthernet0/0
O    222.222.40.0/24 [110/79] via 222.222.30.4, 00:00:41, FastEthernet0/1
                     [110/79] via 222.222.30.2, 00:00:41, FastEthernet0/1
C    222.222.30.0/24 is directly connected, FastEthernet0/1
```

Routing table of R3, after changing cost of f0/1-R3 to 15

Case study – Analyzing the LSDB



R1#show ip ospf database

Link State ID	ADV Router	Age	Seq#
1.1.1.1	1.1.1.1	75	0x80000003
2.2.2.2	2.2.2.2	73	0x80000003
3.3.3.3	3.3.3.3	71	0x80000004
4.4.4.4	4.4.4.4	74	0x80000003

Router Link States (Area 0)

Link State ID	ADV Router	Age	Seq#
222.222.20.3	3.3.3.3	76	0x80000001
222.222.30.4	4.4.4.4	74	0x80000001

Net Link States (Area 0)

Case study – Analyzing the LSDB

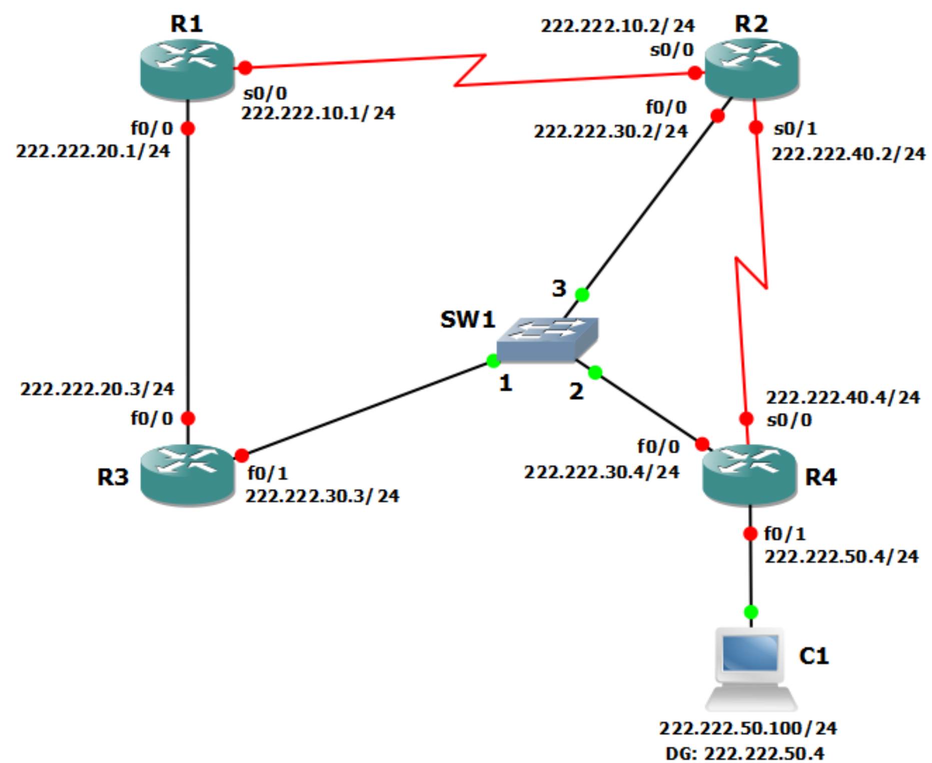
LS age: 1008
Options: (No TOS-capability, DC)
LS Type: Router Links
Link State ID: 4.4.4.4
Advertising Router: 4.4.4.4
LS Seq Number: 80000003
Checksum: 0xA91E
Length: 72
Number of Links: 4

Link connected to: a Stub Network
(Link ID) Network/subnet number: 222.222.50.0
(Link Data) Network Mask: 255.255.255.0
Number of TOS metrics: 0
TOS 0 Metrics: 10

Link connected to: another Router (point-to-point)
(Link ID) Neighboring Router ID: 2.2.2.2
(Link Data) Router Interface address: 222.222.40.4
Number of TOS metrics: 0
TOS 0 Metrics: 64

Link connected to: a Stub Network
(Link ID) Network/subnet number: 222.222.40.0
(Link Data) Network Mask: 255.255.255.0
Number of TOS metrics: 0
TOS 0 Metrics: 64

Link connected to: a Transit Network
(Link ID) Designated Router address: 222.222.30.4
(Link Data) Router Interface address: 222.222.30.4
Number of TOS metrics: 0
TOS 0 Metrics: 10



R1#show ip ospf database router

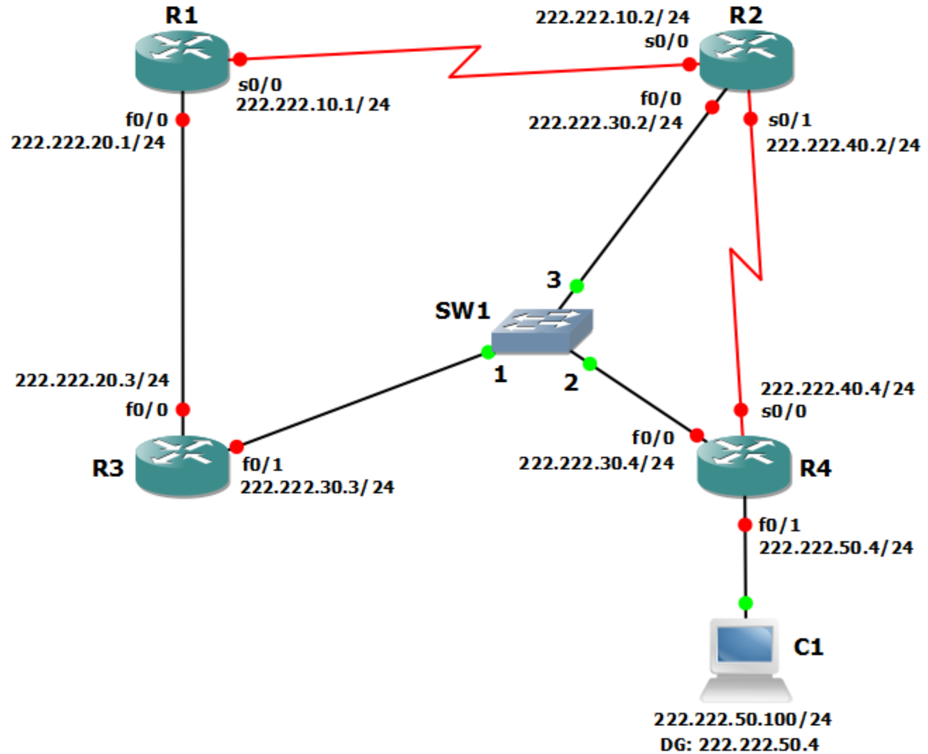
Router-LSA of R4 (4.4.4.4)

R1#show ip ospf database network

Case study - Analyzing the LSDB

```
Routing Bit Set on this LSA
  LS age: 221
  Options: (No TOS-capability, DC)
  LS Type: Network Links
  Link State ID: 222.222.20.3 (address of Designated Router)
  Advertising Router: 3.3.3.3
  LS Seq Number: 80000002
  Checksum: 0x1D2B
  Length: 32
  Network Mask: /24
        Attached Router: 3.3.3.3
        Attached Router: 1.1.1.1

  Routing Bit Set on this LSA
  LS age: 268
  Options: (No TOS-capability, DC)
  LS Type: Network Links
  Link State ID: 222.222.30.4 (address of Designated Router)
  Advertising Router: 4.4.4.4
  LS Seq Number: 80000002
  Checksum: 0xA977
  Length: 36
  Network Mask: /24
        Attached Router: 4.4.4.4
        Attached Router: 2.2.2.2
        Attached Router: 3.3.3.3
```



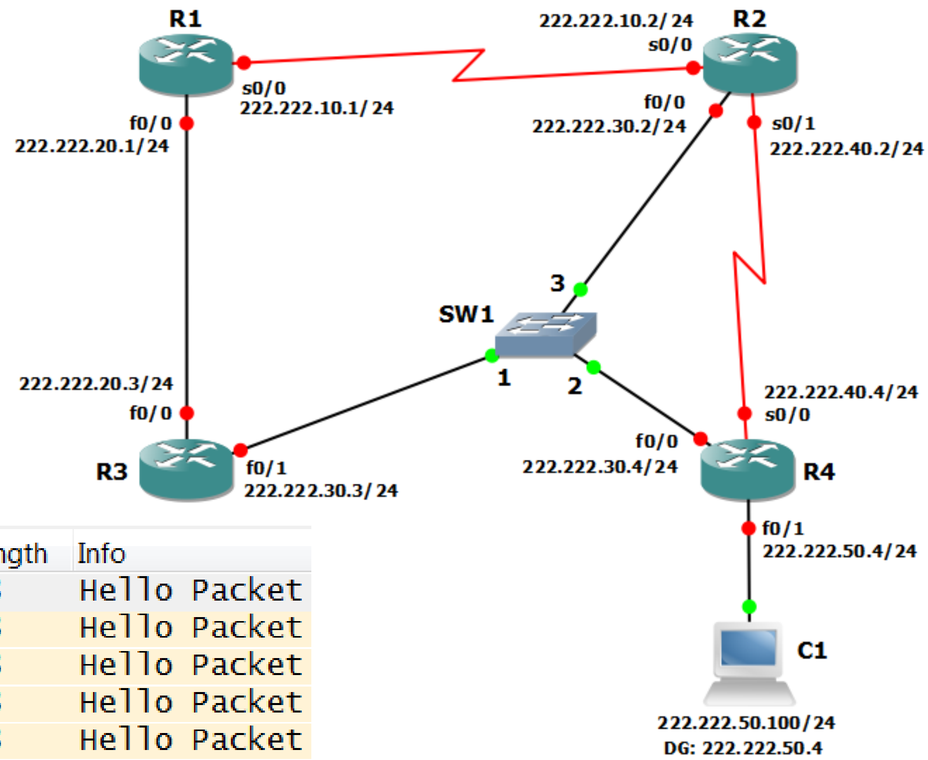
Network-LSAs

Hello protocol: Who are my neighbors?

0–15	16–23	24–31
OSPF packet header		
Network Mask		
HelloInterval	Options	Router Priority
RouterDeadInterval		
Designated Router		
Backup Designated Router		
Neighbor		

- Used to discover and maintain relationship with neighbors; also used in the election of the DR and BDR
- Procedure
  - Each router sends Hello packets every HelloInterval (default is 10 seconds)
  - When a router ceases to receive Hello packets from a neighbor for more than RouterDeadInterval seconds (default is 40 seconds) it considers that the neighbor is down (no longer advertises link with neighbor)
- In broadcast subnets Hello packets are sent to the multicast address AllSPFRouters (224.0.0.5)

Case study - Hello protocol

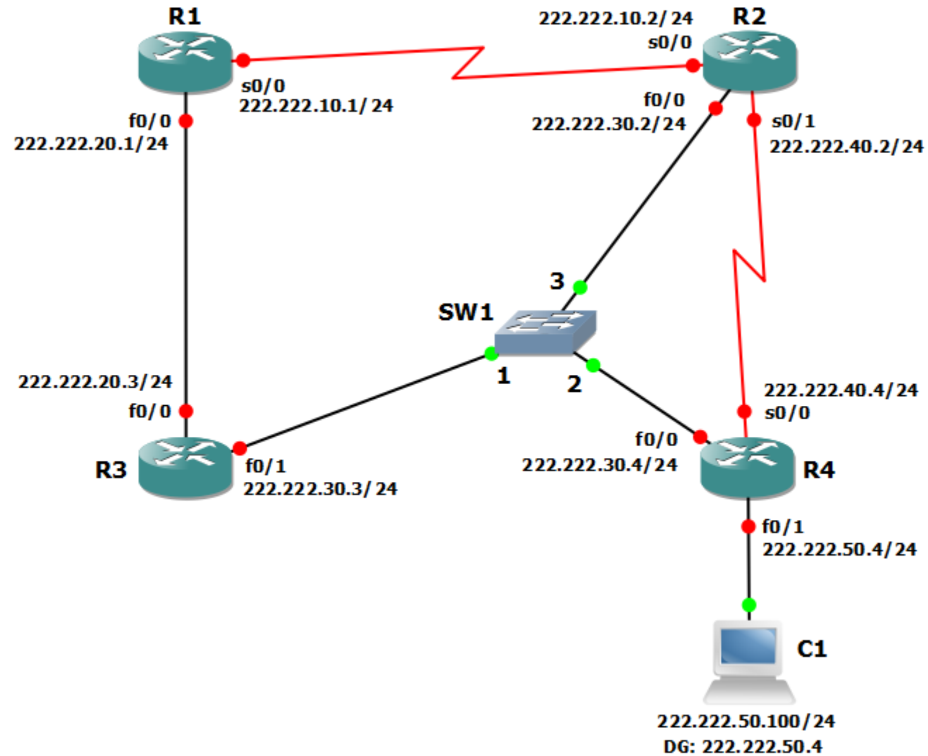


No.	Time	Source	Destination	Protocol	Length	Info
2	1.903000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
3	2.933000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
4	3.198000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
6	11.887000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
7	12.932000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
8	13.197000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
10	21.871000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
11	22.916000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
12	23.213000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
14	31.902000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
15	32.916000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
16	33.212000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
18	41.917000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
19	42.931000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
20	43.196000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
25	51.901000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
26	52.931000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
27	53.227000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
29	61.916000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
30	62.930000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
31	63.211000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet

Hello packets sent on 222.222.30.0/24

Case study - Hello protocol

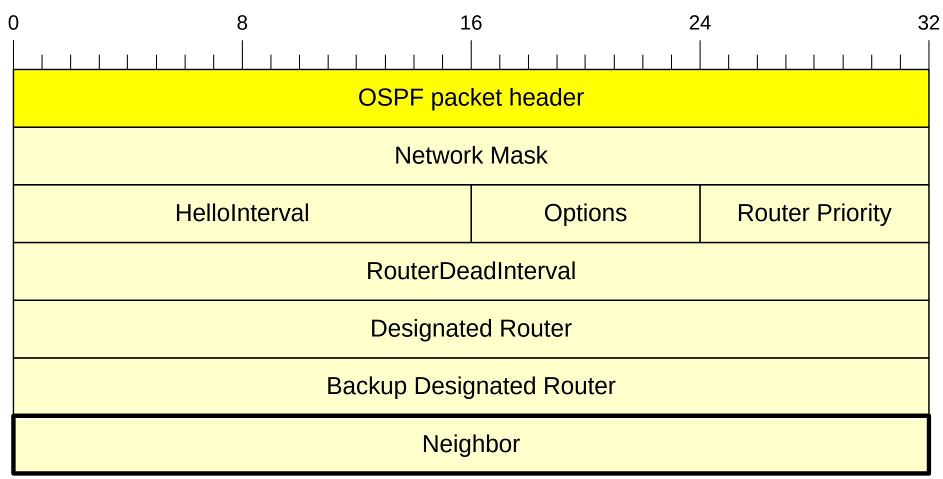
```
⊞ Ethernet II, Src: c2:00:b6:50:00:00 (c2:00
⊞ Internet Protocol Version 4
⊟ Open Shortest Path First
  ⊟ OSPF Header
      OSPF Version: 2
      Message Type: Hello Packet (1)
      <Hello: True>
      Packet Length: 52
      Source OSPF Router: 4.4.4.4 (4.4.4.4)
      Area ID: 0.0.0.0 (Backbone)
      Packet Checksum: 0xe0bf [correct]
      Auth Type: Null
      Auth Data (none)
  ⊟ OSPF Hello Packet
      Network Mask: 255.255.255.0
      Hello Interval: 10 seconds
    ⊞ Options: 0x12 (L, E)
      Router Priority: 1
      Router Dead Interval: 40 seconds
      Designated Router: 222.222.30.4
      Backup Designated Router: 222.222.30.3
      Active Neighbor: 2.2.2.2
      Active Neighbor: 3.3.3.3
  ⊞ OSPF LLS Data Block
```



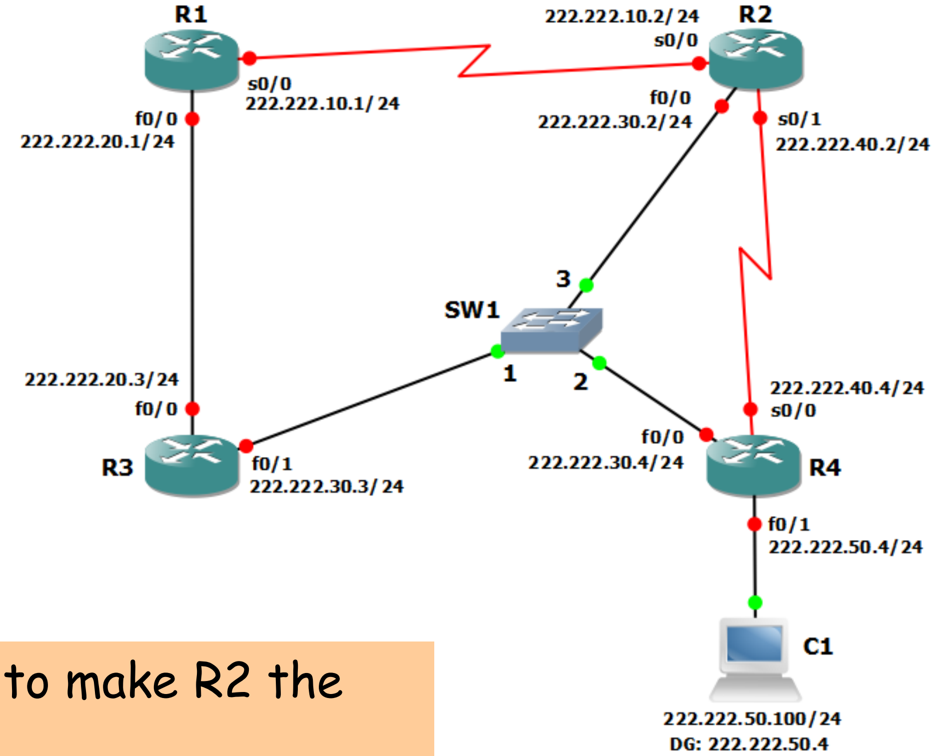
Hello packet sent by R4

Election of the DR and BDR

- Main principle: once a router is elected as DR or BDR no one can takeover its role (unless there is a failure)
- Procedure:
  - The first router to be switched on becomes the DR, and the second one the BDR
  - If the DR fails, the BDR becomes the new DR
  - The new BDR is the one with higher priority (a configurable parameter called **Router Priority**); in case of a tie, the router with higher RID is elected
- The election is performed via Hello packets



Case study - Changing the DR and BDR

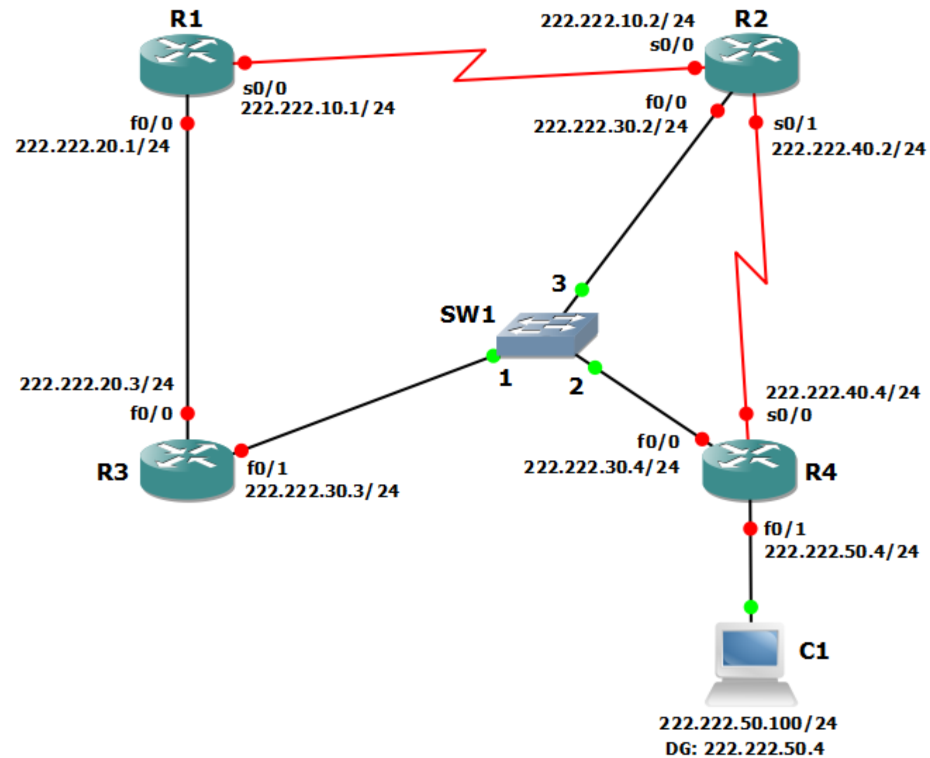


Assuming R4 is DR and R3 is BDR, how to make R2 the DR and R4 the BDR?

1. Deactivate f0/0 of R4 → R3 becomes DR and R2 BDR
2. Deactivate f0/1 of R3 → R2 becomes DR
3. Activate f0/0 of R4 → R4 becomes BDR
4. Activate f0/1 of R3

Use show **ip ospf interface f0/0** at R2 to check who the DR and BDR are

Case study - Changing the DR and BDR




```
⊟ Open Shortest Path First
  ⊞ OSPF Header
  ⊟ OSPF Hello Packet
      Network Mask: 255.255.255.0
      Hello Interval: 10 seconds
    ⊞ Options: 0x12 (L, E)
      Router Priority: 1
      Router Dead Interval: 40 seconds
      Designated Router: 222.222.30.4
      Backup Designated Router: 222.222.30.3
      Active Neighbor: 2.2.2.2
      Active Neighbor: 3.3.3.3
```

Before any change

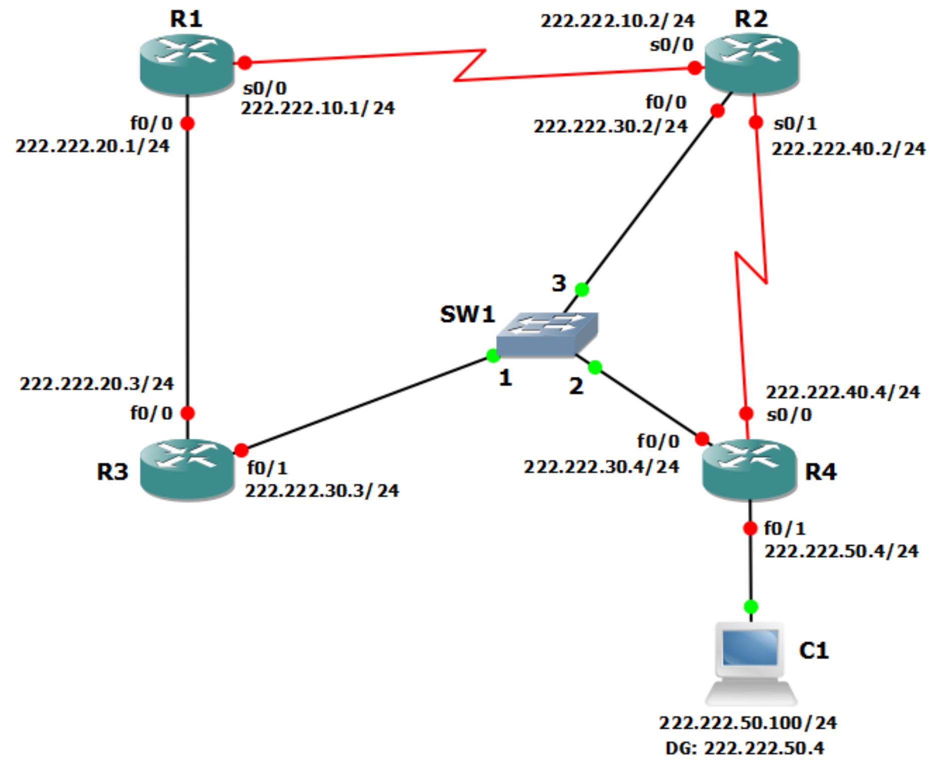
```
⊟ Open Shortest Path First
  ⊞ OSPF Header
  ⊟ OSPF Hello Packet
      Network Mask: 255.255.255.0
      Hello Interval: 10 seconds
    ⊞ Options: 0x12 (L, E)
      Router Priority: 1
      Router Dead Interval: 40 seconds
      Designated Router: 222.222.30.3
      Backup Designated Router: 222.222.30.2
      Active Neighbor: 3.3.3.3
```

After f0/0 of R4 deactivated

```
⊟ Open Shortest Path First
  ⊞ OSPF Header
  ⊟ OSPF Hello Packet
      Network Mask: 255.255.255.0
      Hello Interval: 10 seconds
    ⊞ Options: 0x12 (L, E)
      Router Priority: 1
      Router Dead Interval: 40 seconds
      Designated Router: 222.222.30.2
      Backup Designated Router: 0.0.0.0
```

After f0/1 of R3 deactivated

Case study – Changing the DR and the BDR




```
⊟ Open Shortest Path First
  ⊞ OSPF Header
  ⊟ OSPF Hello Packet
      Network Mask: 255.255.255.0
      Hello Interval: 10 seconds
    ⊞ Options: 0x12 (L, E)
      Router Priority: 1
      Router Dead Interval: 40 seconds
      Designated Router: 0.0.0.0
      Backup Designated Router: 0.0.0.0
```

First Hello sent by R4 when its f0/0 activated again

```
⊟ Open Shortest Path First
  ⊞ OSPF Header
  ⊟ OSPF Hello Packet
      Network Mask: 255.255.255.0
      Hello Interval: 10 seconds
    ⊞ Options: 0x12 (L, E)
      Router Priority: 1
      Router Dead Interval: 40 seconds
      Designated Router: 222.222.30.2
      Backup Designated Router: 222.222.30.4
      Active Neighbor: 2.2.2.2
```

After f0/0 of R4 activated

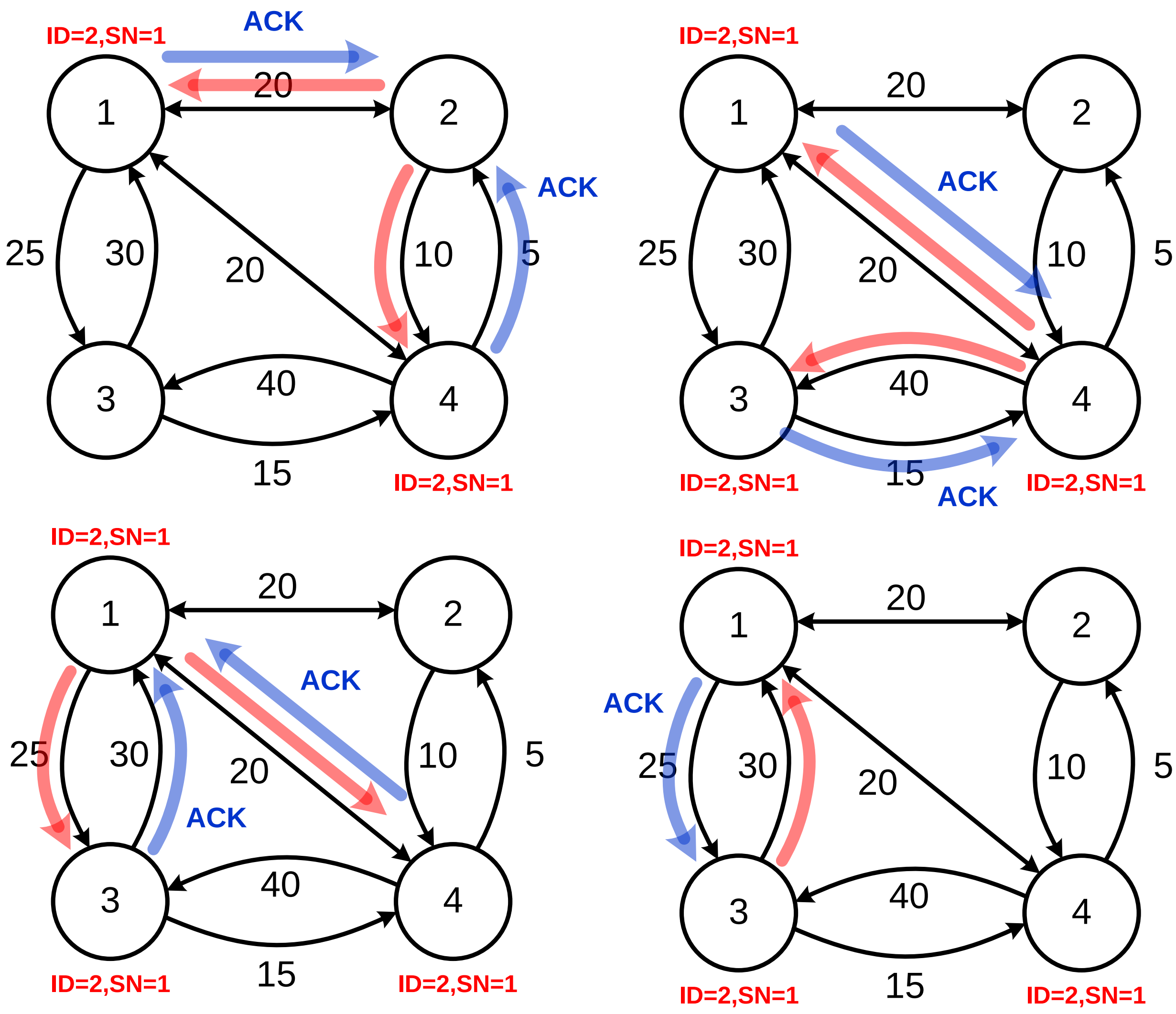
```
⊟ Open Shortest Path First
  ⊞ OSPF Header
  ⊟ OSPF Hello Packet
      Network Mask: 255.255.255.0
      Hello Interval: 10 seconds
    ⊞ Options: 0x12 (L, E)
      Router Priority: 1
      Router Dead Interval: 40 seconds
      Designated Router: 222.222.30.2
      Backup Designated Router: 222.222.30.4
      Active Neighbor: 2.2.2.2
      Active Neighbor: 3.3.3.3
```

After f0/1 of R3 activated

The flooding procedure

- The process used for distribution of the LSAs over the whole OSPF network
- Flooding is controlled by the LSA identifier and LSA freshness triplets
  - LSA identifier = (Advertising Router, LS Type, LS ID)
  - LSA freshness = (LS Sequence Number, LS Age, LS Checksum)
- If an LSA arrives at router and is a new LSA or a fresher instance of an already existing LSA it is installed at the LSDB and transmitted on all interfaces except the receiving one; otherwise it is not transmitted
- LSAs are flooded encapsulated in LS Update packets
- Reliable flooding: each router is required to acknowledge the reception of an LSA to the neighbor that sent it using a LS Acknowledgement packet

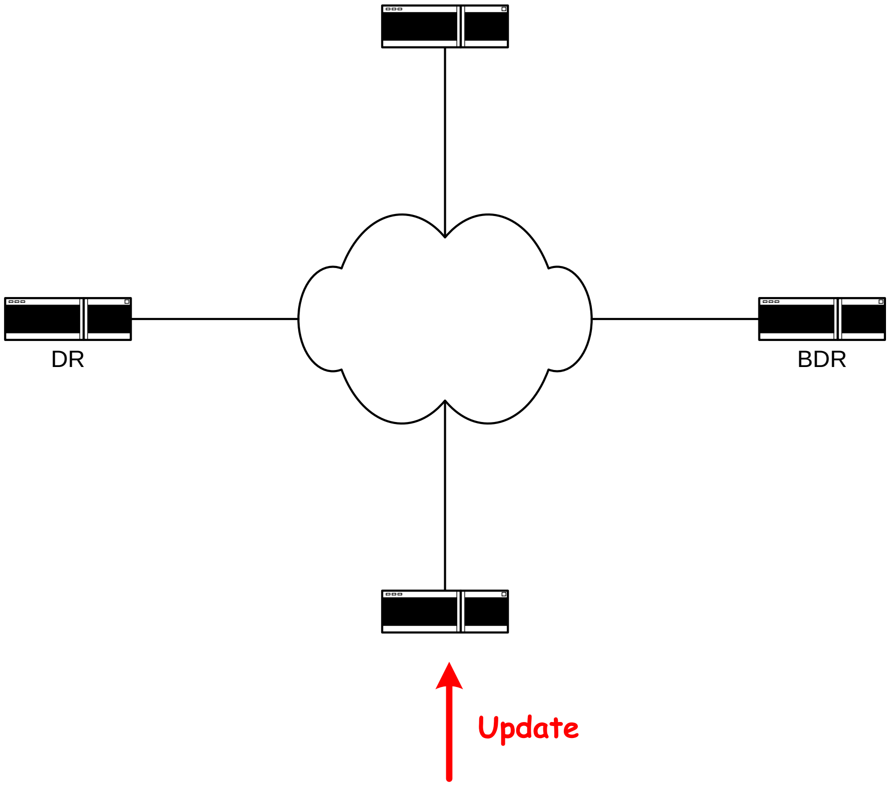
Reliable flooding

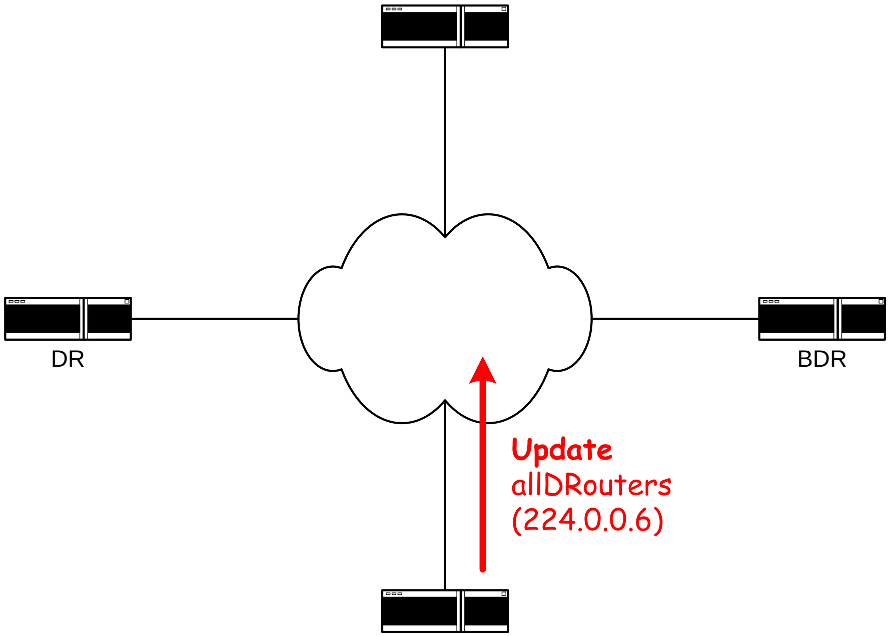


Flooding in broadcast subnets

- In broadcast subnets, flooding is via the DR
- DR and BDR transmit on AllSPFRouters (224.0.0.5) address; all other routers transmit on AllDRouters (224.0.0.6) address
- In principle an LSA broadcasted on a subnet must be acknowledged by all other routers… but there are several special cases

Flooding in broadcast subnets

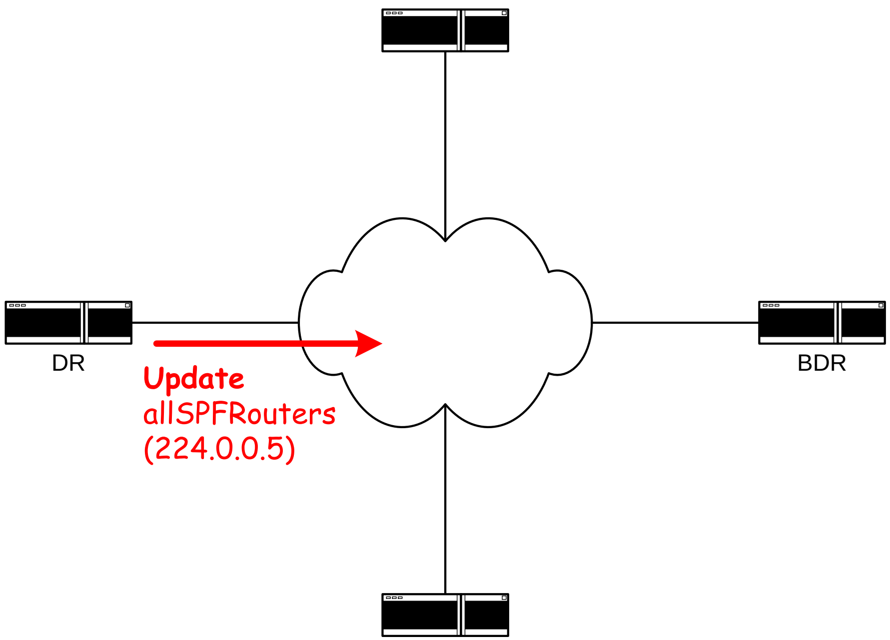


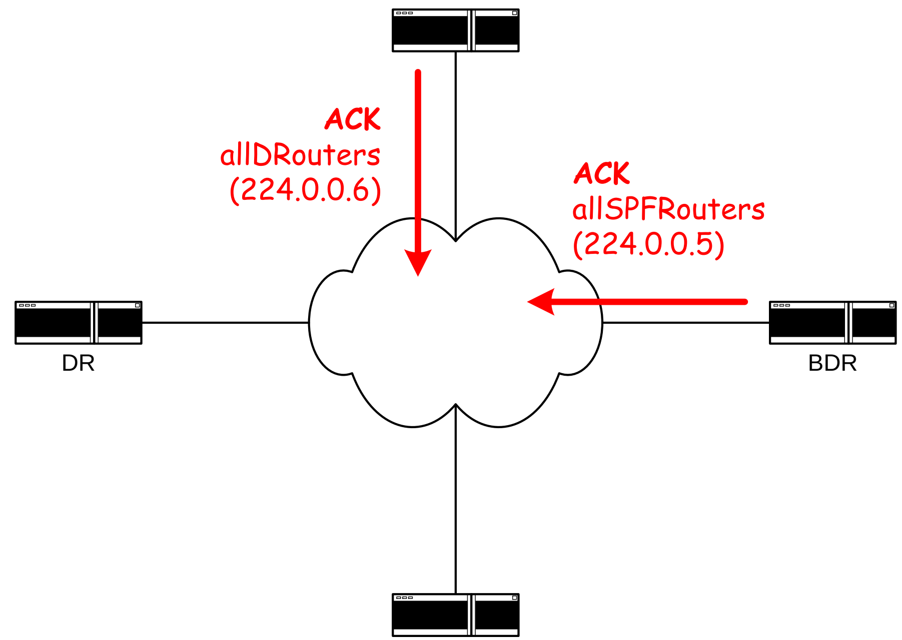


Router (not DR nor BDR) receives Update packet to be flooded on broadcast subnet

Sends to DR and BDR using multicast address allDRouters (224.0.0.6)

Flooding in broadcast subnets

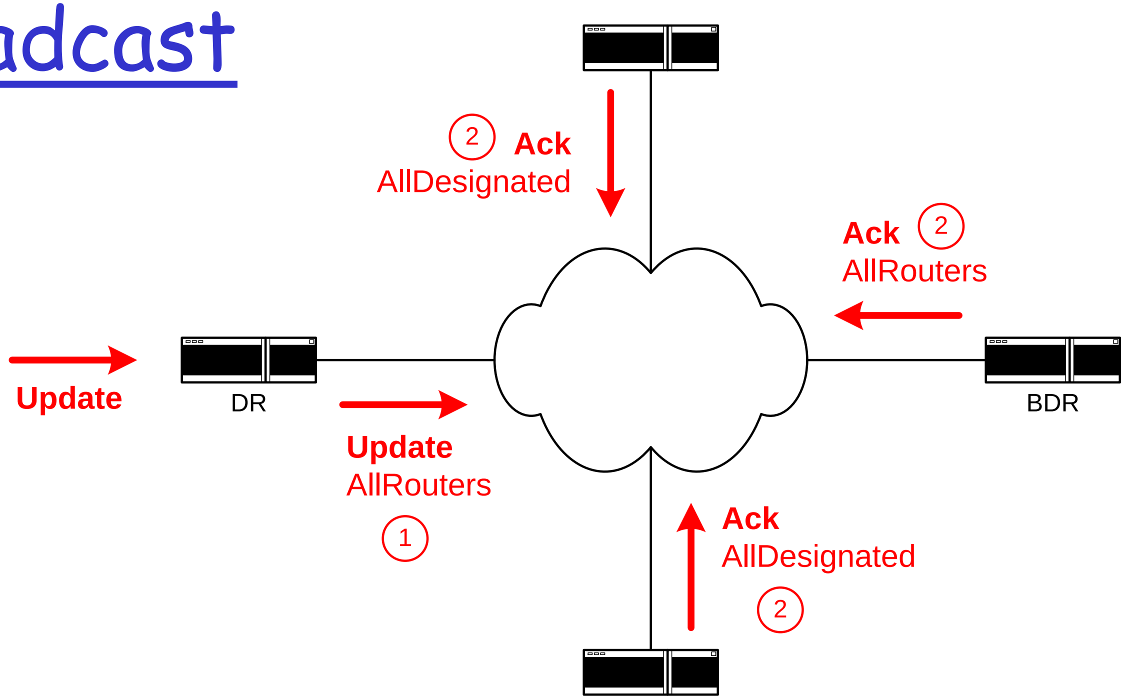


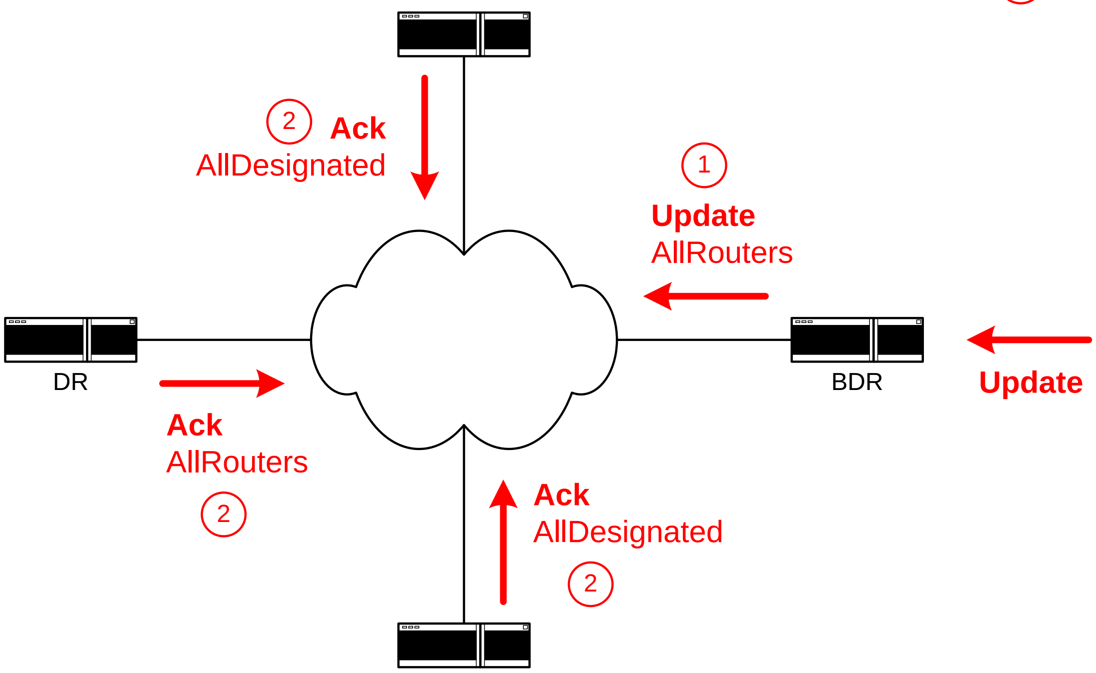


DR sends to all routers using multicast address allSPFRouters (224.0.0.5)

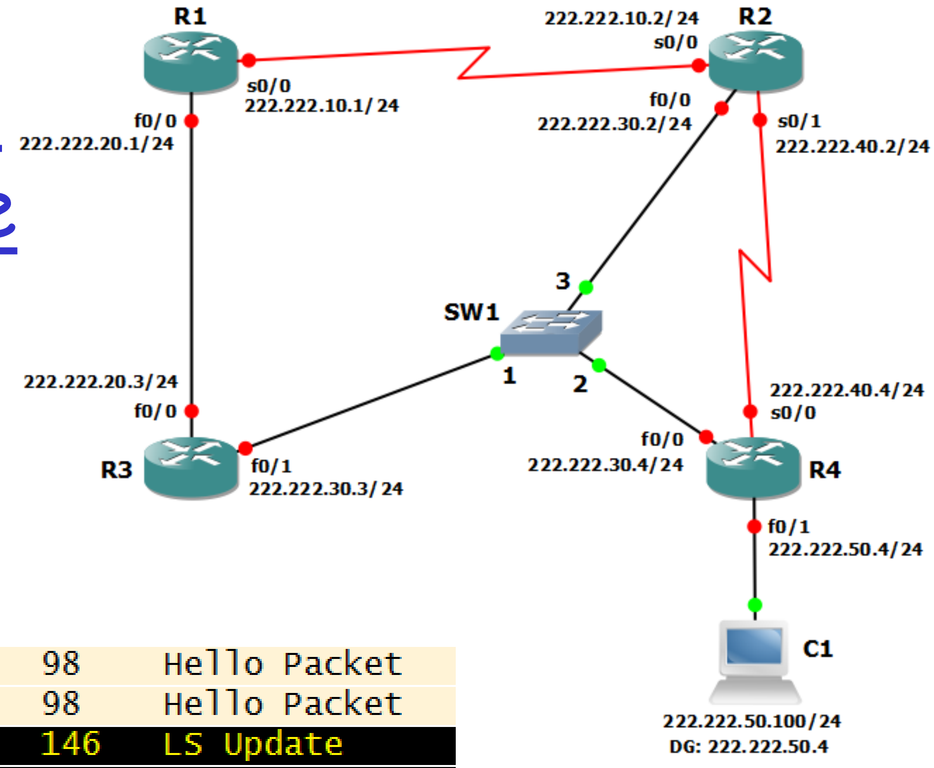
Each router sends ACK packet to the DR (except the initial router)

Flooding in broadcast subnets





Case study – Analyzing the flooding procedure

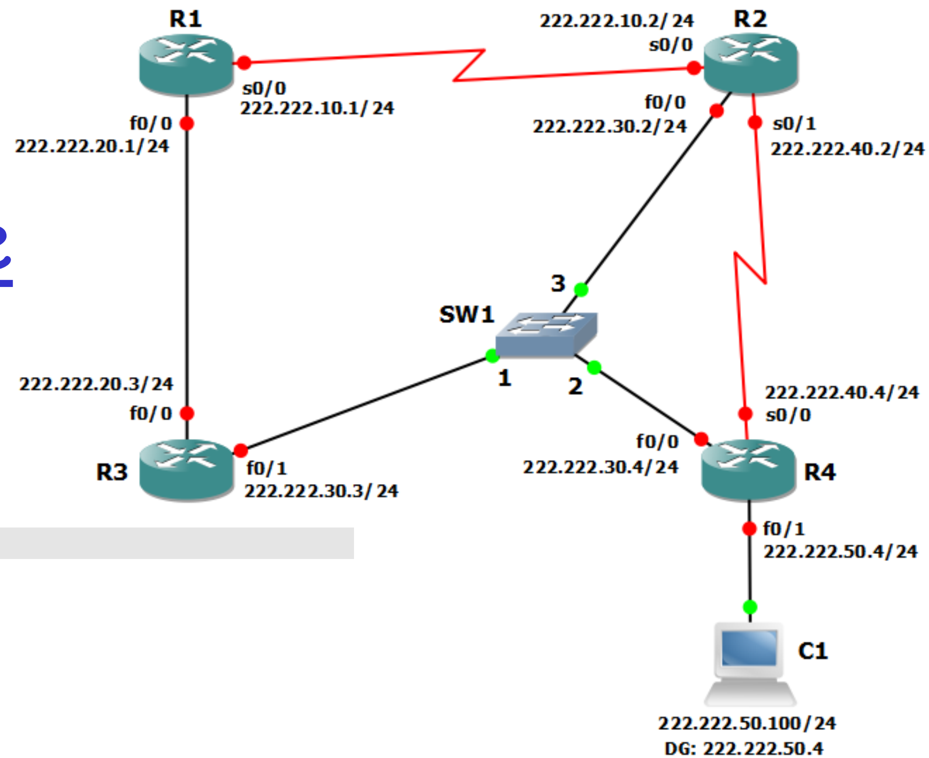


EXPERIMENT: Change cost of s0/0-R2 to 100. Observe LS Update and LS Acknowledge packets exchanged at 222.222.30.0/34. DR is R2 and BDR is R4.

70	150.209000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
72	153.798000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
73	158.818000	222.222.30.2	224.0.0.5	OSPF	146	LS Update
74	158.852000	222.222.30.4	224.0.0.5	OSPF	146	LS Update
75	160.003000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
76	160.223000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
77	161.326000	222.222.30.3	224.0.0.6	OSPF	78	LS Acknowledge
78	161.334000	222.222.30.4	224.0.0.5	OSPF	78	LS Acknowledge
80	163.822000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
81	170.012000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet

Both DR and BDR multicast same LSA. R3 acknowledges to AllDRouters multicast address (224.0.0.6); DR and BDR use AllSPFRouters multicast address (224.0.0.5)
IMPORTANT: the routing tables will not change, but the network graph must be updated

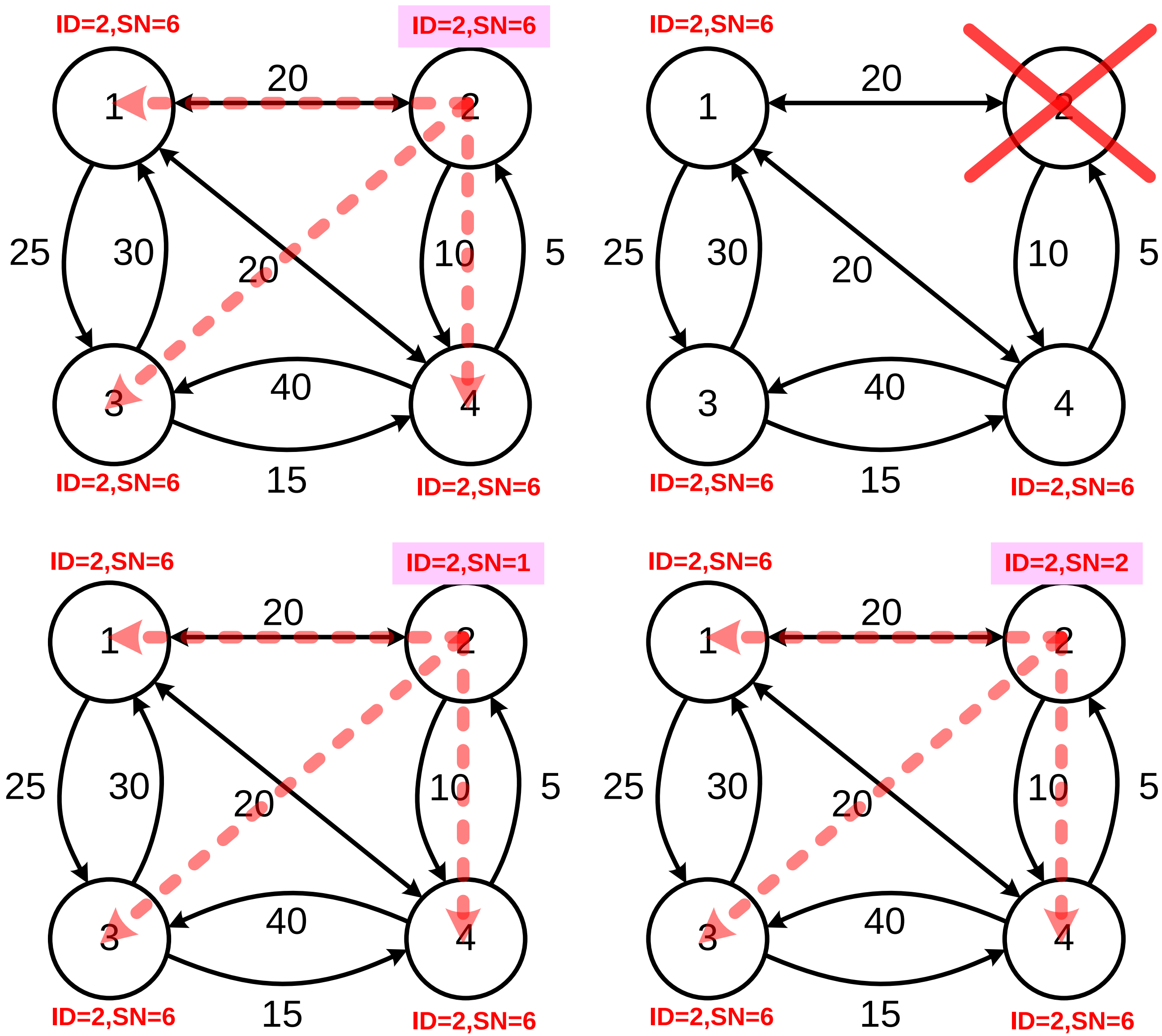
Case study - Analyzing the flooding procedure




```
⊟ Open Shortest Path First
  ⊞ OSPF Header
  ⊟ LS Update Packet
      Number of LSAs: 1
    ⊟ LS Type: Router-LSA
        LS Age: 1 seconds
        Do Not Age: False
      ⊞ Options: 0x22 (DC, E)
        Link-State Advertisement Type: Router-LSA (1)
        <Router LSA: True>
        Link State ID: 2.2.2.2
        Advertising Router: 2.2.2.2 (2.2.2.2)
        LS Sequence Number: 0x80000020
        LS Checksum: 0xbd88
        Length: 84
      ⊞ Flags: 0x00
        Number of Links: 5
      ⊞ Type: PTP       ID: 4.4.4.4        Data: 222.222.40.2    Metric: 64
      ⊞ Type: Stub      ID: 222.222.40.0   Data: 255.255.255.0   Metric: 64
      ⊞ Type: Transit   ID: 222.222.30.2   Data: 222.222.30.2    Metric: 10
      ⊞ Type: PTP       ID: 1.1.1.1        Data: 222.222.10.2    Metric: 100
      ⊞ Type: Stub      ID: 222.222.10.0   Data: 255.255.255.0   Metric: 100
```

LS Update packet sent by R2

Initial synchronization of the LSBD



Router is switched off and then switched on again

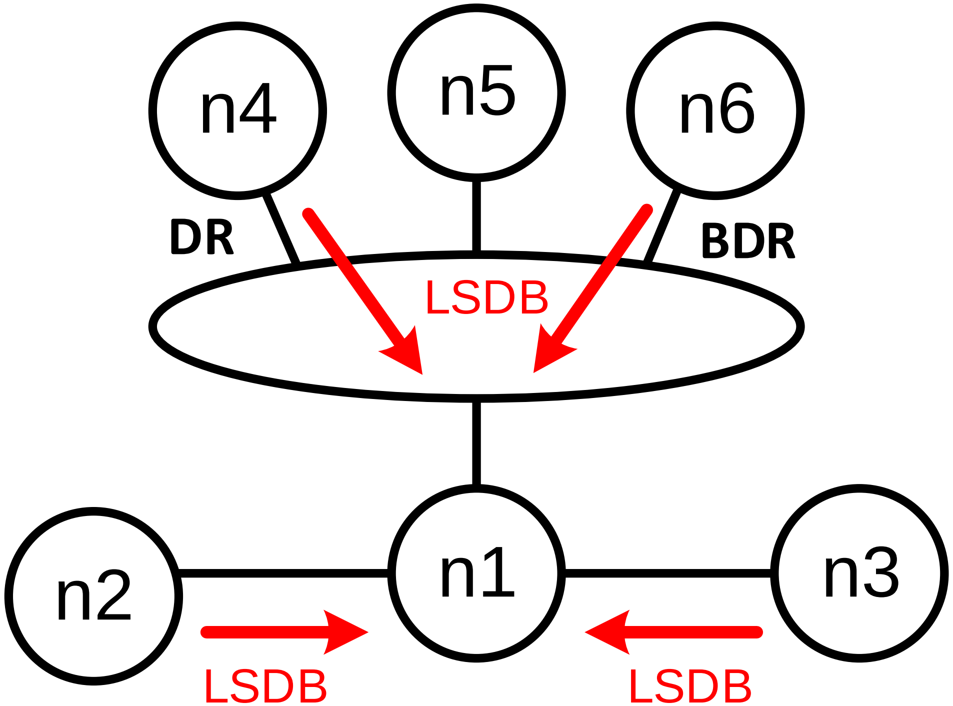
Updates of reborn router will only propagate when SN > 6

Initial synchronization of the LSDB

- Problem: when a router is switched on how does it get to know the network topology?
  - Recall that updates are not sent periodically (except for the long 30 min period); they are only sent by a router when it perceives a change in a link with a neighbor

- Solution: when a router is switched on it tries to get the LSAs from its neighbors

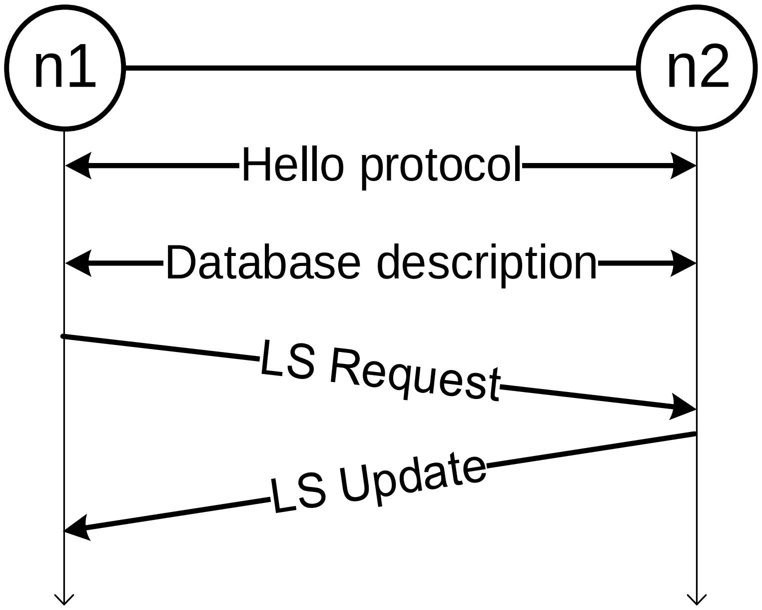
Initial synchronization of the LSDB



- Router (n1 in this case) synchronizes with every neighbor that has a point-to-point link and the DR and BDR in a broadcast subnet

Initial synchronization of the LSDB

- First exchange summary information, only after request complete information if needed
  - OSPF uses Database Description messages to get the LSA headers
  - When it verifies that the LSA body is also needed, the router asks it using a Link State Request message, and the requested LSA is sent using a Link State Update message



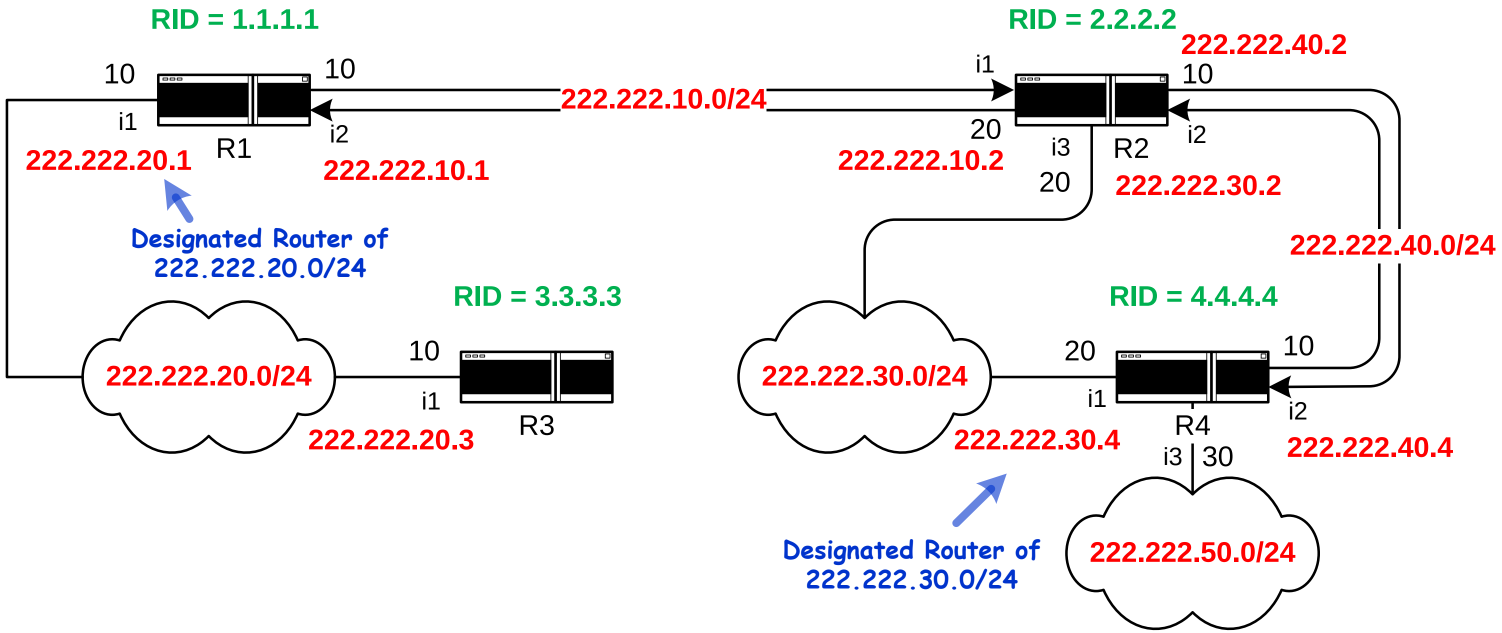
Exchange of Database Description packets

0	8	16	24	32
OSPF packet header				
Interface MTU		Options	0 0 0 0 0 I M MS	
DD Sequence Number				
LSA Headers				

- Neighbors establish Master/Slave relationship and use a stop-and-wait protocol
- The Master is the neighbor with higher RID
  - The **Master/Slave** bit (**MS-bit**) indicates who the Master is
- Protocol
  - Either neighbor can send the first DD packet; it will have the **Init** bit (**I-bit**) set to 1
  - DD request-response exchanges are initiated by the Master; Slave answers using the Sequence Number received from the Master (**DD Sequence Number**)

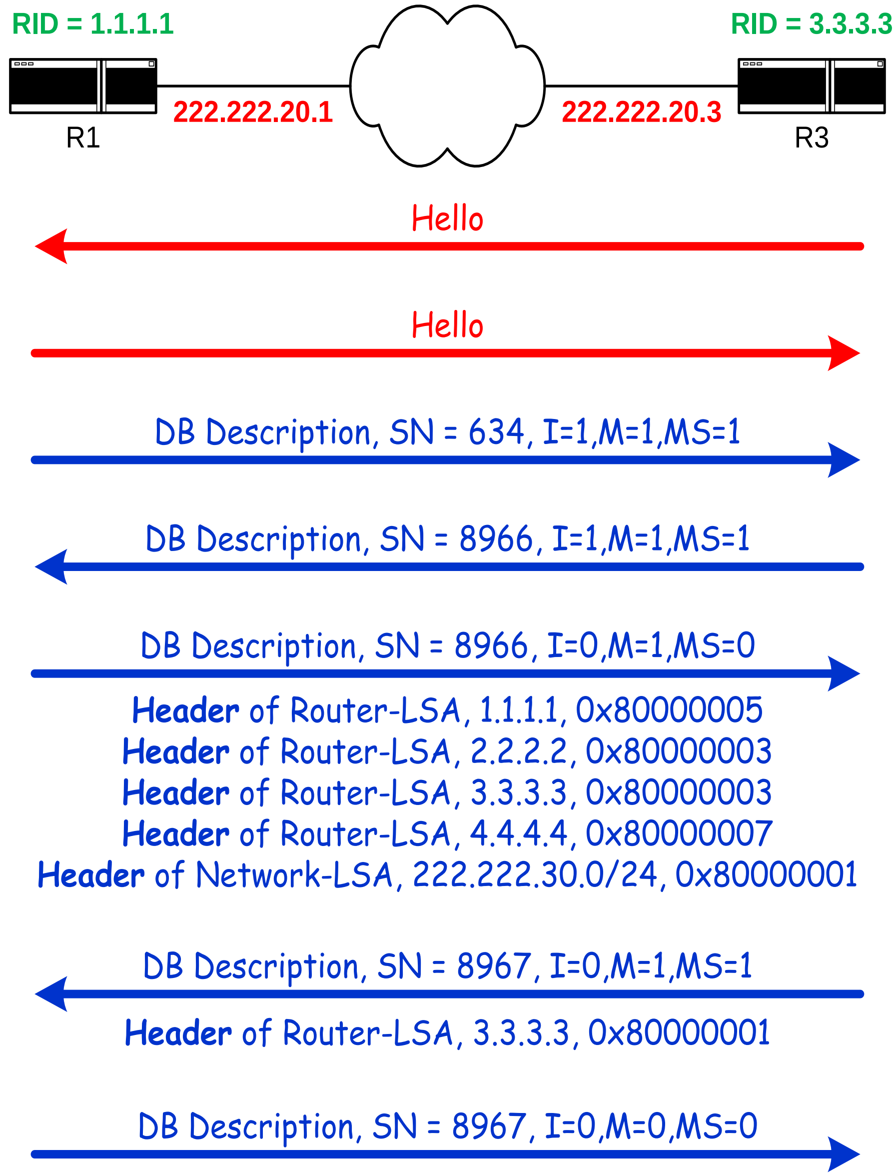
- Only the Master can retransmit packets; timeout period is **RxmtInterval** (RFC suggests 5 seconds on a LAN)
- Neighbors signal each other that they have nothing else to send using the **More** bit (**M-bit**); only the Master can end a DD exchange (when its M-bit is zero, and the one of the Slave is also 0)

Initial synchronization of the LSBD - example

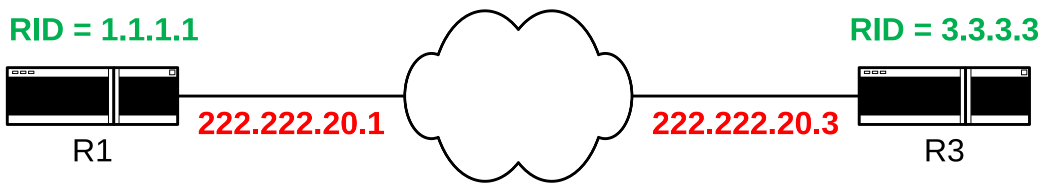


- R3 is not directly connected with 222.222.30.0/24
- Switch off R3, wait until R1 updates its LSAs, switch on R3 again

Initial synchronization of the LSDB - example



Initial synchronization of the LSDB - example



DB Description, SN = 8968, I=0,M=0,MS=1 ←

DB Description, SN = 8968, I=0,M=0,MS=0 →

LS Request, directed to R1 ←

Header of Router-LSA, 1.1.1.1, 0x80000005
Header of Router-LSA, 2.2.2.2, 0x80000003
Header of Router-LSA, 3.3.3.3, 0x80000003
Header of Router-LSA, 4.4.4.4, 0x80000007
Header of Network-LSA, 222.222.30.0/24, 0x80000001

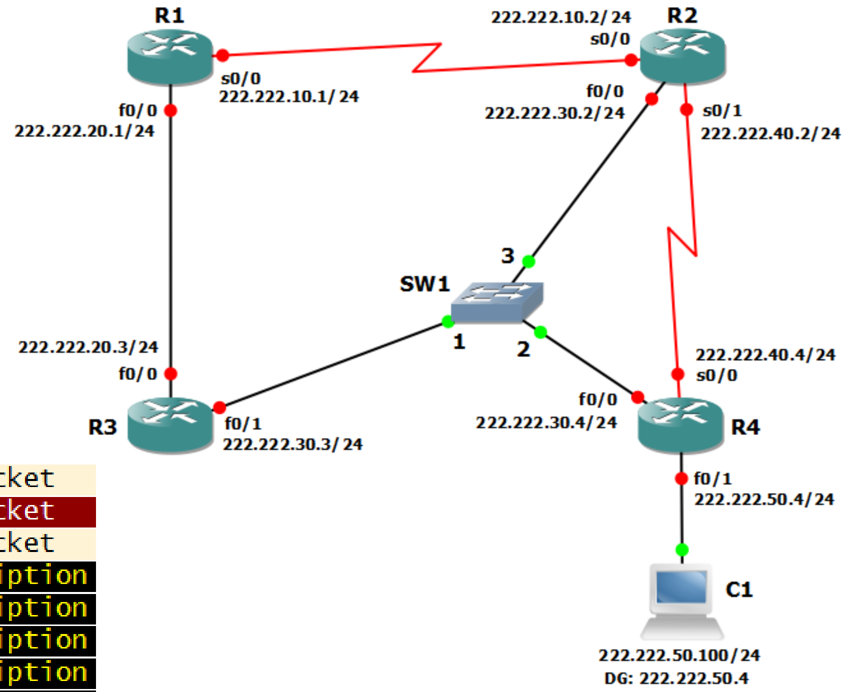
LS Update, directed to R3 →

Complete Router-LSA, 1.1.1.1, 0x80000005
Complete Router-LSA, 2.2.2.2, 0x80000003
Complete Router-LSA, 3.3.3.3, <u>0x80000003</u>
Complete Router-LSA, 4.4.4.4, 0x80000007
Complete Network-LSA, 222.222.30.0/24, 0x80000001

LS Update, flooded ←

Complete Router-LSA, 3.3.3.3, <u>0x80000004</u>

Case study - Initial synchronization of the LSDB



26	45.793000	222.222.20.3	224.0.0.5	OSPF	90	Hello Packet
27	45.803000	222.222.20.1	222.222.20.3	OSPF	94	Hello Packet
32	49.529000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet
33	50.856000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
34	50.877000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
35	50.897000	222.222.20.1	222.222.20.3	OSPF	198	DB Description
36	50.907000	222.222.20.3	222.222.20.1	OSPF	98	DB Description
37	50.917000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
38	50.927000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
39	50.945000	222.222.20.3	222.222.20.1	OSPF	130	LS Request
40	50.945000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
41	50.955000	222.222.20.1	222.222.20.3	OSPF	390	LS Update

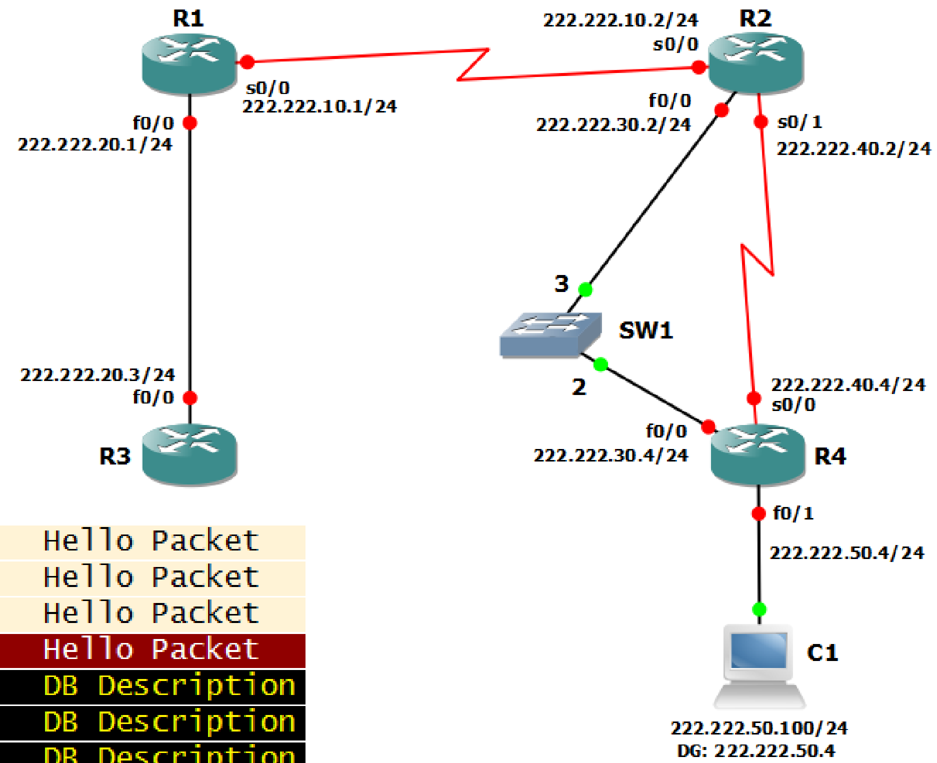
EXPERIMENT:
1. Switch off R3
2. Switch on R3 again

R3 synchronizes with R1 and with the DR and BDR of 222.222.30.0/24

Too many things happening at the same time!

42	50.248000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
43	50.817000	222.222.30.3	222.222.30.2	OSPF	78	DB Description
44	50.838000	222.222.30.3	222.222.30.4	OSPF	78	DB Description
45	50.843000	222.222.30.2	222.222.30.3	OSPF	78	DB Description
46	50.854000	222.222.30.2	222.222.30.3	OSPF	198	DB Description
47	50.858000	222.222.30.4	222.222.30.3	OSPF	78	DB Description
48	50.868000	222.222.30.3	222.222.30.2	OSPF	98	DB Description
49	50.878000	222.222.30.3	222.222.30.4	OSPF	98	DB Description
50	50.881000	222.222.30.2	222.222.30.3	OSPF	78	DB Description
51	50.888000	222.222.30.3	222.222.30.2	OSPF	78	DB Description
52	50.888000	222.222.30.4	222.222.30.3	OSPF	198	DB Description
53	50.906000	222.222.30.3	222.222.30.2	OSPF	130	LS Request
54	50.906000	222.222.30.2	222.222.30.3	OSPF	78	DB Description

Case study - Initial synchronization of the LSDB



33	125.241000	222.222.20.1	224.0.0.5	OSPF	90	Hello Packet
35	135.242000	222.222.20.1	224.0.0.5	OSPF	90	Hello Packet
41	138.674000	222.222.20.3	224.0.0.5	OSPF	90	Hello Packet
42	138.684000	222.222.20.1	222.222.20.3	OSPF	94	Hello Packet
48	143.724000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
49	143.737000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
50	143.747000	222.222.20.1	222.222.20.3	OSPF	178	DB Description
51	143.757000	222.222.20.3	222.222.20.1	OSPF	98	DB Description
52	143.767000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
53	143.778000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
54	143.788000	222.222.20.3	222.222.20.1	OSPF	118	LS Request
55	143.790000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
56	143.800000	222.222.20.1	222.222.20.3	OSPF	358	LS Update
57	144.243000	222.222.20.1	224.0.0.5	OSPF	122	LS Update
58	144.288000	222.222.20.1	224.0.0.5	OSPF	94	LS Update
59	145.260000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet
61	146.331000	222.222.20.3	224.0.0.5	OSPF	198	LS Acknowledge
62	148.671000	222.222.20.3	224.0.0.5	OSPF	94	Hello Packet
63	148.814000	222.222.20.3	224.0.0.5	OSPF	110	LS Update
65	151.354000	222.222.20.1	224.0.0.5	OSPF	78	LS Acknowledge
66	155.246000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet
68	158.672000	222.222.20.3	224.0.0.5	OSPF	94	Hello Packet
70	165.248000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet

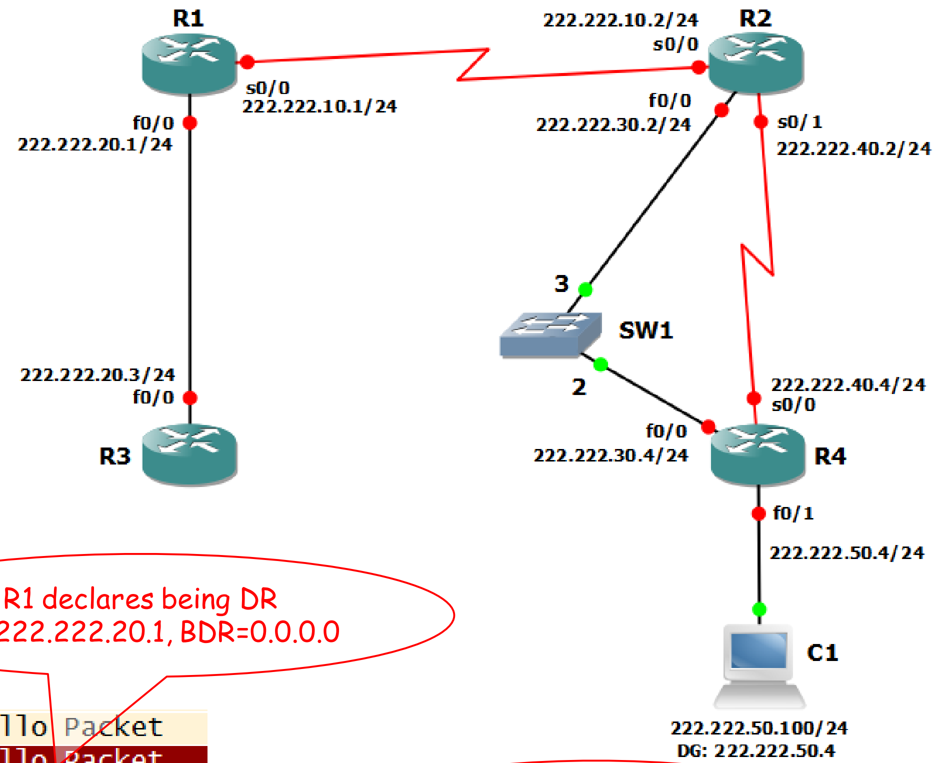
EXPERIMENT:

- R3 is only connected to R1; Initially, R1 is the DR at 222.222.20.0/24

1. Switch off R3
2. Wait for a while until R1 updates its LSAs
3. Switch on R3 again

NOTE: the old router-LSA of R3 is still in the LSDB when R3 is switched on

Case study - Initial synchronization of the LSDB



Initial Hello sent by R3
DR=0.0.0.0, BDR=0.0.0.0

R1 declares being DR
DR=222.222.20.1, BDR=0.0.0.0

41	138.674000	222.222.20.3	224.0.0.5	OSPF	90	Hello Packet
42	138.684000	222.222.20.1	222.222.20.3	OSPF	94	Hello Packet
48	143.724000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
49	143.737000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
50	143.747000	222.222.20.1	222.222.20.3	OSPF	178	DB Description
51	143.757000	222.222.20.3	222.222.20.1	OSPF	98	DB Description
52	143.767000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
53	143.778000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
54	143.788000	222.222.20.3	222.222.20.1	OSPF	118	LS Request
55	143.790000	222.222.20.1	222.222.20.3	OSPF	78	DB Description

Initial DD pkt sent R3
I=1,M=1,MS=1, SN=8966

Initial DD pkt sent R1
I=1,M=1,MS=1, SN=634

R1 assumes being slave
I=0,M=1,MS=0, SN=8966
Sends all its 5 LSA headers

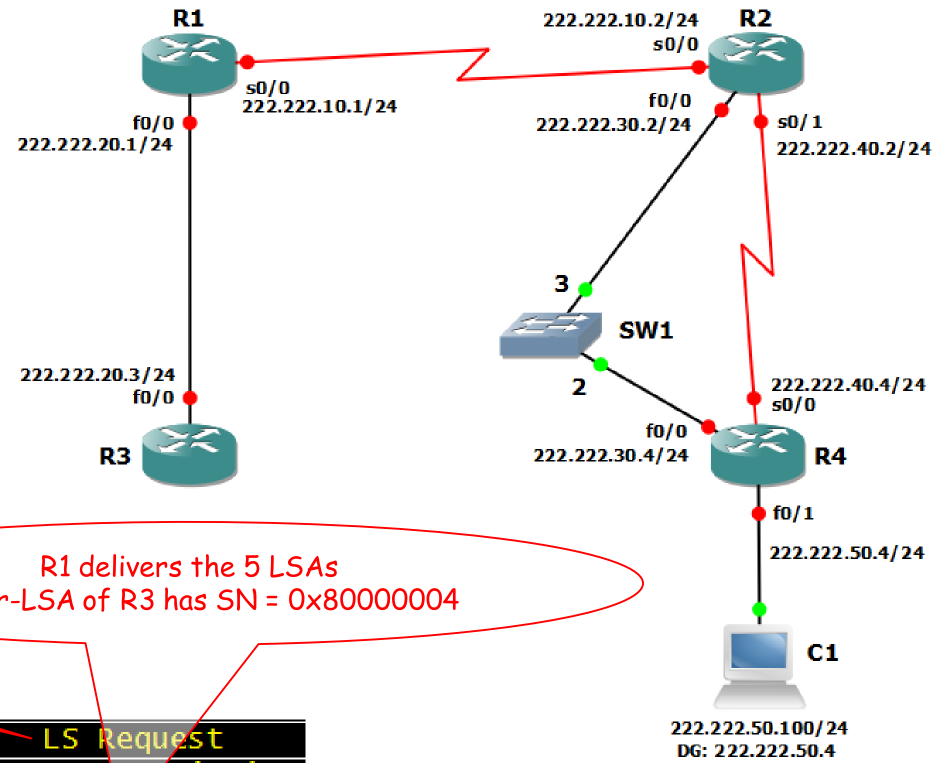
R3 sends header of its router-LSA with SN = 0x80000001, I=0,M=1,MS=1, SN=8967

I=0,M=0,MS=0, SN=8967

I=0,M=0,MS=0, SN=8968

R3 initiates end of DD exchange,
I=0,M=0,MS=1, SN=8968

Case study - Initial synchronization of the LSDB



R3 requests the 5 LSAs

R1 delivers the 5 LSAs
Router-LSA of R3 has SN = 0x80000004

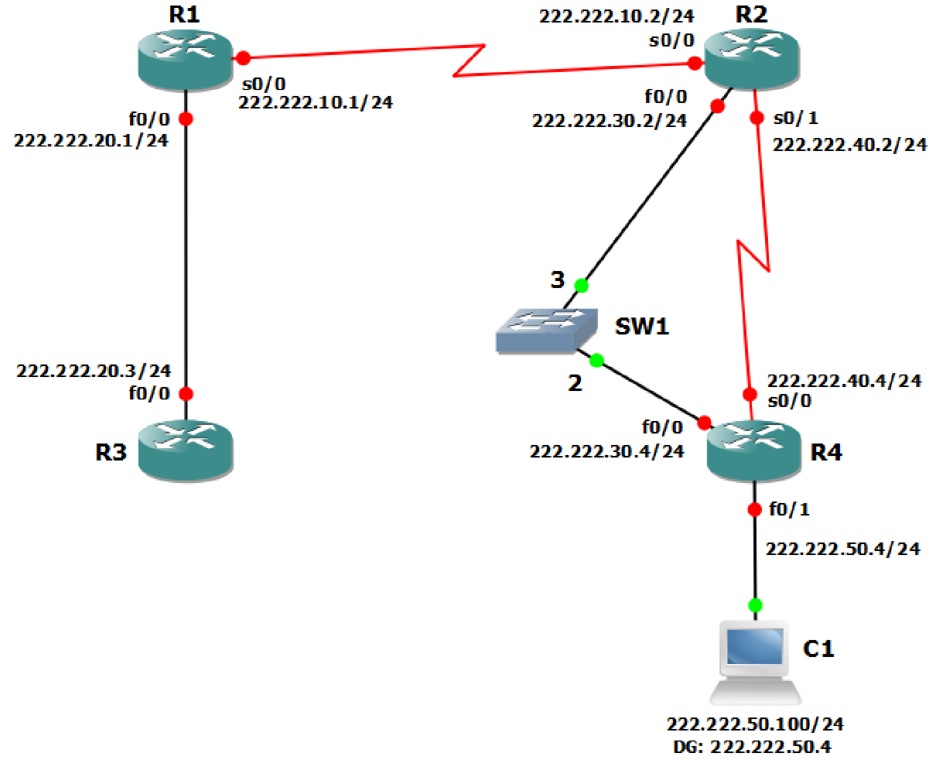
54	143.788000	222.222.20.3	222.222.20.1	OSPF	118	LS Request
55	143.790000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
56	143.800000	222.222.20.1	222.222.20.3	OSPF	358	LS Update
57	144.243000	222.222.20.1	224.0.0.5	OSPF	122	LS Update
58	144.288000	222.222.20.1	224.0.0.5	OSPF	94	LS Update
59	145.260000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet
61	146.331000	222.222.20.3	224.0.0.5	OSPF	198	LS Acknowledge
62	148.671000	222.222.20.3	224.0.0.5	OSPF	94	Hello Packet
63	148.814000	222.222.20.3	224.0.0.5	OSPF	110	LS Update
65	151.354000	222.222.20.1	224.0.0.5	OSPF	78	LS Acknowledge

Flooding of new router-LSA of R1
222.222.20.0/24 is no longer stub

Flooding of new network-LSA of
222.222.20.0/24; it is no longer stub

R3 floods router-LSA with SN =
0x80000005; replaces old one

Case study - Initial synchronization of the LSDB



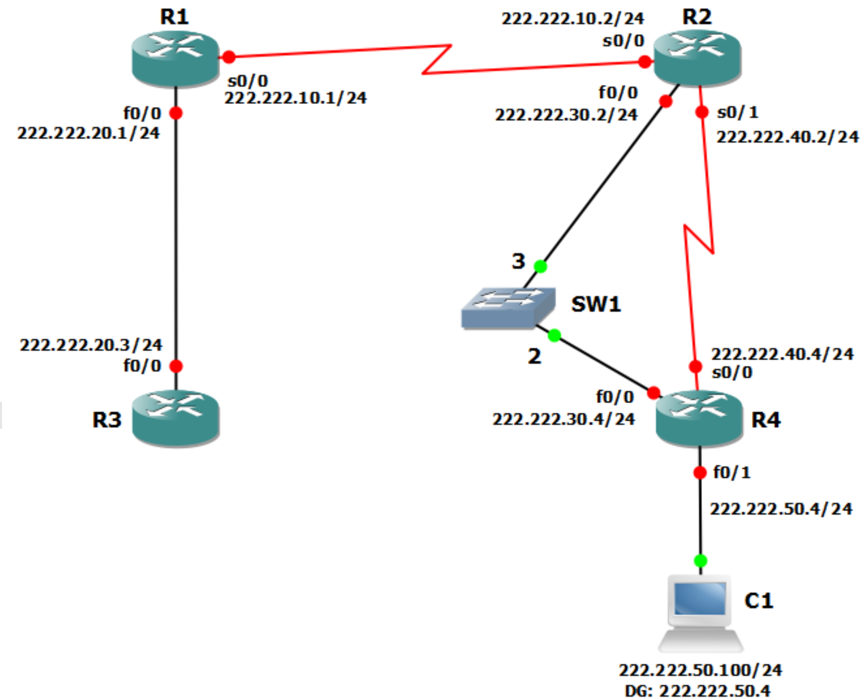

```
Open Shortest Path First
⊞ OSPF Header
⊞ OSPF DB Description
⊞ LSA Header
⊞ LSA Header
⊟ LSA Header
    LS Age: 583 seconds
    Do Not Age: False
  ⊞ Options: 0x22 (DC, E)
    Link-State Advertisement Type: Router-LSA (1)
    <Router LSA: True>
    Link State ID: 3.3.3.3
    Advertising Router: 3.3.3.3 (3.3.3.3)
    LS Sequence Number: 0x80000004
    LS Checksum: 0x3140
    Length: 48
⊞ LSA Header
⊞ LSA Header
⊞ OSPF LLS Data Block
```

DB Description sent by R1

```
Open Shortest Path First
⊞ OSPF Header
⊞ OSPF DB Description
⊟ LSA Header
    LS Age: 4 seconds
    Do Not Age: False
  ⊞ Options: 0x22 (DC, E)
    Link-State Advertisement Type: Router-LSA (1)
    <Router LSA: True>
    Link State ID: 3.3.3.3
    Advertising Router: 3.3.3.3 (3.3.3.3)
    LS Sequence Number: 0x80000001
    LS Checksum: 0xfd54
    Length: 48
⊞ OSPF LLS Data Block
```

DB Description sent by R3

Case study – Initial synchronization of the LSDB



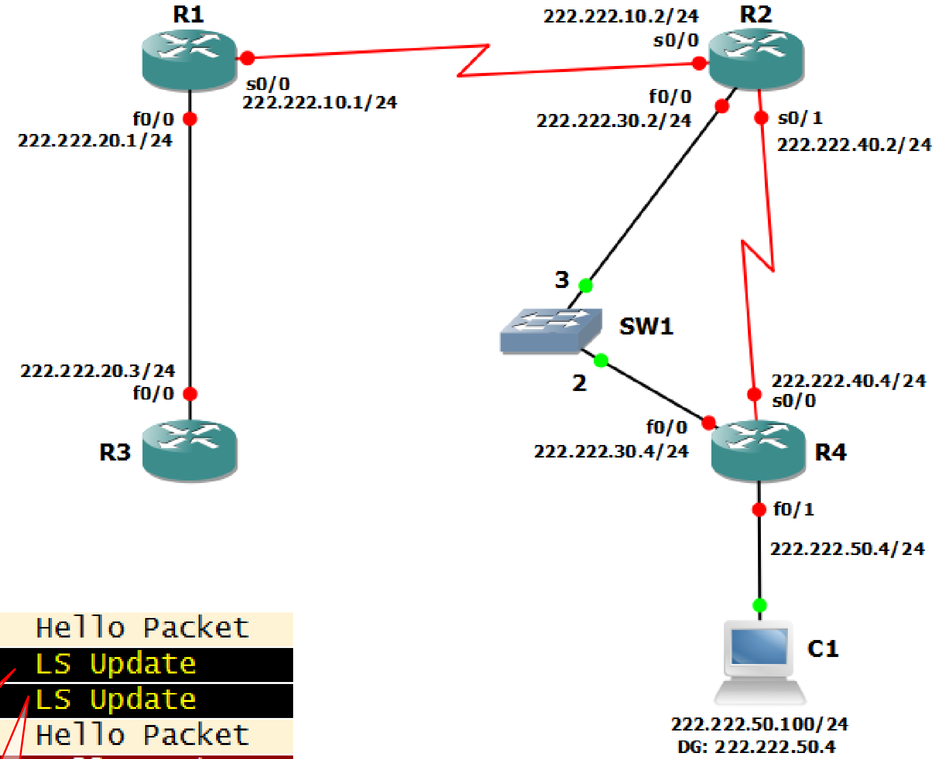

```
Open Shortest Path First
⊞ OSPF Header
⊟ LS Update Packet
    Number of LSAs: 5
  ⊞ LS Type: Router-LSA
  ⊞ LS Type: Router-LSA
  ⊟ LS Type: Router-LSA
      LS Age: 584 seconds
      Do Not Age: False
    ⊞ Options: 0x22 (DC, E)
      Link-State Advertisement Type: Router-LSA (1)
      <Router LSA: True>
      Link State ID: 3.3.3.3
      Advertising Router: 3.3.3.3 (3.3.3.3)
      LS Sequence Number: 0x80000004
      LS Checksum: 0x3140
      Length: 48
    ⊞ Flags: 0x00
      Number of Links: 2
    ⊞ Type: Stub      ID: 222.222.30.0    Data: 255.255.255.0   Metric: 10
    ⊞ Type: Transit   ID: 222.222.20.1    Data: 222.222.20.3    Metric: 10
  ⊞ LS Type: Router-LSA
  ⊞ LS Type: Network-LSA
```

LS Update with requested LSAs

```
Open Shortest Path First
⊞ OSPF Header
⊟ Link State Request
    Link-State Advertisement Type: Router-LSA (1)
    Link State ID: 1.1.1.1
    Advertising Router: 1.1.1.1 (1.1.1.1)
⊟ Link State Request
    Link-State Advertisement Type: Router-LSA (1)
    Link State ID: 2.2.2.2
    Advertising Router: 2.2.2.2 (2.2.2.2)
⊟ Link State Request
    Link-State Advertisement Type: Router-LSA (1)
    Link State ID: 3.3.3.3
    Advertising Router: 3.3.3.3 (3.3.3.3)
⊟ Link State Request
    Link-State Advertisement Type: Router-LSA (1)
    Link State ID: 4.4.4.4
    Advertising Router: 4.4.4.4 (4.4.4.4)
⊟ Link State Request
    Link-State Advertisement Type: Network-LSA (2)
    Link State ID: 222.222.30.4
    Advertising Router: 4.4.4.4 (4.4.4.4)
```

LS Request

Case study - Initial synchronization of the LSDB



R3#clear ip ospf process

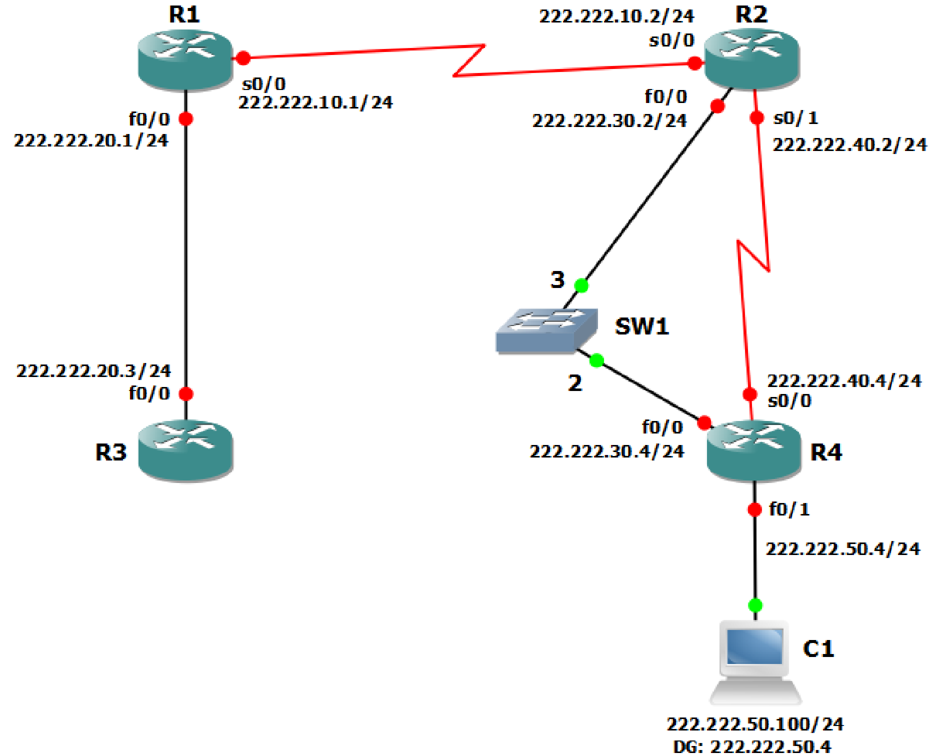
24	51.493000	222.222.20.3	224.0.0.5	OSPF	94	Hello Packet
27	58.258000	222.222.20.3	224.0.0.5	OSPF	110	LS Update
28	58.271000	222.222.20.3	224.0.0.5	OSPF	94	LS Update
29	58.344000	222.222.20.3	224.0.0.5	OSPF	90	Hello Packet
30	58.359000	222.222.20.1	222.222.20.3	OSPF	94	Hello Packet
31	58.379000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
32	58.389000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
33	58.389000	222.222.20.3	222.222.20.1	OSPF	94	Hello Packet
34	58.399000	222.222.20.1	222.222.20.3	OSPF	158	DB Description
35	58.409000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
36	58.429000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
37	58.449000	222.222.20.3	222.222.20.1	OSPF	106	LS Request
38	58.459000	222.222.20.1	222.222.20.3	OSPF	310	LS Update
39	58.791000	222.222.20.3	224.0.0.5	OSPF	110	LS Update

Eliminates router-LSA of R3

Eliminates network-LSA of 222.222.20.0/24;
R3 was the DR

EXPERIMENT:
- Same as initial experiment but OSPF process is cleared at R3 (instead of the router being switched off)
- ***OSPF has some time to think!***

Case study - Initial synchronization of the LSDB



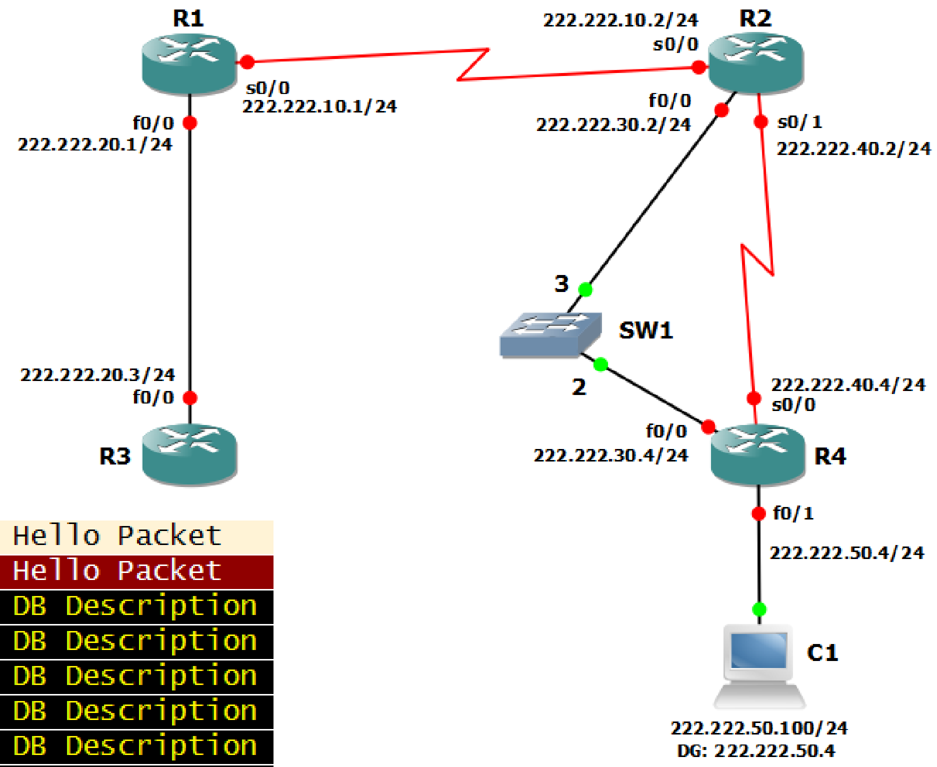

```
Open Shortest Path First
⊞ OSPF Header
⊟ LS Update Packet
    Number of LSAs: 1
  ⊟ LS Type: Network-LSA
      LS Age: 3600 seconds
      Do Not Age: False
    ⊞ Options: 0x22 (DC, E)
      Link-State Advertisement Type: Network-LSA (2)
      <Network LSA: True>
      Link State ID: 222.222.20.3
      Advertising Router: 3.3.3.3 (3.3.3.3)
      LS Sequence Number: 0x80000001
      LS Checksum: 0x1f2a
      Length: 32
      Netmask: 255.255.255.0
      Attached Router: 3.3.3.3
      Attached Router: 1.1.1.1
```

LS Update clearing network-LSA of 222.222.20.0/24

```
Open Shortest Path First
⊞ OSPF Header
⊟ LS Update Packet
    Number of LSAs: 1
  ⊟ LS Type: Router-LSA
      LS Age: 3600 seconds
      Do Not Age: False
    ⊞ Options: 0x22 (DC, E)
      Link-State Advertisement Type: Router-LSA (1)
      <Router LSA: True>
      Link State ID: 3.3.3.3
      Advertising Router: 3.3.3.3 (3.3.3.3)
      LS Sequence Number: 0x80000003
      LS Checksum: 0xbca9
      Length: 36
    ⊞ Flags: 0x00
      Number of Links: 1
    ⊞ Type: Transit   ID: 222.222.20.3    Data: 222.222.20.3    Metric: 10
```

LS Update clearing the router-LSA of R3

Case study - Initial synchronization of the LSDB



29	92.459000	222.222.20.3	224.0.0.5	OSPF	90	Hello Packet
30	92.479000	222.222.20.1	222.222.20.3	OSPF	94	Hello Packet
35	97.528000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
36	97.548000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
37	97.558000	222.222.20.1	222.222.20.3	OSPF	198	DB Description
38	97.578000	222.222.20.3	222.222.20.1	OSPF	98	DB Description
39	97.588000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
40	97.598000	222.222.20.3	222.222.20.1	OSPF	78	DB Description
41	97.608000	222.222.20.1	222.222.20.3	OSPF	78	DB Description
42	97.608000	222.222.20.3	222.222.20.1	OSPF	130	LS Request
43	97.618000	222.222.20.1	222.222.20.3	OSPF	378	LS Update
44	97.628000	222.222.20.3	224.0.0.5	OSPF	94	LS Update
45	97.638000	222.222.20.1	224.0.0.5	OSPF	94	LS Update
46	98.052000	222.222.20.1	224.0.0.5	OSPF	122	LS Update
47	98.132000	222.222.20.1	224.0.0.5	OSPF	94	LS Update
50	99.993000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet
51	100.136000	222.222.20.3	224.0.0.5	OSPF	238	LS Acknowledge
52	100.146000	222.222.20.1	224.0.0.5	OSPF	78	LS Acknowledge
54	102.472000	222.222.20.3	224.0.0.5	OSPF	94	Hello Packet
55	102.655000	222.222.20.3	224.0.0.5	OSPF	98	LS Update
56	105.175000	222.222.20.1	224.0.0.5	OSPF	78	LS Acknowledge
58	109.997000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet

EXPERIMENT:
- Same as initial experiment but R3 was initially DR at 222.222.20.0/24

Eliminates network-LSA of 222.222.20.0/24;
R3 was the DR before being switched off; realizes it is no longer the DR

OSPF packets

0	8	16	24–32
Version #	Type	Packet length	
Router ID			
Area ID			
Checksum		AuType	
Authentication			
Authentication			

OSPF Packet Header

0	8	16	24–32
OSPF packet header			
# LSAs			
LSA headers			

LS Update

0	8	16	24–32
OSPF packet header			
LS Type			
LS ID			
Advertising Router			

LS Request

0	8	16	24–32
OSPF packet header			
LSA headers			

LS Acknowledgement

0	8	16	24–32
OSPF packet header			
Interface MTU		Options	0 0 0 0 0 I M MS
DD Sequence Number			
LSA Headers			

Database Description

0	8	16	24–32
OSPF packet header			
Network Mask			
HelloInterval		Options	Router Priority
RouterDeadInterval			
Designated Router			
Backup Designated Router			
Neighbor			

Hello

OSPF packets are encapsulated directly over IP (protocol number = 89)

OSPF multicasts

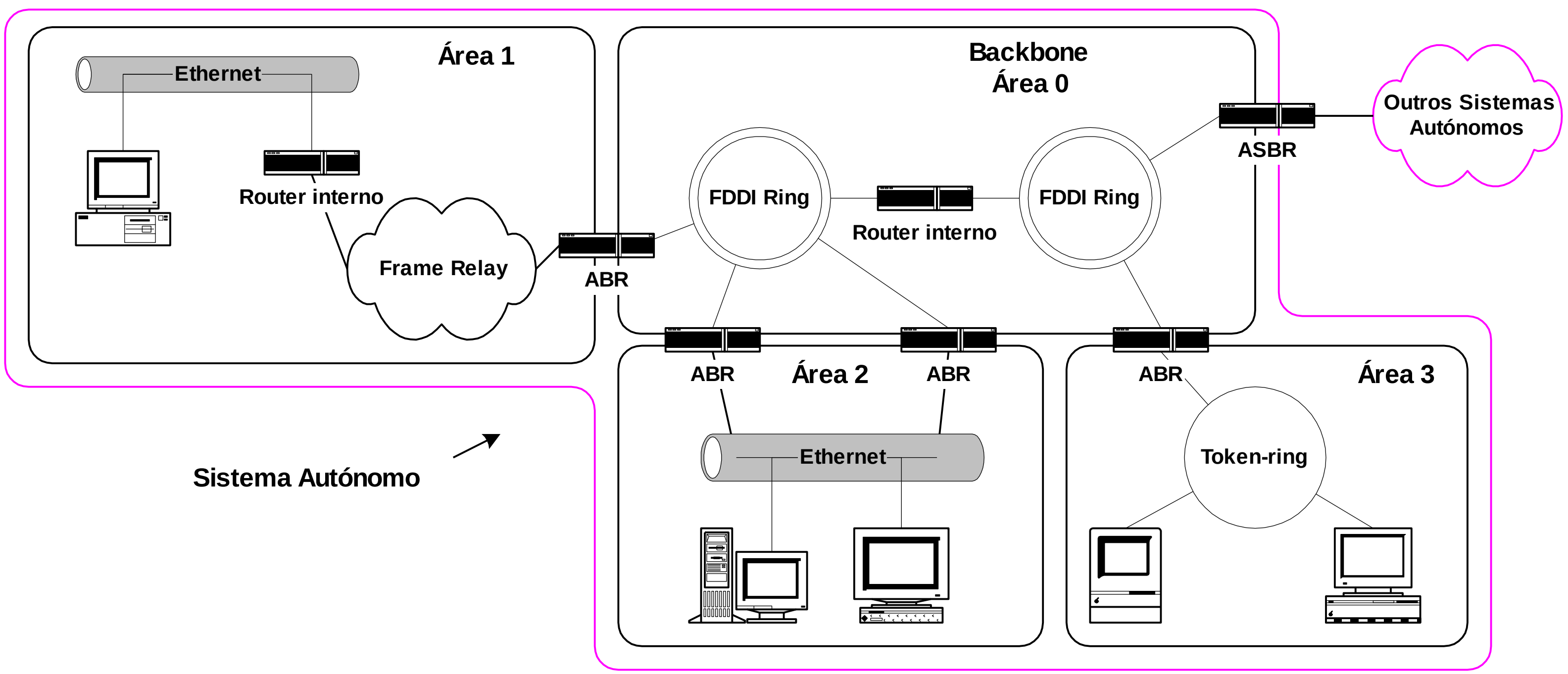
- OSPF uses two multicast addresses: AllSPFRouters (224.0.0.5) and AllDRouters (224.0.0.6).
- OSPF IP multicast packets are destined for the subnet of the originating router only. Thus, they are sent with TTL=1.
- On Ethernet networks IP multicast addresses map to Ethernet multicast addresses in this way:
  - the first 24 bits of the Ethernet multicast address (from bit 48 to bit 25) are 0x01005e;
  - bit 24 is 0;
  - bit 23 to bit 1 are the last 23 bits of the IP multicast address.
- For example, IP packets addressed to 222.0.0.5 will be encapsulated in Ethernet packets addressed to 0x01005e000005.

Summary of the essential OSPF structures and mechanisms

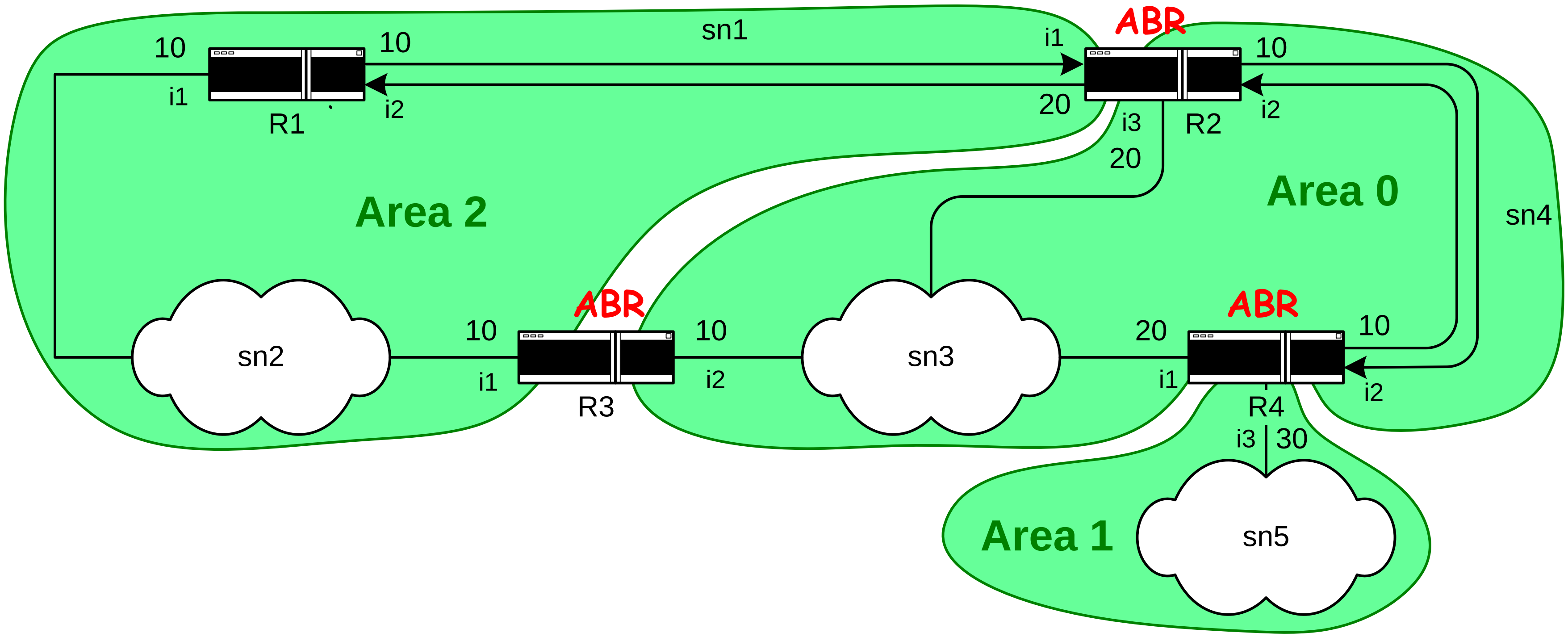
- Hello protocol
  - Each router gets to know its local portion of the network topology by sending Hello packets to its neighbors.
- Flooding process
  - Each router broadcast to all other routers its local portion of the network topology using a reliable flooding process.
- The Link State Database (LSDB)
  - The network graph obtained by each router through the flooding process is stored in the LSDB. The LSDB is structured in several parts called LSAs; each LSA describes a portion of the network topology and has a responsible router, the only one that can create it, update it or delete it.
- Initial Database Synchronization process
  - A new router joining the network builds its LSDB by retrieving a copy of it from its neighbors

Hierarchical OSPF

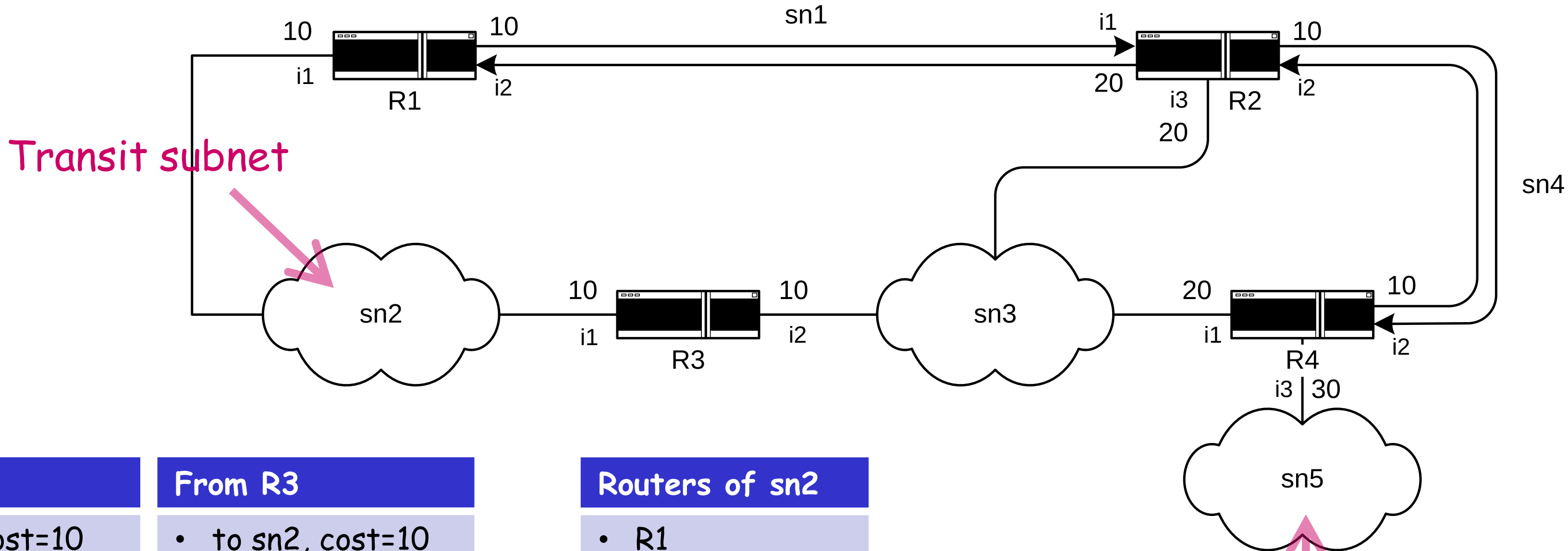
- Partition of the OSPF network in areas
- 2-level hierarchy
  - Higher level area, backbone = Area 0
  - Lower level areas connect to Area 0 through Area Border Routers (ABRs); they do not communicate directly with each other; only communicate via Area 0 (except in special cases)
- Main goal: improve scalability by reducing the size of the LSDB



Hierarchical OSPF



LSDB with a single area



From R1
• to R2, cost=10
• to sn2, cost=10

From R2
• to R1, cost=20
• to sn3, cost=20
• to R4, cost=10

From R3
• to sn2, cost=10
• to sn3, cost=10

From R4
• to R2, cost=10
• to sn3, cost=20
• to sn5, cost=30

Router-LSAs
(describes one router and its outgoing links)

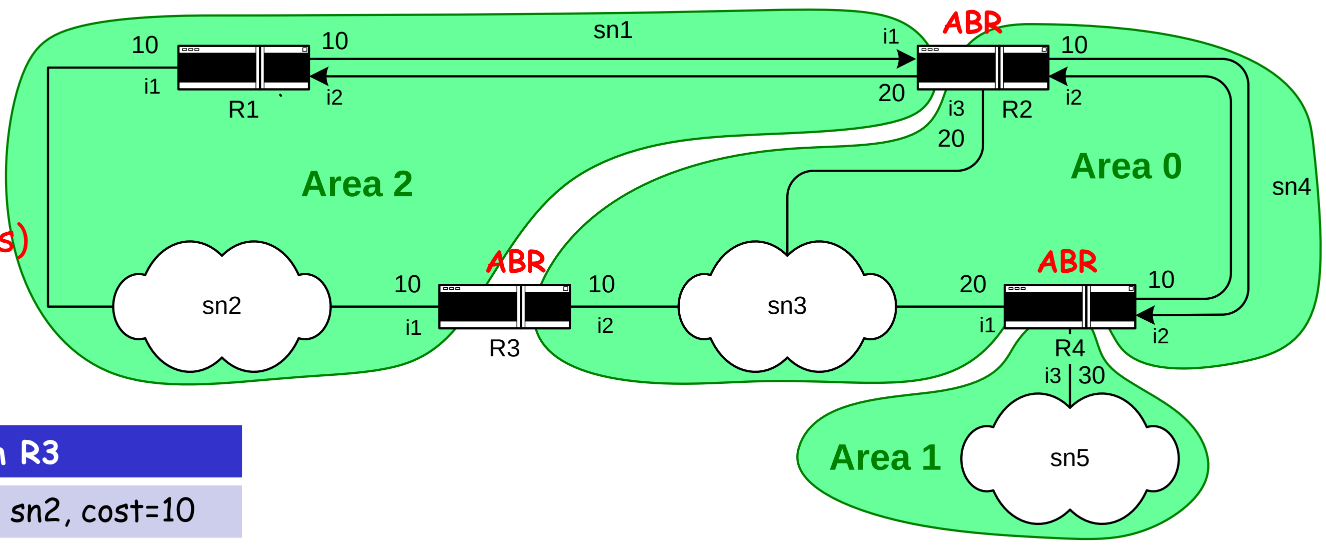
Routers of sn2
• R1
• R3

Routers of sn3
• R2
• R3
• R4

Network-LSAs
(describes one broadcast subnet and its attached routers)

- Routers are identified by RID (Router ID)
- Transit broadcast subnets are identified by address of Designated Router (DR)
- Stub subnets are represented in router-LSA by subnet address

LSDB in hierarchical OSPF



LSDB of R1
(IMPORTANT NOTE: it is no longer the same as other routers)

From R1
• to R2, cost=10
• to sn2, cost=10

From R3
• to sn2, cost=10

From R2
• to R1, cost=20

Router-LSAs
(describes one router and its outgoing links; IMPORTANT NOTE: routers and outgoing links of other areas are not represented)

Routers of sn2
• R1
• R3

Network-LSAs
(describes one broadcast subnet and its attached routers; IMPORTANT NOTE: only internal subnets are represented)

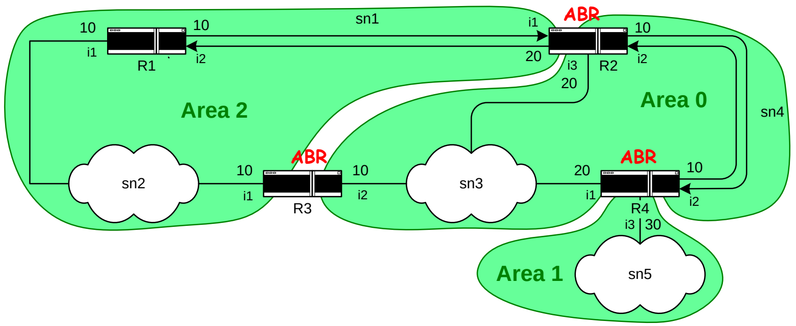
From R3	From R2
• sn3, cost=10	• sn3, cost=20

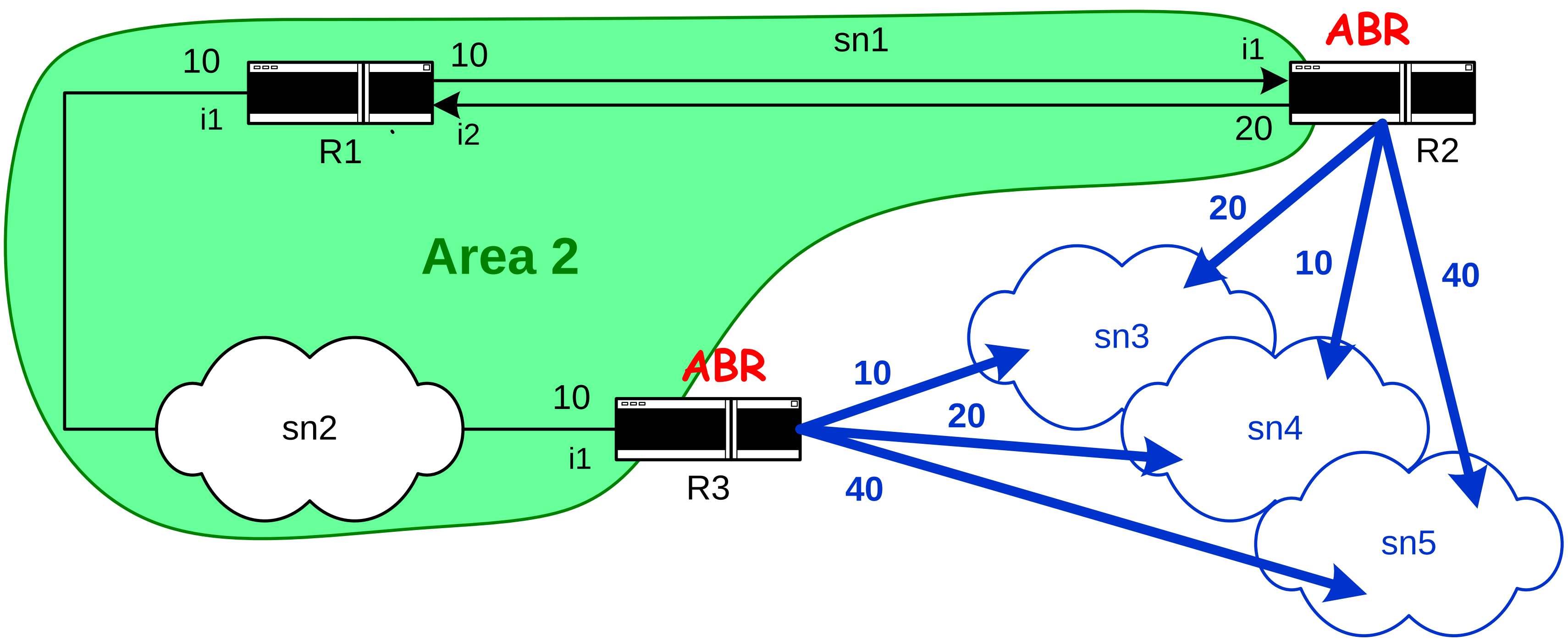
From R3	From R2
• sn4, cost=20	• sn4, cost=10

From R3	From R2
• sn5, cost=40	• sn5, cost=40

Summary-LSAs
(describes subnets of other areas and the cost from ABR to them)

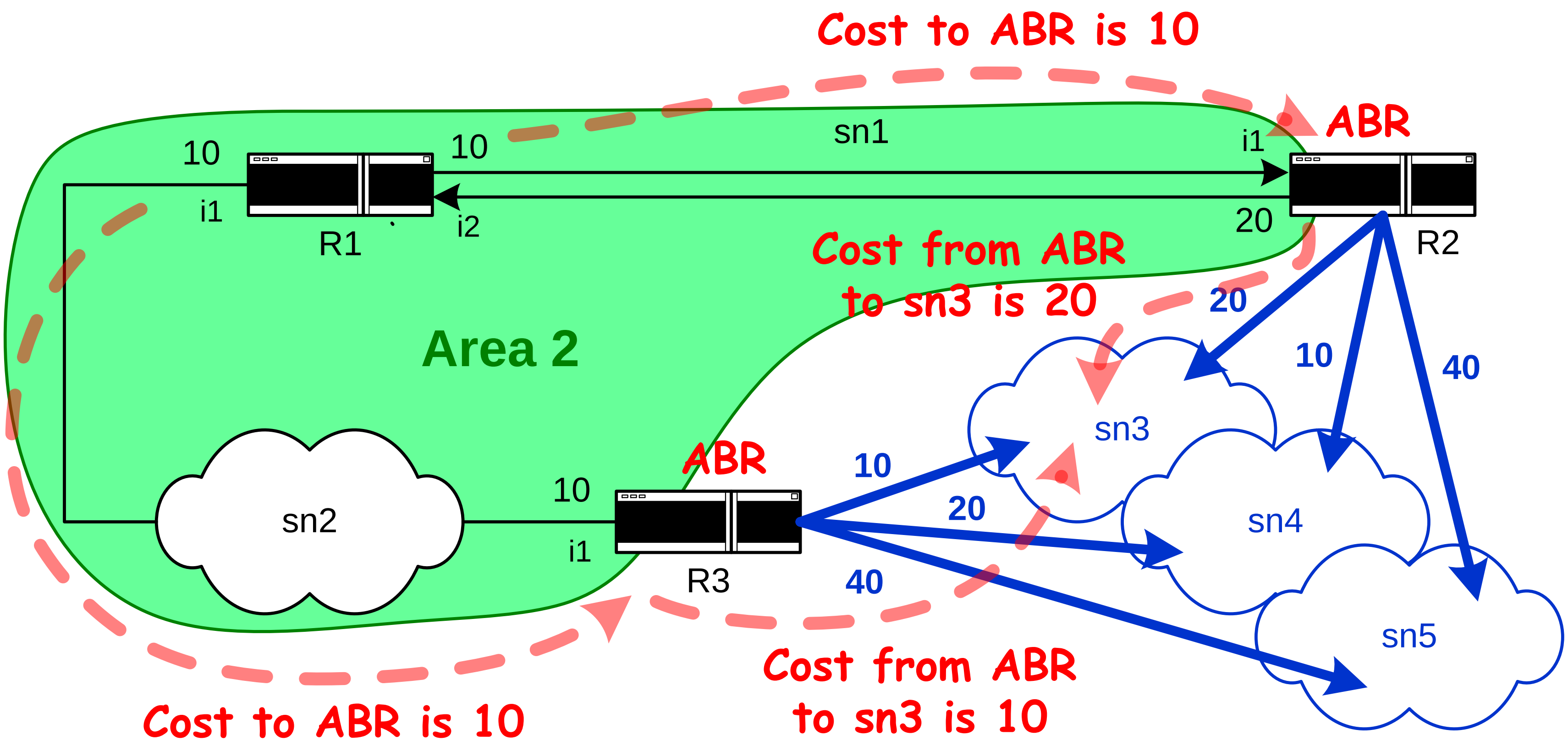
LSDB in hierarchical OSPF





How R1 views the OSPF network?

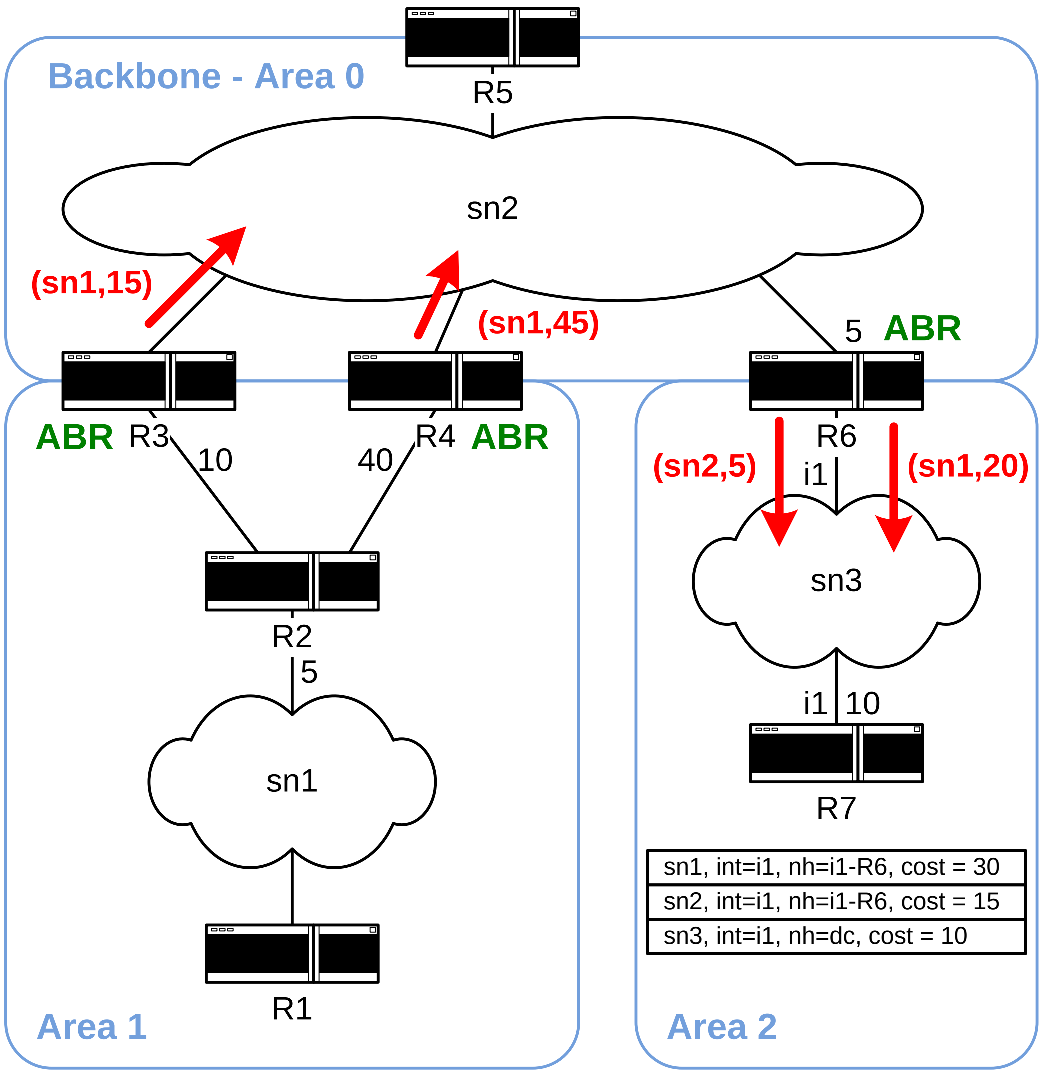
LSDB in hierarchical OSPF



How does R1 determines shortest path to sn3?

- Using its view of Area 2 (obtained via router-LSAs and network-LSAs) determines cost to each ABR
- Using the costs broadcasted by ABRs (obtained via summary-LSAs) determine ABR that provides the least-cost route

LSDB in hierarchical OSPF



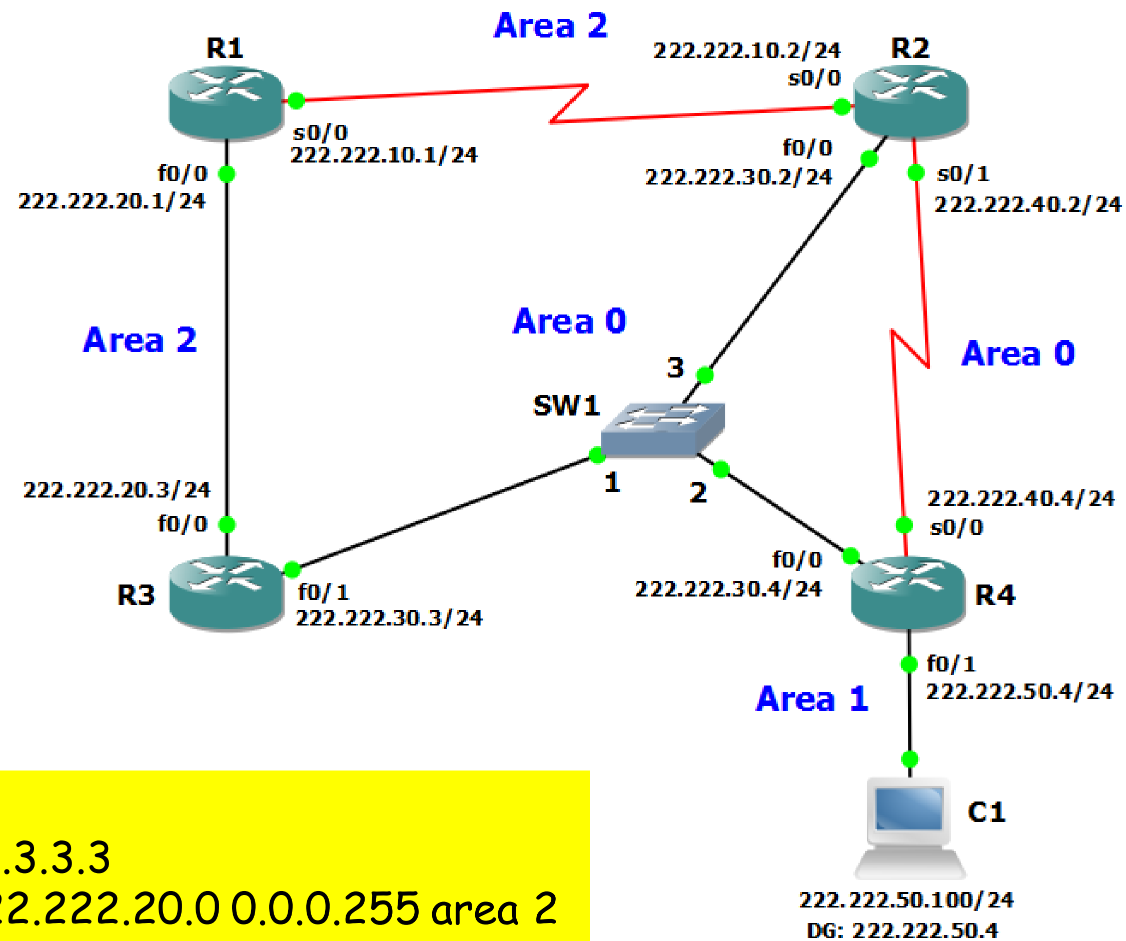
Summary-LSAs that notify R7 about routes to subnets in other areas, sn1 and sn2.

Summary-LSA format

- LS Type = 3
- Advertising Router
  - Area Border Router responsible for the LSA
- Link State ID
  - IP address of destination subnet
- Network Mask
  - Network mask of destination subnet
- Metric
  - Cost of route from Advertising Router to destination subnet

<table>
<tr><th>0</th><th>8</th><th>16</th><th>24 … 32</th></tr>
<tr><td colspan="2">LS age</td><td>Options</td><td>LS Type</td></tr>
<tr><td colspan="4">Link State ID</td></tr>
<tr><td colspan="4">Advertising Router</td></tr>
<tr><td colspan="4">LS Sequence Number</td></tr>
<tr><td colspan="2">LS Checksum</td><td colspan="2">Length</td></tr>
<tr><td colspan="4">Network Mask</td></tr>
<tr><td>0</td><td colspan="3">Metric</td></tr>
<tr><td>TOS</td><td colspan="3">TOS</td></tr>
</table>

Case study – Configuration of hierarchical OSPF




```
R3(config)#router ospf 1
R3(config-router)# router-id 3.3.3.3
R3(config-router)# network 222.222.20.0 0.0.0.255 area 2
R3(config-router)# network 222.222.30.0 0.0.0.255 area 0
```

Configuration of hierarchical OSPF at R3

Case study - LSDB with areas

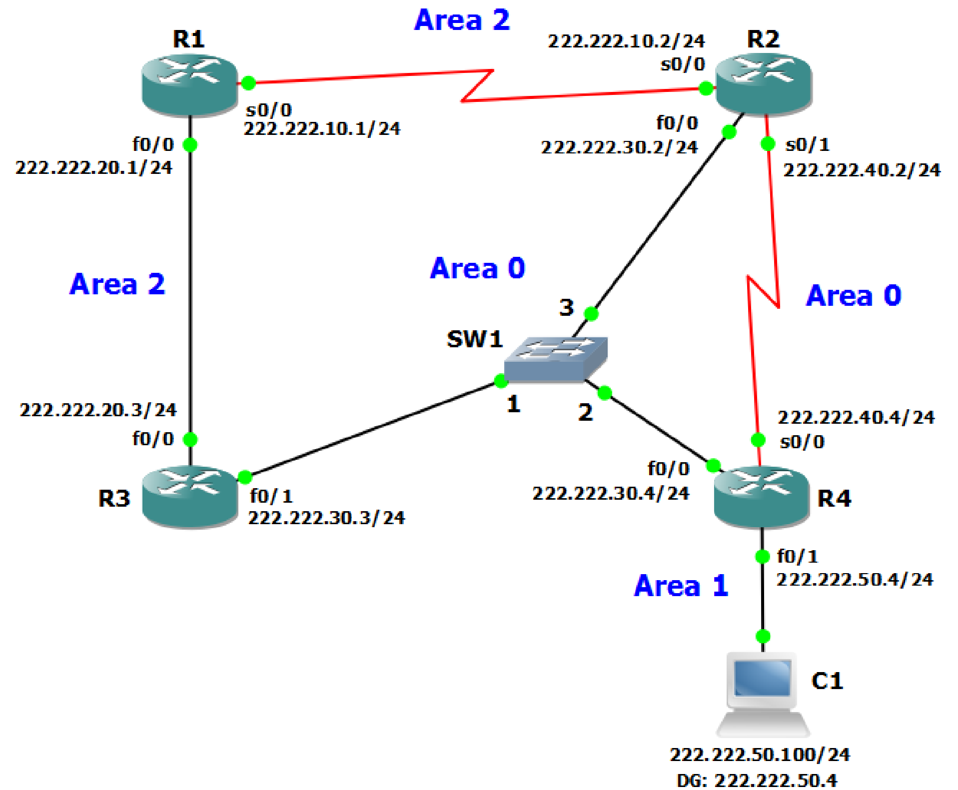
R1#show ip ospf database

LS ID	ADV Router	Age	Seq#
1.1.1.1	1.1.1.1	669	0x80000004
2.2.2.2	2.2.2.2	670	0x80000001
3.3.3.3	3.3.3.3	730	0x80000001

Router Link States (Area 2)

LS ID	ADV Router	Age	Seq#
222.222.30.0	2.2.2.2	671	0x80000001
222.222.30.0	3.3.3.3	730	0x80000001
222.222.40.0	2.2.2.2	671	0x80000001
222.222.40.0	3.3.3.3	730	0x80000001
222.222.50.0	2.2.2.2	544	0x80000003
222.222.50.0	3.3.3.3	544	0x80000003

Summary Net Link States (Area 2)

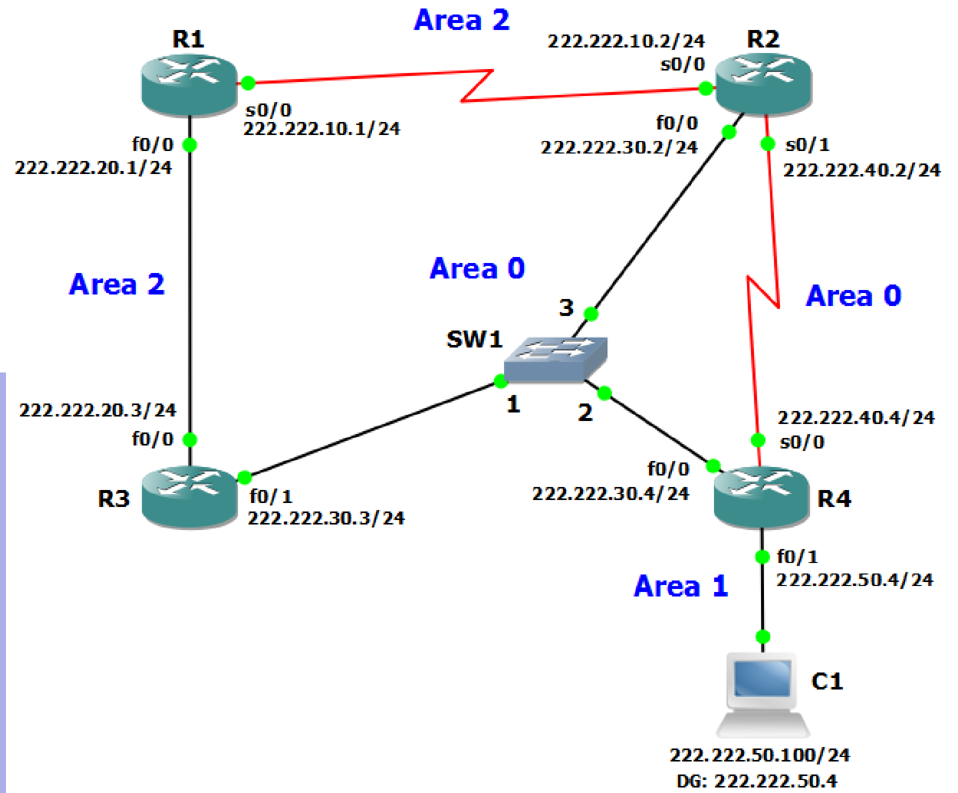


LS ID	ADV Router	Age	Seq#
222.222.20.1	1.1.1.1	729	0x80000001

Net Link States (Area 2)

LSDB of R1
(Internal router - only knows routers and subnets of Area 2)

Case study - LSDB with areas



Routing Bit Set on this LSA
LS age: 628
Options: (No TOS-capability, DC, Upward)
LS Type: Summary Links(Network)
Link State ID: 222.222.40.0 (summary Network Number)
Advertising Router: 2.2.2.2
LS Seq Number: 80000002
Checksum: 0x50BD
Length: 28
Network Mask: /24
TOS: 0 Metric: 64

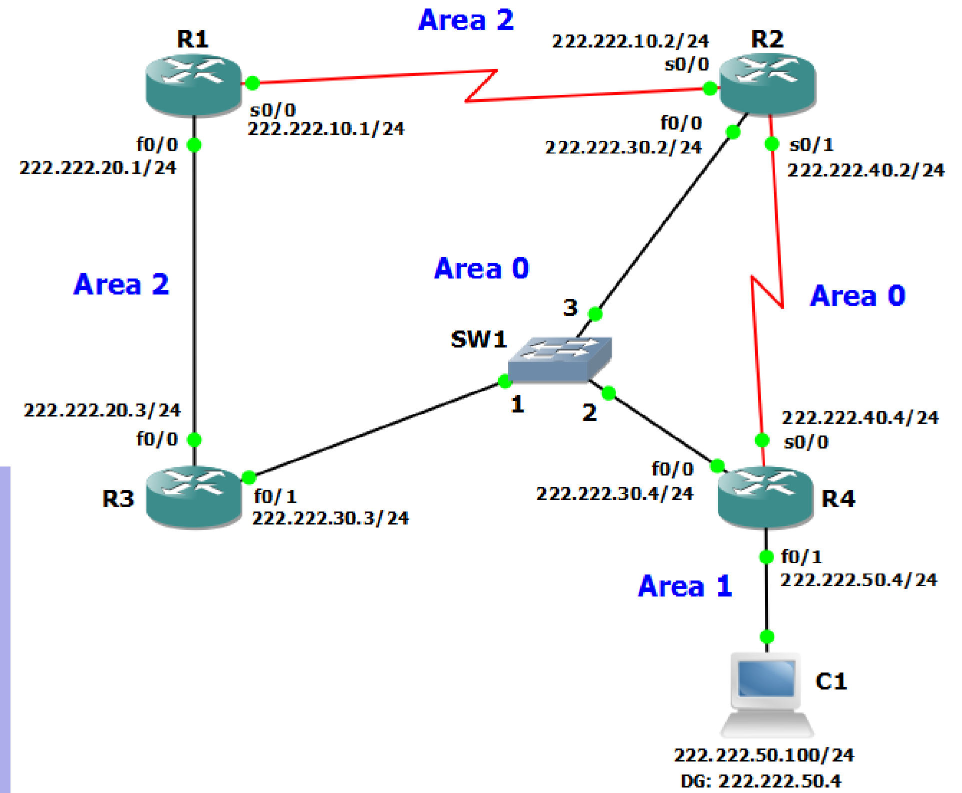
Routing Bit Set on this LSA
LS age: 592
Options: (No TOS-capability, DC, Upward)
LS Type: Summary Links(Network)
Link State ID: 222.222.40.0 (summary Network Number)
Advertising Router: 3.3.3.3
LS Seq Number: 80000002
Checksum: 0x9669
Length: 28
Network Mask: /24
TOS: 0 Metric: 74

Summary-LSA (Area 2)
Relative to subnet 222.222.40.0/24

Case study - LSDB with areas

Routing Bit Set on this LSA
LS age: 1191
Options: (No TOS-capability, DC)
LS Type: Router Links
Link State ID: 3.3.3.3
Advertising Router: 3.3.3.3
LS Seq Number: 80000012
Checksum: 0xA1B4
Length: 36
Area Border Router
Number of Links: 1

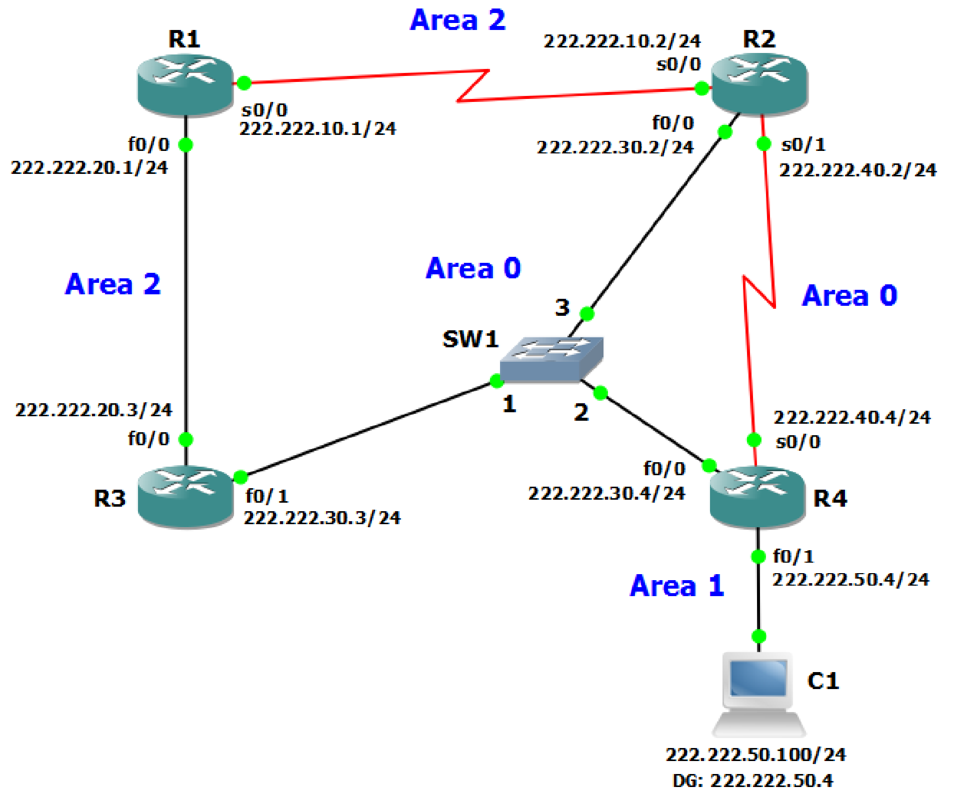
Link connected to: a Transit Network
(Link ID) Designated Router address: 222.222.20.3
(Link Data) Router Interface address: 222.222.20.3
Number of TOS metrics: 0
TOS 0 Metrics: 10



Router-LSA of R3 (Area 2)
(Only interface 222.222.20.3 is known)

Case study - LSDB with areas

R4#show ip ospf database



LS ID	ADV Router	Age	Seq#
2.2.2.2	2.2.2.2	48	0x80000003
3.3.3.3	3.3.3.3	48	0x80000003
4.4.4.4	4.4.4.4	47	0x80000003

Router Link States (Area 0)

LS ID	ADV Router	Age	Seq#
222.222.30.4	4.4.4.4	47	0x80000001

Net Link States (Area 0)

LS ID	ADV Router	Age	Seq#
222.222.10.0	2.2.2.2	77	0x80000001
222.222.10.0	3.3.3.3	47	0x80000001
222.222.20.0	2.2.2.2	77	0x80000001
222.222.20.0	3.3.3.3	78	0x80000002
222.222.50.0	4.4.4.4	78	0x80000002

Summary Net Link States (Area 0)

LSDB of R4
(Since it is an ABR, LSDB has two parts, one for Area 0 and another for Area 1)

Case study - LSDB with areas

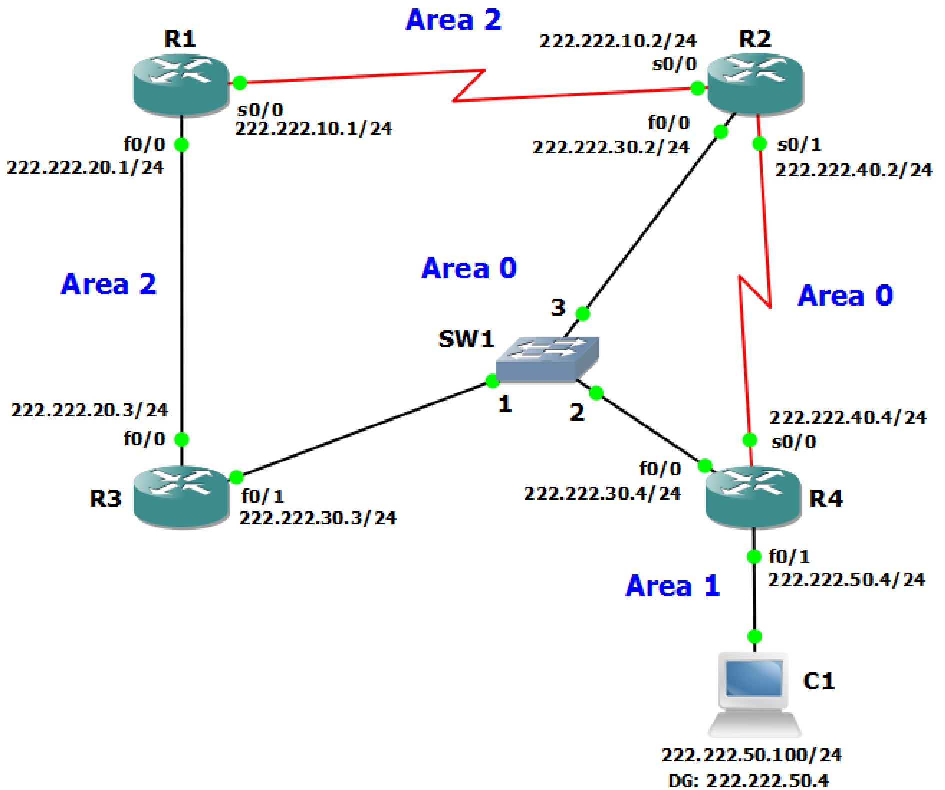
R4#show ip ospf database

LS ID	ADV Router	Age	Seq#
4.4.4.4	4.4.4.4	83	0x80000002

Router Link States (Area 1)

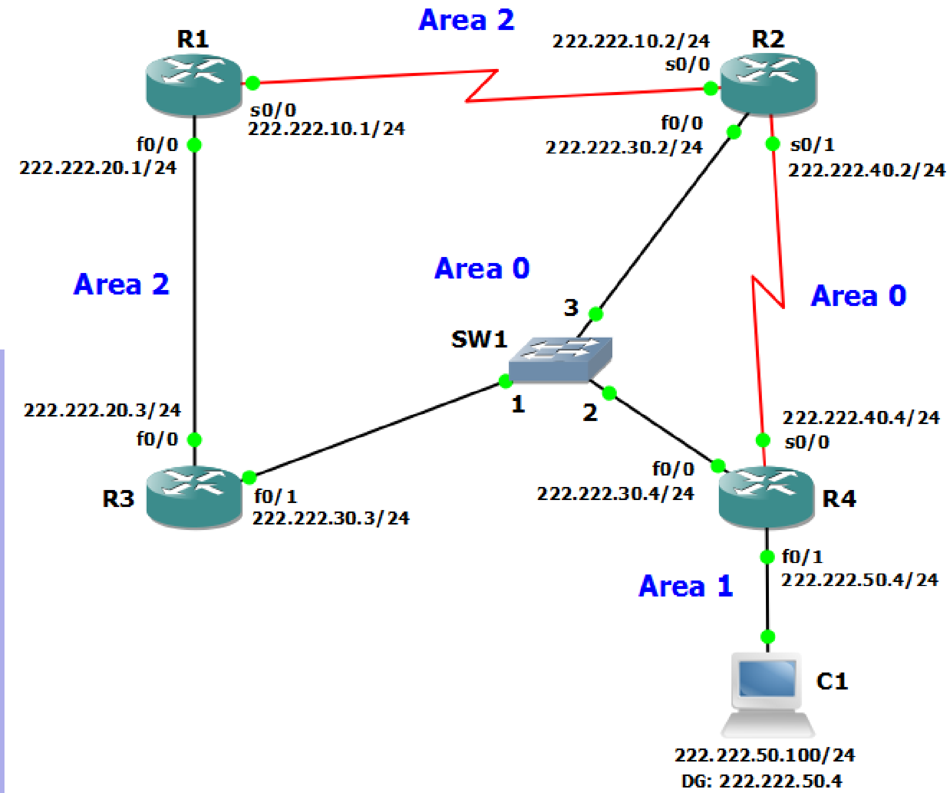
LS ID	ADV Router	Age	Seq#
222.222.10.0	4.4.4.4	53	0x80000002
222.222.20.0	4.4.4.4	53	0x80000002
222.222.30.0	4.4.4.4	84	0x80000002
222.222.40.0	4.4.4.4	84	0x80000001

Summary Net Link States (Area 1)



LSDB of R4
(Since it is an ABR, LSDB has two parts, one for Area 0 and another for Area 1)

Case study - LSDB with areas



Routing Bit Set on this LSA
LS age: 13
Options: (No TOS-capability, DC, Upward)
LS Type: Summary Links(Network)
Link State ID: 222.222.50.0 (summary Network Number)
Advertising Router: 2.2.2.2
LS Seq Number: 80000002
Checksum: 0x2808
Length: 28
Network Mask: /24
TOS: 0 Metric: 20

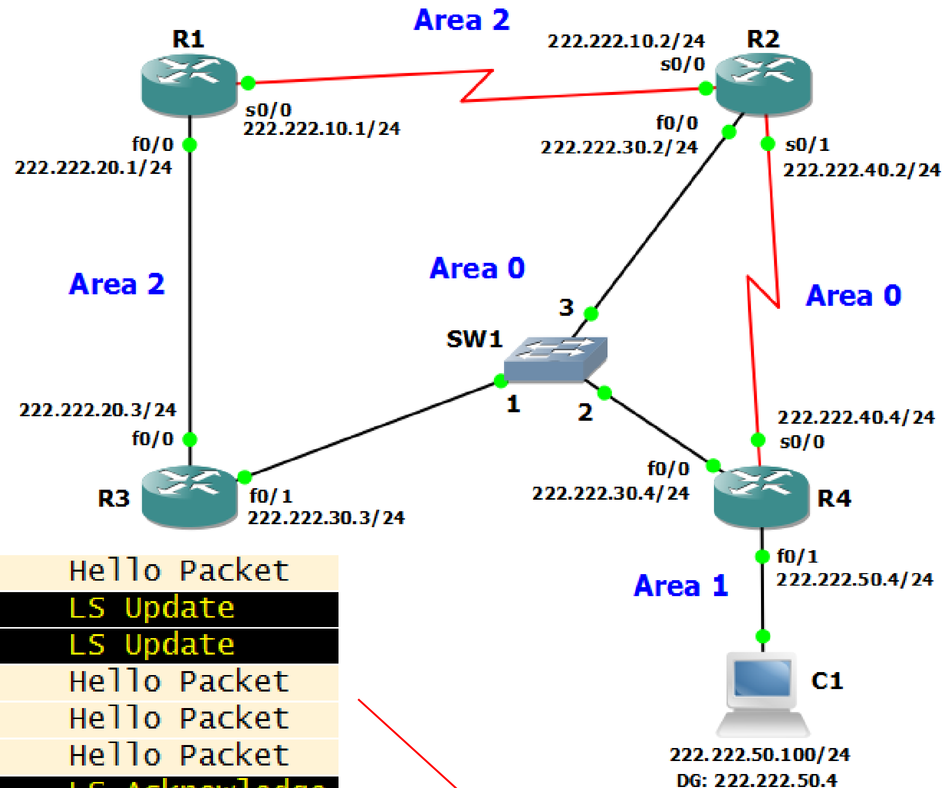
Routing Bit Set on this LSA
LS age: 15
Options: (No TOS-capability, DC, Upward)
LS Type: Summary Links(Network)
Link State ID: 222.222.50.0 (summary Network Number)
Advertising Router: 3.3.3.3
LS Seq Number: 80000001
Checksum: 0xC21
Length: 28
Network Mask: /24
TOS: 0 Metric: 20

Summary-LSAs relative to subnet 222.222.50.0/24 injected in Area 2 by R2 and R3

Case study - Flooding with areas

R4(config)#int f0/1
R4(config-if)#ip ospf cost 30

EXPERIMENT: Change cost of f0/1-R4 to 30



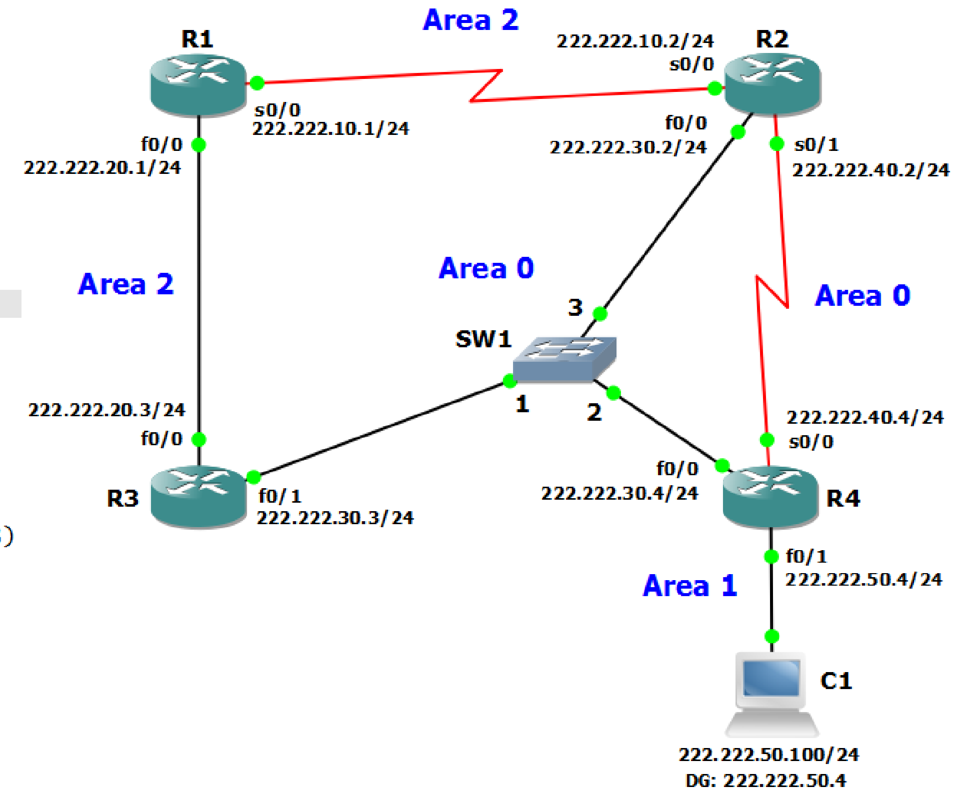
23	41.341000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
25	48.862000	222.222.30.4	224.0.0.5	OSPF	90	LS Update
26	48.891000	222.222.30.2	224.0.0.6	OSPF	90	LS Update
27	50.000000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet
28	50.798000	222.222.30.2	224.0.0.5	OSPF	98	Hello Packet
29	51.350000	222.222.30.3	224.0.0.5	OSPF	98	Hello Packet
30	51.378000	222.222.30.3	224.0.0.5	OSPF	78	LS Acknowledge
32	59.989000	222.222.30.4	224.0.0.5	OSPF	98	Hello Packet

Packets @ 222.222.30.0/24; LS Updates carry same summary-LSA updating cost from R4 to 222.222.50.0/24; DR is R4 and BDR is R3

22	43.404000	222.222.20.3	224.0.0.5	OSPF	94	Hello Packet
25	51.059000	222.222.20.3	224.0.0.5	OSPF	90	LS Update
26	51.070000	222.222.20.1	224.0.0.5	OSPF	90	LS Update
27	51.984000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet
28	53.387000	222.222.20.3	224.0.0.5	OSPF	94	Hello Packet
29	53.545000	222.222.20.1	224.0.0.5	OSPF	78	LS Acknowledge
30	53.595000	222.222.20.3	224.0.0.5	OSPF	78	LS Acknowledge
33	62.015000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet

Packets @ 222.222.20.0/24; LS Updates carry summary-LSAs, one broadcasted by R3 and the other by R2 (the ABRs of Area 2), updating the cost from each ABR to subnet 222.222.50.0/24

Case study - Flooding with areas



Open Shortest First
⊞ OSPF Header
⊟ LS Update Packet
Number of LSAs: 1
⊟ LS Type: Summary-LSA (IP network)
LS Age: 1 seconds
Do Not Age: False
⊞ Options: 0x22 (DC, E)
Link-State Advertisement Type: Summary-LSA (IP network) (3)
<Summary LSA (IP Network): True>
Link State ID: 222.222.50.0
Advertising Router: 4.4.4.4 (4.4.4.4)
LS Sequence Number: 0x80000007
LS Checksum: 0x46d2
Length: 28
Netmask: 255.255.255.0
Metric: 30

Summary-LSA injected by R4 in Area 0

Open Shortest Path First
⊞ OSPF Header
⊟ LS Update Packet
Number of LSAs: 1
⊟ LS Type: Summary-LSA (IP network)
LS Age: 1 seconds
Do Not Age: False
⊞ Options: 0x22 (DC, E)
Link-State Advertisement Type: Summary-LSA (IP network
<Summary LSA (IP Network): True>
Link State ID: 222.222.50.0
Advertising Router: 3.3.3.3 (3.3.3.3)
LS Sequence Number: 0x80000006
LS Checksum: 0xca49
Length: 28
Netmask: 255.255.255.0
Metric: 40

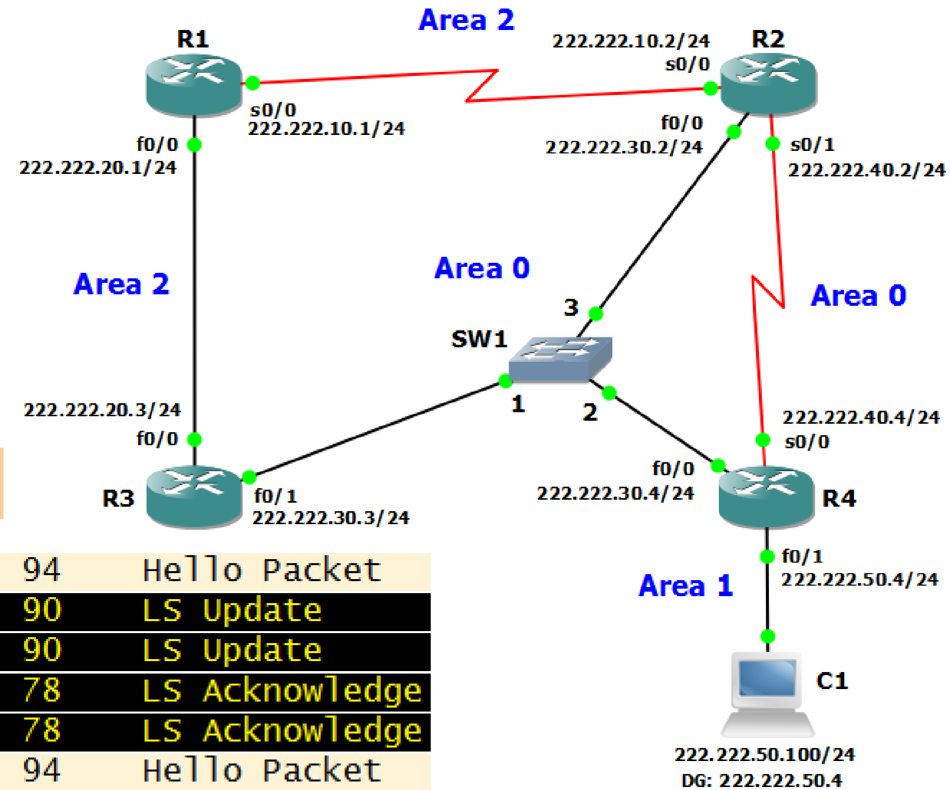
Summary-LSA injected by R3 in Area 2

Open Shortest Path First
⊞ OSPF Header
⊟ LS Update Packet
Number of LSAs: 1
⊟ LS Type: Summary-LSA (IP network)
LS Age: 2 seconds
Do Not Age: False
⊞ Options: 0x22 (DC, E)
Link-State Advertisement Type: Summary-LSA (IP network) (3)
<Summary LSA (IP Network): True>
Link State ID: 222.222.50.0
Advertising Router: 2.2.2.2 (2.2.2.2)
LS Sequence Number: 0x80000007
LS Checksum: 0xe630
Length: 28
Netmask: 255.255.255.0
Metric: 40

Summary-LSA injected by R2 in Area 2

Case study - Flooding with areas

R4(config)#int f0/1
R4(config-if)#shutdown



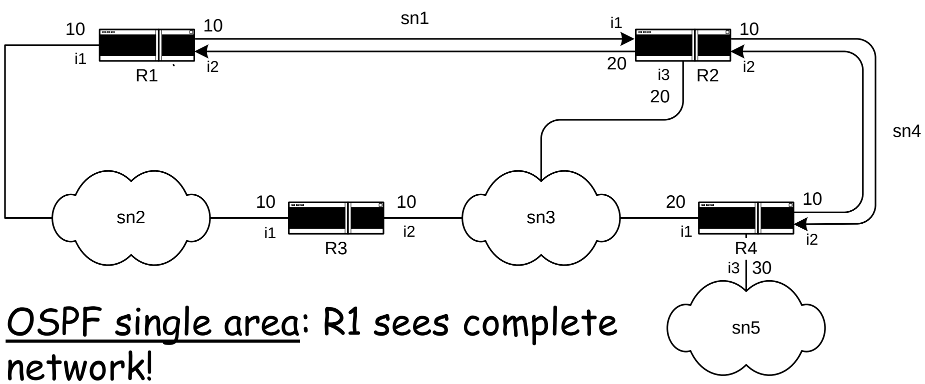
EXPERIMENT: Deactivate f0/1-R4

21	46.073000	222.222.20.3	224.0.0.5	OSPF	94	Hello Packet
22	47.538000	222.222.20.1	224.0.0.5	OSPF	90	LS Update
23	47.558000	222.222.20.3	224.0.0.5	OSPF	90	LS Update
26	50.036000	222.222.20.3	224.0.0.5	OSPF	78	LS Acknowledge
27	50.066000	222.222.20.1	224.0.0.5	OSPF	78	LS Acknowledge
29	54.620000	222.222.20.1	224.0.0.5	OSPF	94	Hello Packet

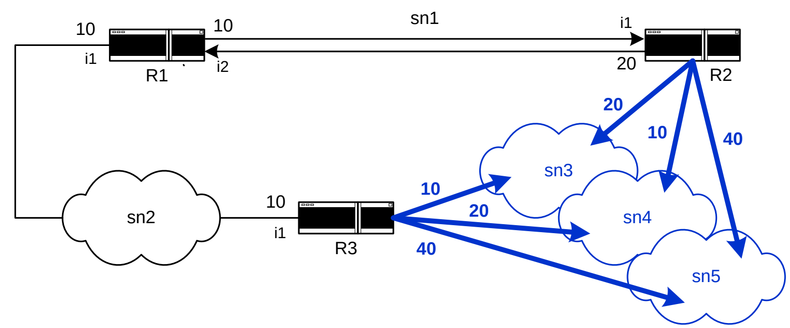
```
Open Shortest Path First
⊞ OSPF Header
⊟ LS Update Packet
    Number of LSAs: 1
  ⊟ LS Type: Summary-LSA (IP network)
      LS Age: 3600 seconds
      Do Not Age: False
    ⊞ Options: 0x22 (DC, E)
      Link-State Advertisement Type: Summary-LSA (IP network) (3)
      <Summary LSA (IP Network): True>
      Link State ID: 222.222.50.0
      Advertising Router: 2.2.2.2 (2.2.2.2)
      LS Sequence Number: 0x80000009
      LS Checksum: 0x51eb
      Length: 28
      Netmask: 255.255.255.0
      Metric: 16777215
```

R3 and R2 inject in Area 0 summary-LSAs to delete instance relative to 222.222.50.0/24 (no longer reachable)

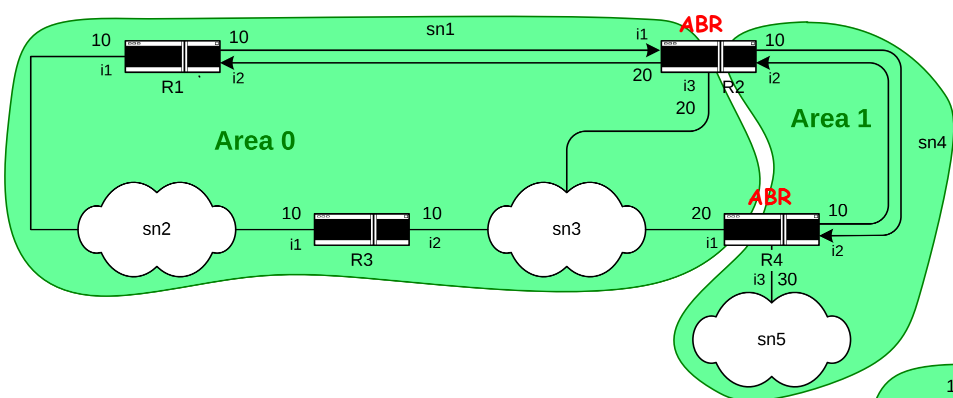
Routing protocols: different views of the network topology



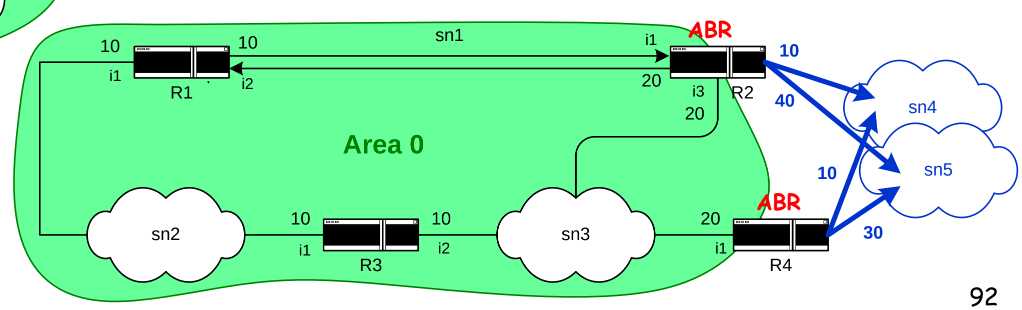
OSPF single area: R1 sees complete network!



RIP (distance vector): R1 only sees neighbors (and all subnets)



Hierarchical OSPF: R1 sees complete area (and all subnets)



Bibliography

- John Moy, “OSPF Anatomy of an Internet Routing Protocol”, Addison Wesley, 1998 – chapters 4, 5 and 6
- John Moy, “OSPF Version 2”, RFC 2328, April 1998