Wireless – there is no cat!

"You see, wire telegraph is a kind of a very, very long cat. You pull his tail in New York and his head is meowing in Los Angeles. And radio operates exactly the same way…
The only difference is that there is no cat."

Albert Einstein,
when asked to describe radio.

Yahel Ben-David
Yahel @ eecs.berkeley.edu

EE 122: Intro to Communication Networks

Materials with thanks to **Scott Shenker,** Jennifer Rexford, Ion Stoica, Vern Paxson and other colleagues at Princeton and UC Berkeley


Bluetooth
WiMAX
CDMA
GSM
WiFi
LTE
802.11n
802.11g
W-CDMA
HSDPA
Zigbee
EV-DO
802.15.4
Wibree
EDGE
HSPA
RTT
UMTS-TDD
802.11a
Wireless-USB
Wi-Fi
802.11.1
CDMA2000
802.11b
UMTS
GPRS
WCDMA
OFDM
iBurst

Metrics for evaluation / comparison of wireless technologies

- **Bitrate or Bandwidth**
- **Range - PAN, LAN, MAN, WAN**
- **Stationary / Mobile**
- **Two-way / One-way**
- **Digital / Analog**
- **Multi-Access / Point-to-Point**
- **Applications and industries**
- **Operating environment**

- **Frequency / Wavelength**

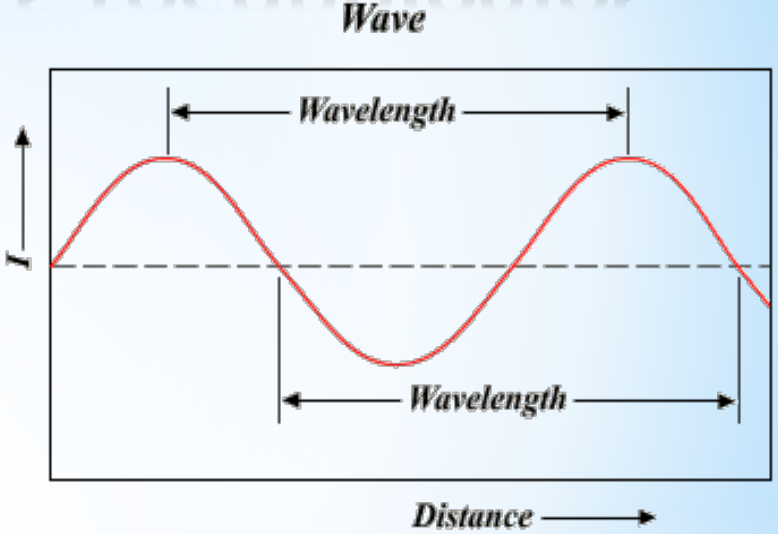
Metrics for evaluation / comparison of wireless technologies

- **Frequency/Wave-Length –**

C is the speed of light
f is frequency
λ (lambda) is wavelength

Wavelength $\lambda = \frac{C}{f}$

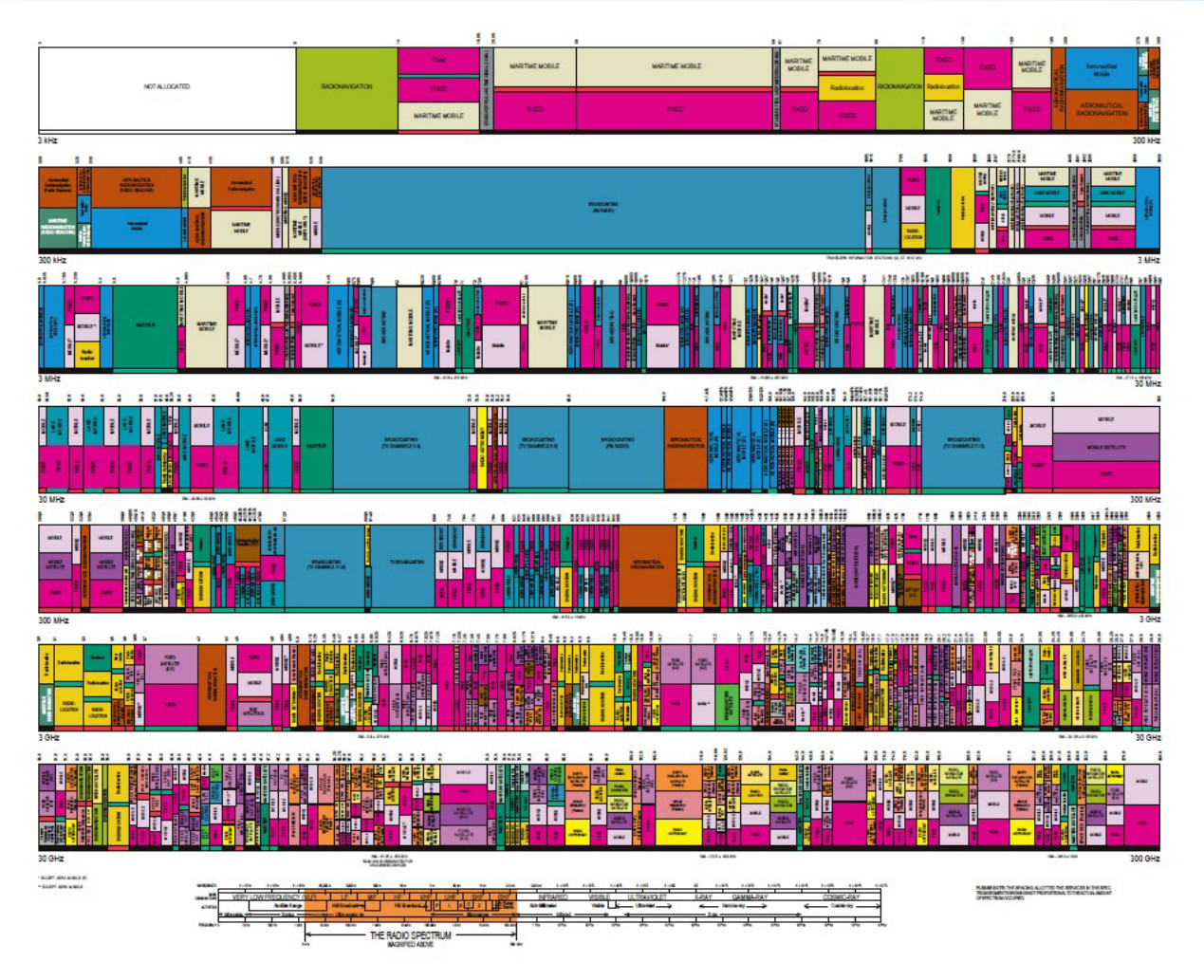
Frequency $f = \frac{C}{\lambda}$



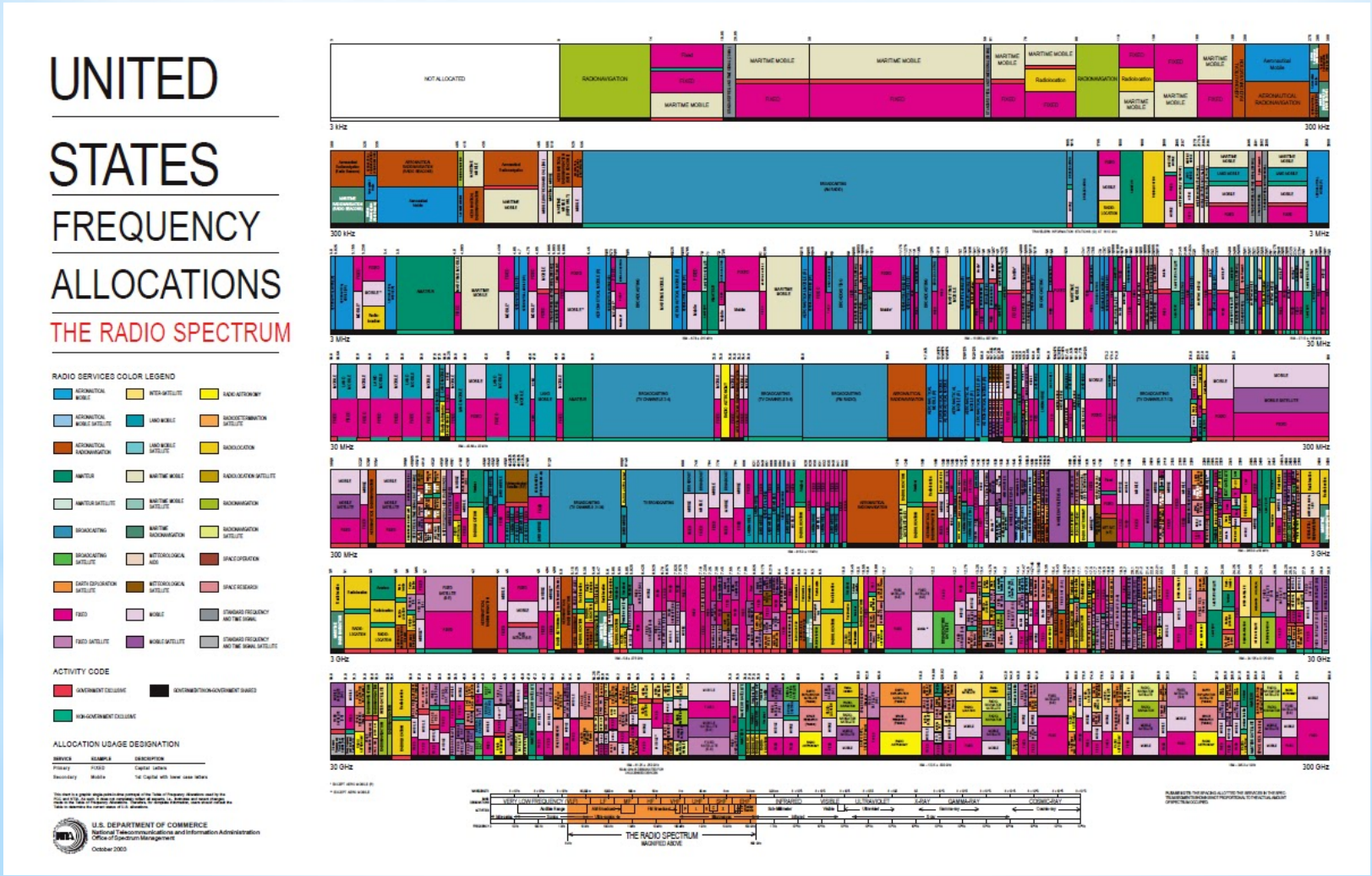
Affects most physical properties:
- **Distance (free-space loss)**
- **Penetration, Reflection, Absorption**
- **Line of Sight (Fresnel zone)**
- **Size of antenna**
- **Energy proportionality**

Policy & Law: Licensed / Deregulated

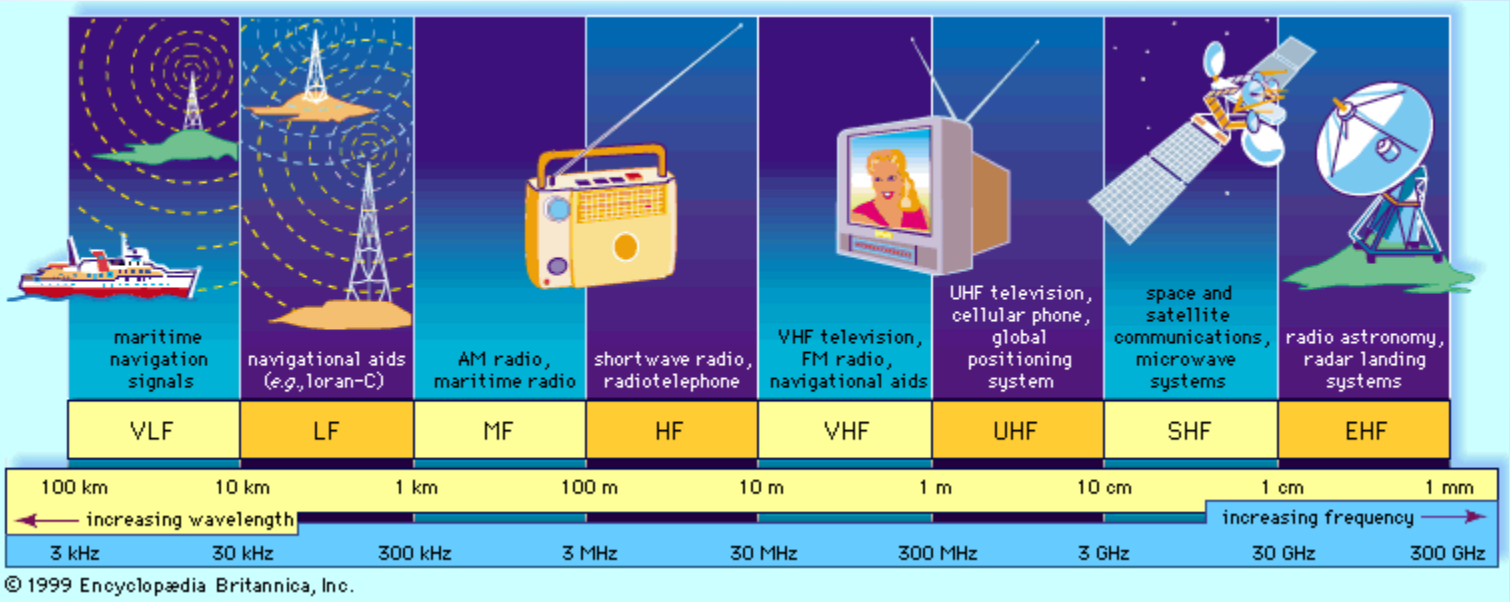
Modern art?

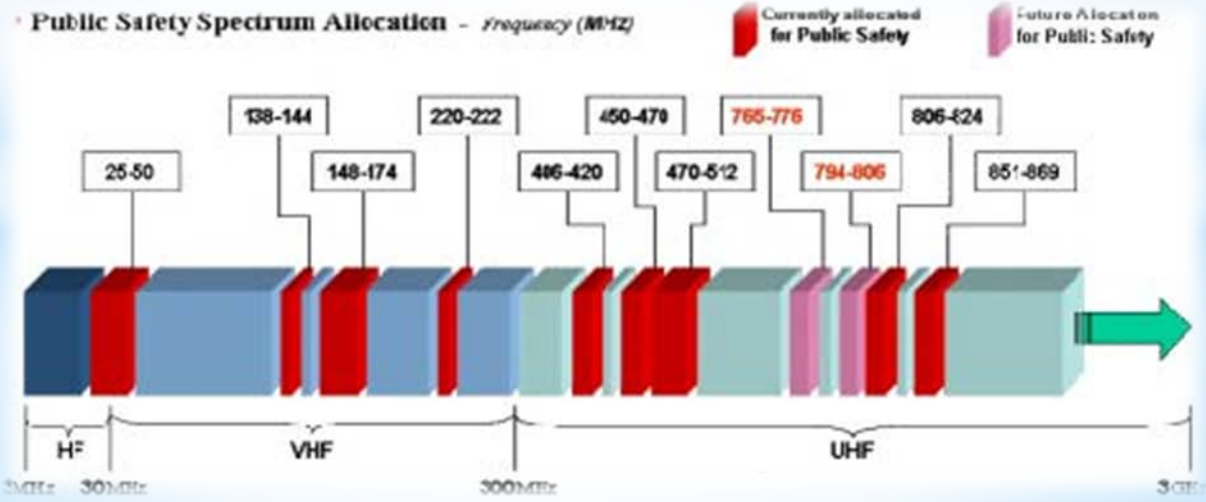

NOT ALLOCATED
RADIONAVIGATION
MARITIME MOBILE
FIXED
Radiolocation
AERONAUTICAL RADIONAVIGATION
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
THE RADIO SPECTRUM

Old mess!


UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003
THE RADIO SPECTRUM
MAGNIFIED ABOVE

The Wireless Spectrum





Common Wireless Standards

- Cellular (Typically 800/900/1800/1900Mhz):
  - 2G: GSM / GPRS /EDGE / CDMA / CDMA2000/
  - 3G: UMTS/HSDPA/EVDO
  - 4G: LTE, WiMax
- IEEE 802.11 (aka WiFi):
  - b: 2.4Ghz band, 11Mbps (*~4.5 Mbps operating rate*)
  - g: 2.4Ghz, 54-108Mbps (*~19 Mbps operating rate*)
  - a: 5.0Ghz band, 54-108Mbps (*~19 Mbps operating rate*)
  - n: 2.4/5Ghz, 150-600Mbps (4x4 mimo).
- IEEE 802.15 – lower power wireless:
  - 802.15.1: 2.4Ghz, 2.1 Mbps (Bluetooth)
  - 802.15.4: 2.4Ghz, 250 Kbps (Sensor Networks)

Wireless Link Characteristics

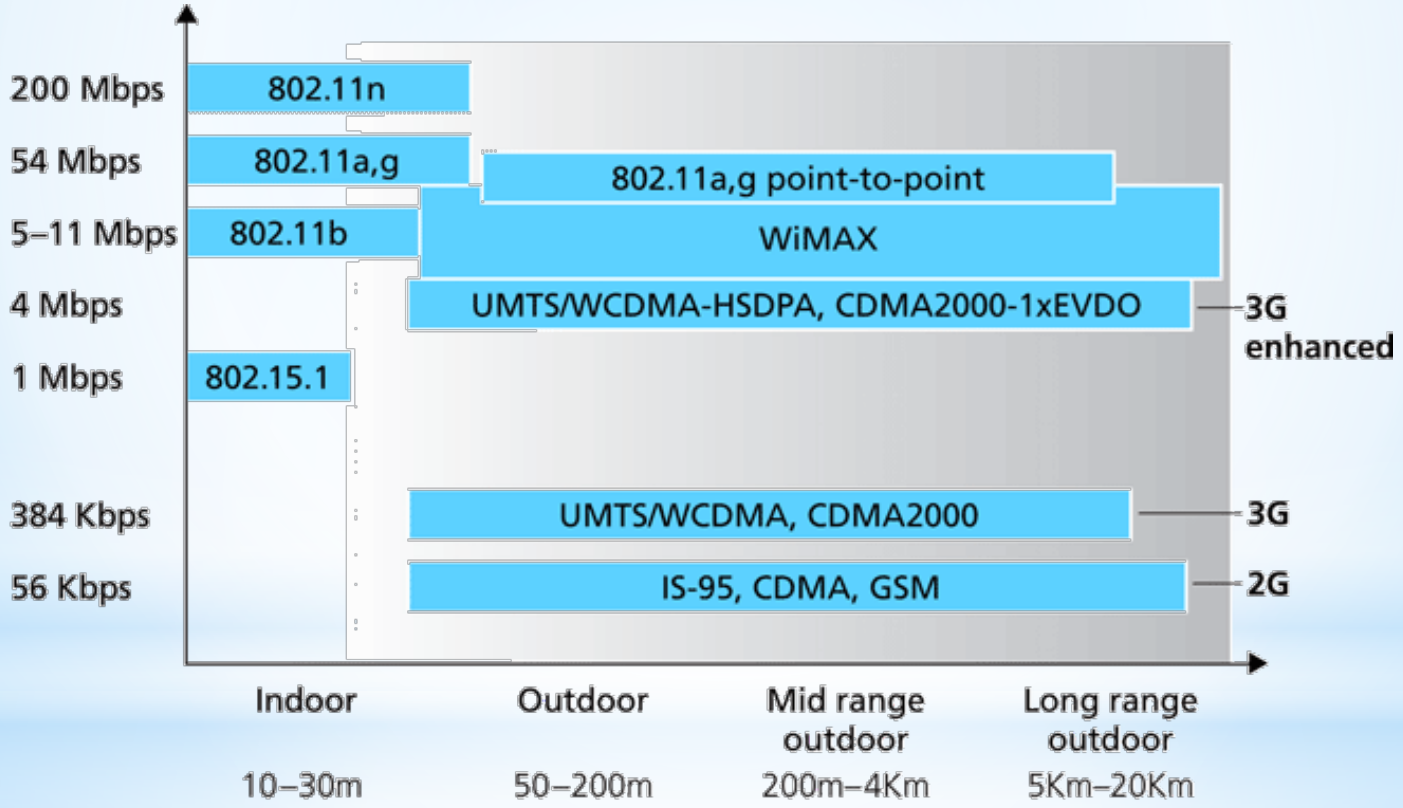


Figure 6.2 ♦ Link characteristics of selected wireless network standards

(Figure Courtesy of Kurose and Ross)

Antennas / Aerials

An electrical device which converts electric currents into radio waves, and vice versa.

Gain: 2-3dB

8-12dB

15-18dB

28-34dB

Q: What does “higher-gain antenna” mean?

A: Antennas are passive devices –
more gain means focused and more directional.
Directionality means more energy gets to where it needs to go and less interference everywhere.

Q: What are omni-directional antennas?

How many radios/antennas ?

- WiFi 802.11n - 2.4 & 5Ghz (MiMo?)
- 2G – GSM "Quad band" 800/900 & 1800/1900
- 3G – HSDPA+
- 4G – LTE
- Bluetooth
- NFC
- GPS Receiver
- FM-Radio receiver
  (antenna is the headphones cable)

What has changed?

What Makes Wireless Different?

- Broadcast medium…
  - Anybody in proximity can hear and interfere
- Cannot receive while transmitting…
  - Our own (or nearby) transmission is deafening our receiver

- Signals sent by sender don't always end up at receiver intact
  - Complicated physics involved, which we won't discuss
  - But what can go wrong?

Path Loss / Path Attenuation

- Free Space Path Loss:

$$\mathrm{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$$

d = distance

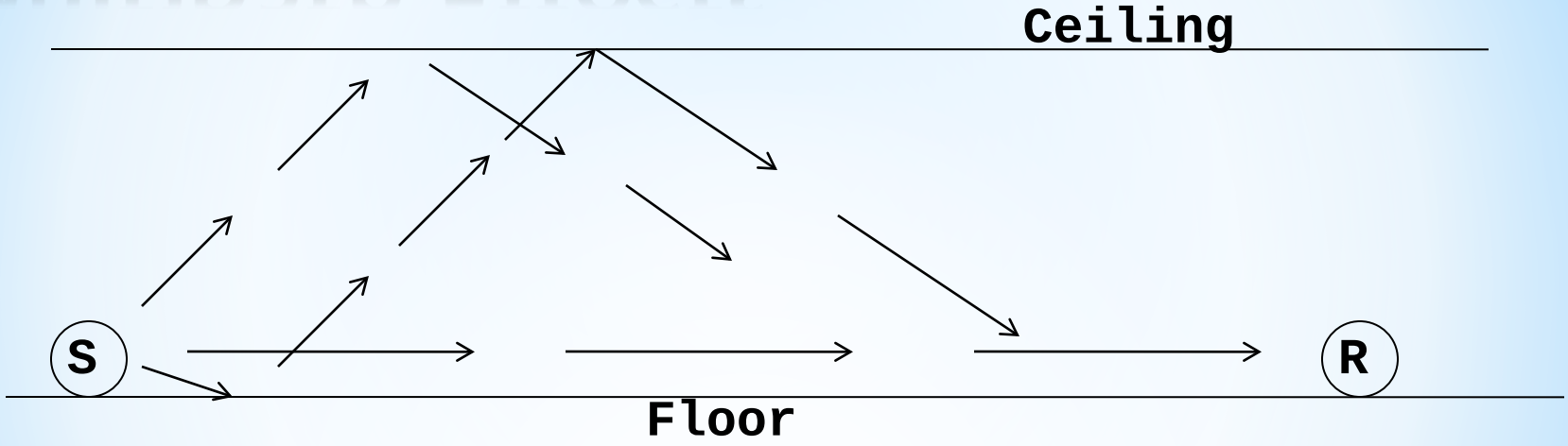
λ = wave length

f = frequency

c = speed of light

- Reflection, Diffraction, Absorption
- Terrain contours (Urban, Rural, Vegetation).
- Humidity

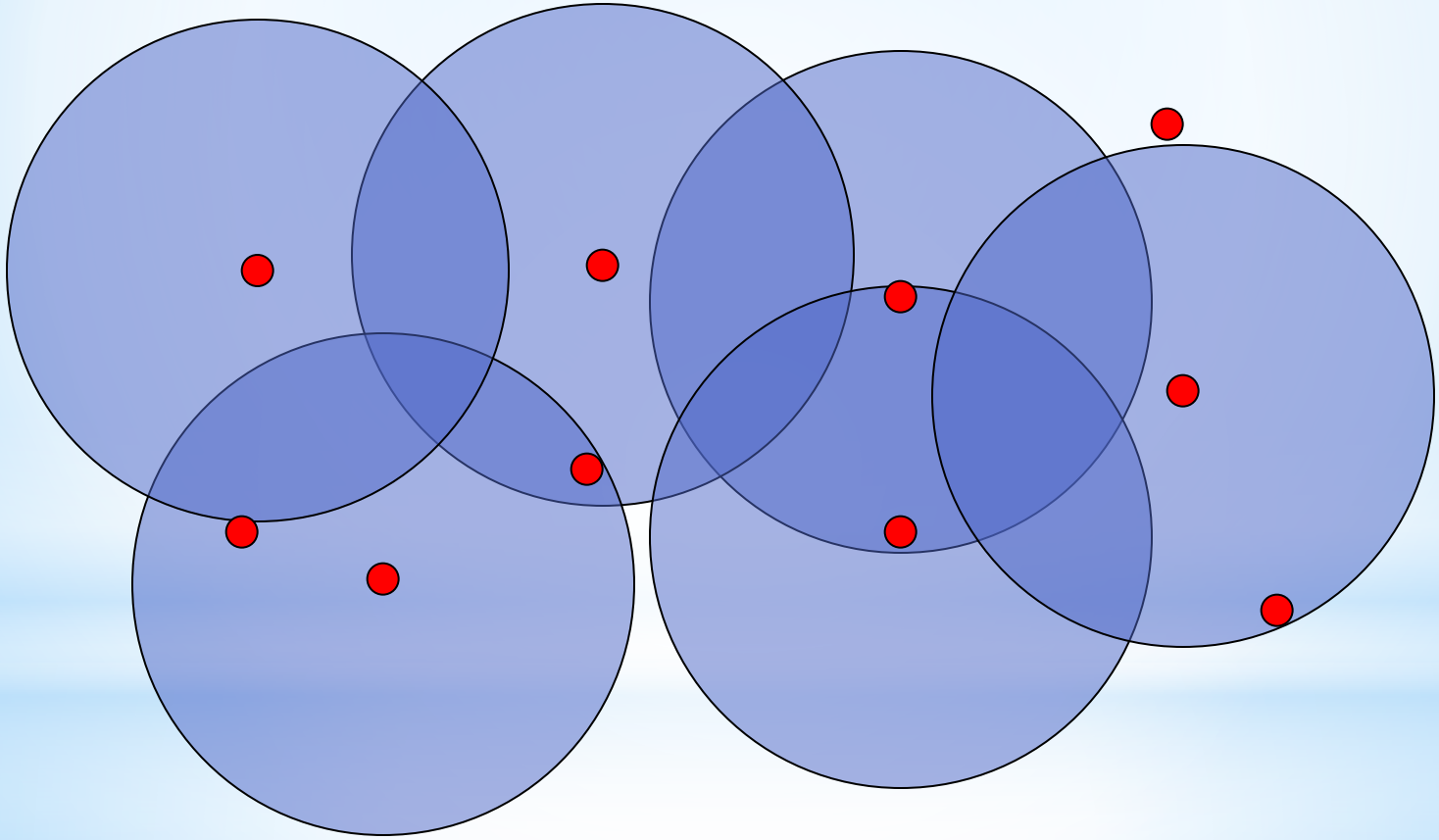
Multipath Effects



- Signals bounce off surface and interfere with one another
- Self-interference

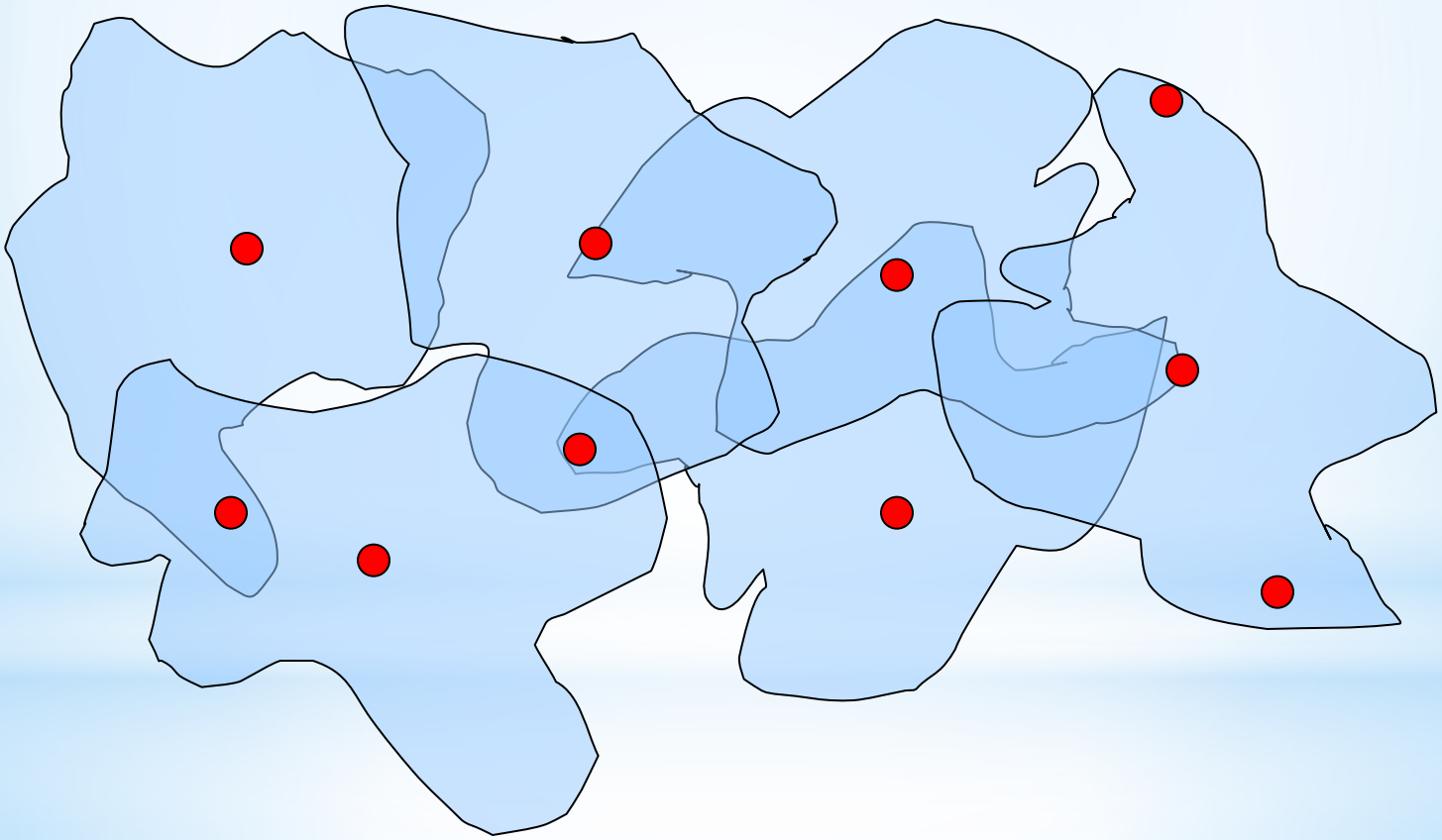
Ideal Radios

(courtesy of Gilman Tolle and Jonathan Hui, ArchRock)



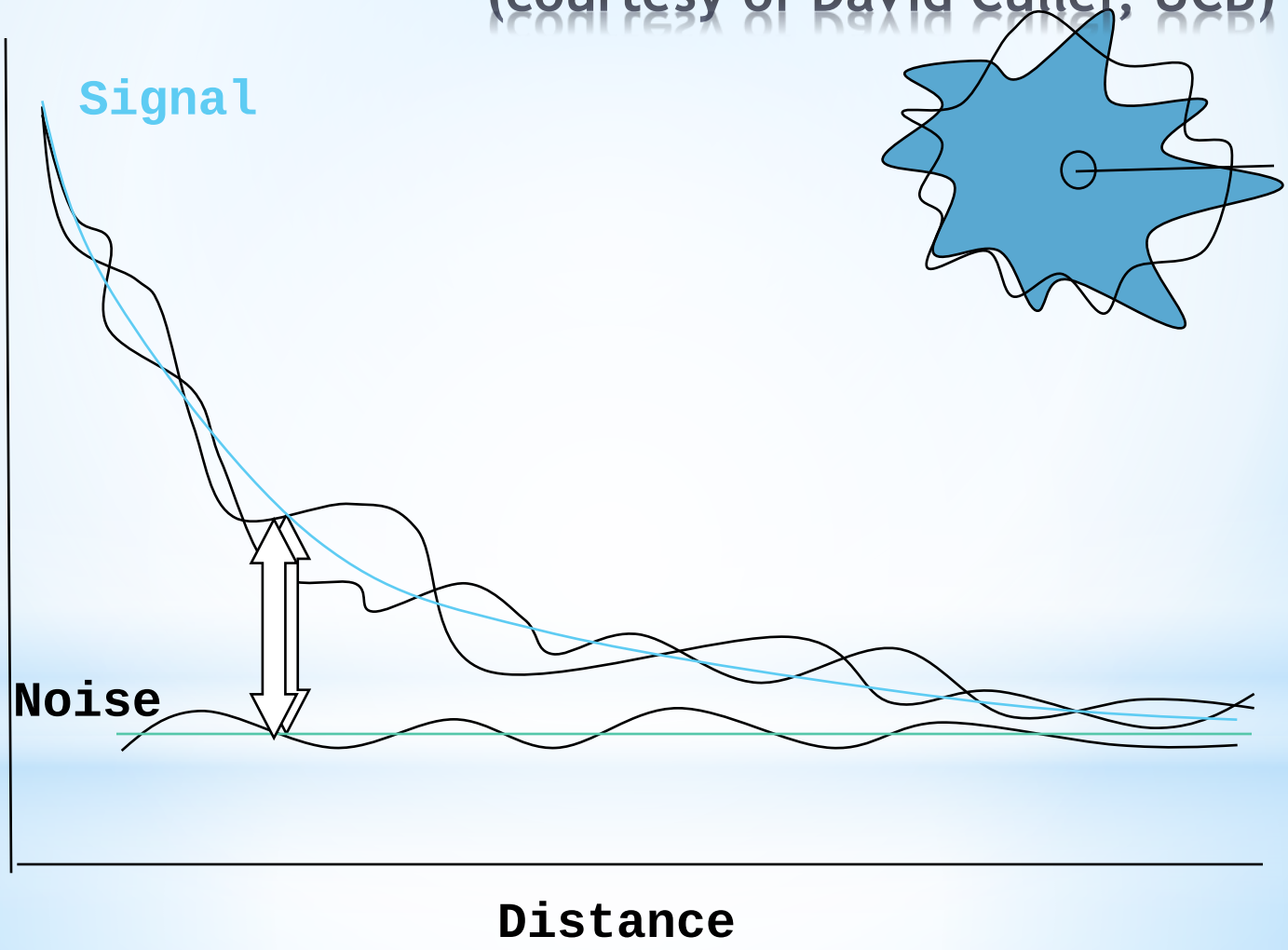
Real Radios

(courtesy of Gilman Tolle and Jonathan Hui, ArchRock)



*The Amoeboed "cell"

(courtesy of David Culler, UCB)



Interference from Other Sources

* External Interference
  - Microwave oven is turned on and blocks your signal
  - Would that affect the sender or the receiver?
* Internal Interference
  - Nodes (of the same network) within range of each other collide with one another's transmission

* We have to tolerate external interference and path loss, multipath, etc.
  but we can avoid internal interference?

Bitrate (aka data-rate)

- The higher the SNR (Signal to Noise Ratio) – the higher the (theoretical) bitrate.

- Modern radios use adaptive /dynamic bitrates.

Q: In face of loss,
should we decrease or increase the bitrate?

A: If caused by free-space loss or multi-path fading
-lower the bitrate.
If external interference - often higher bitrates
(shorter bursts) are probabilistically better.

Wireless Bit Errors

- The lower the SNR (Signal/Noise) the higher the Bit Error Rate (BER)
- We could make the signal stronger…
- Why is this not always a good idea?
  - Increased signal strength requires more power
  - Increases the interference range of the sender, so you interfere with more nodes around you
    - And then they increase their power…….
- How would TCP behave in face of losses?
- Local link-layer Error Correction schemes can correct some problems (should be TCP aware).

802.11

aka - WiFi …
What makes it special?

Deregulation > Innovation > Adoption > Lower cost = Ubiquitous technology

802.11 Architecture

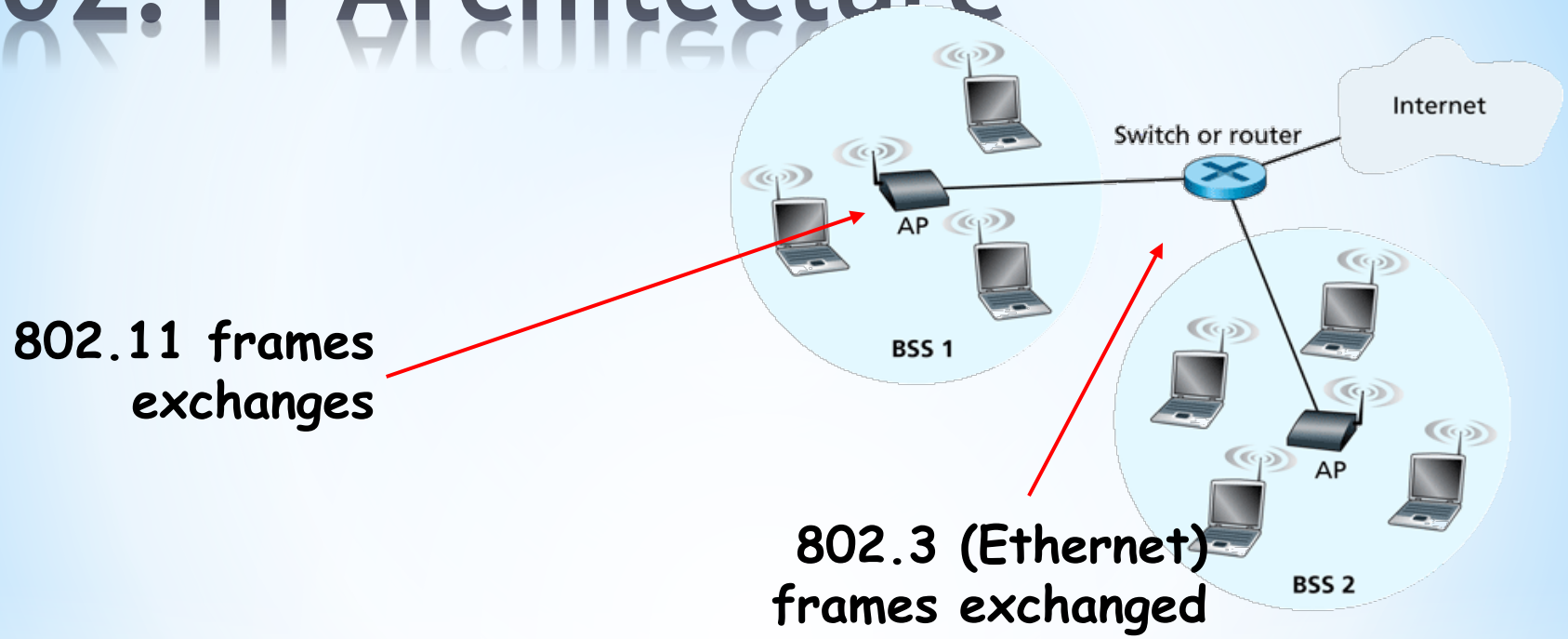


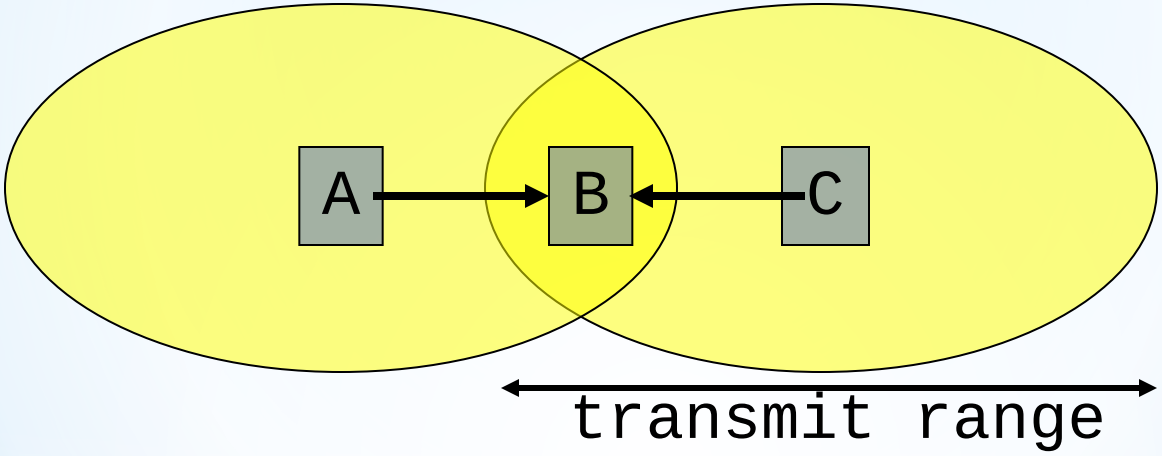
Figure 6.7 ♦ IEEE 802.11 LAN architecture

- Designed for limited area
- AP's (Access Points) set to specific channel
- Broadcast beacon messages with SSID (Service Set Identifier) and MAC Address periodically
- Hosts scan all the channels to discover the AP's
  - Host associates with AP

Wireless Multiple Access Technique

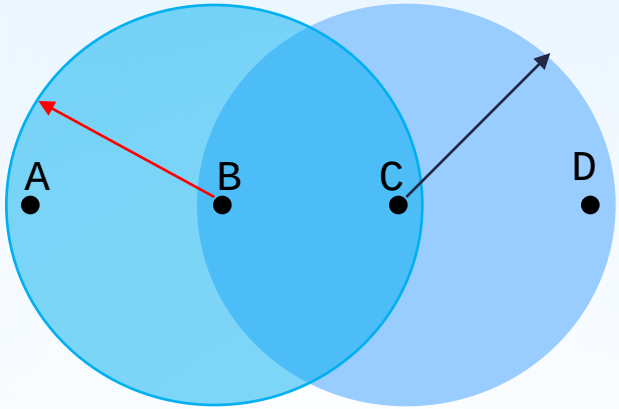
- Collision Detection?
  - Where do collisions occur?
  - How can you detect them?
- Carrier Sense?
  - Sender can listen before sending
  - What does that tell the sender?

Hidden Terminals



- A and C can both send to B but can't hear each other
  - A is a *hidden terminal* for C and vice versa
- Carrier Sense will be ineffective

Exposed Terminals



- Exposed node: B sends a packet to A; C hears this and decides not to send a packet to D (despite the fact that this will not cause interference)!
- Carrier sense would prevent a successful transmission.

5 Minute Break

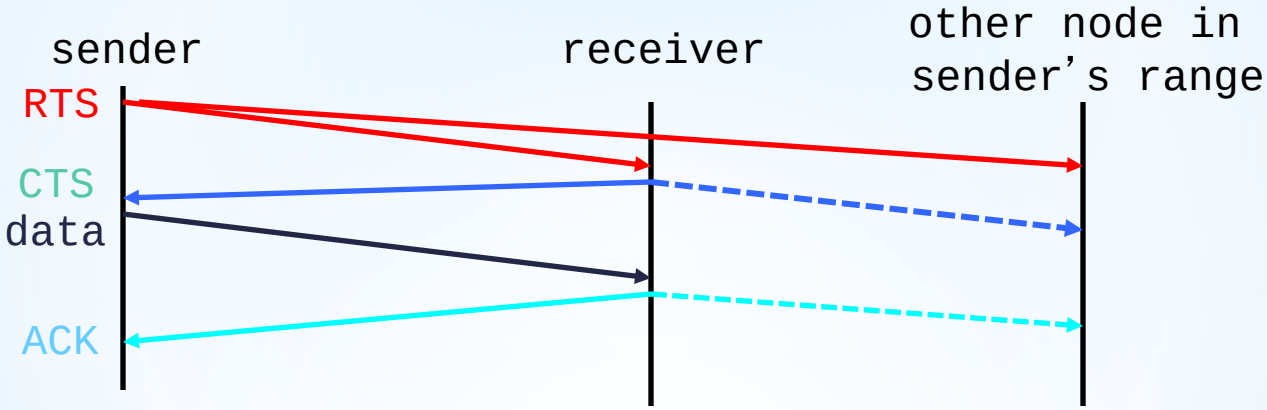
Key Points

- No concept of a global collision
  - Different receivers hear different signals
  - Different senders reach different receivers
- Collisions are at receiver, not sender
  - Only care if receiver can hear the sender clearly
  - It does not matter if sender can hear someone else
  - As long as that signal does not interfere with receiver
- Goal of protocol:
  - Detect if receiver can hear sender
  - Tell senders who might interfere with receiver to shut up

Basic Collision Avoidance

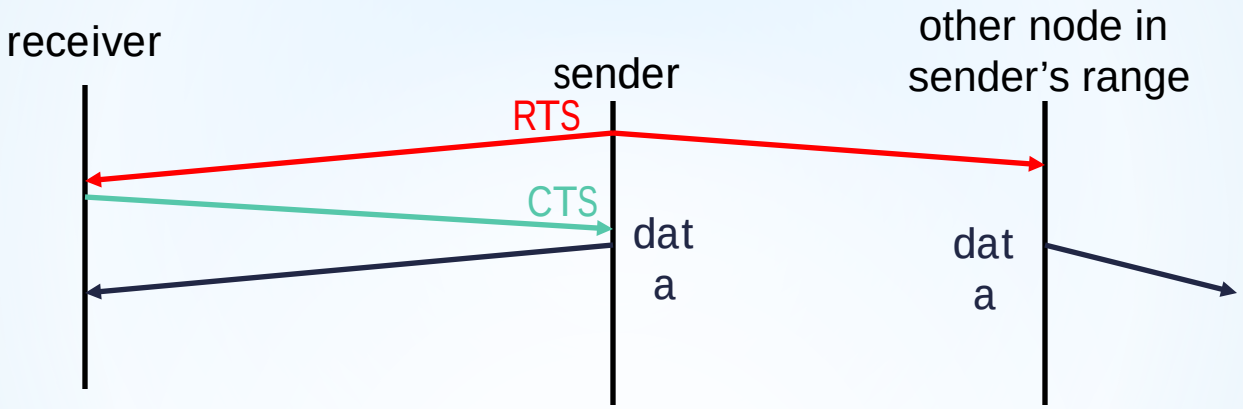
- Since can't detect collisions, we try to *avoid* them
- Carrier sense:
  - When medium busy, choose random interval
  - Wait that many **idle** timeslots to pass before sending
- When a collision is inferred, retransmit with binary exponential backoff (like Ethernet)
  - Use ACK from receiver to infer "no collision"
  - Use exponential backoff to adapt contention window

CSMA/CA - Collision Avoidance



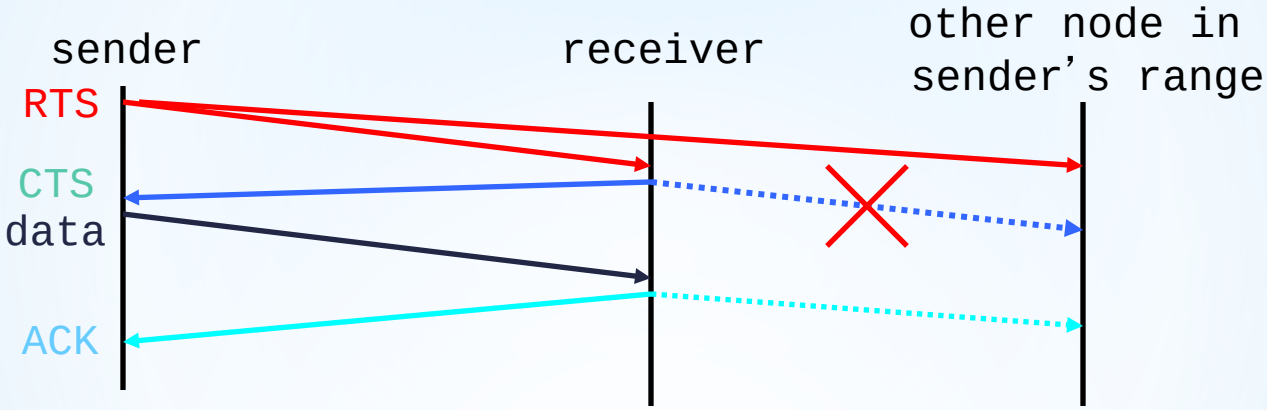
- Before every data transmission
  - Sender sends a Request to Send (RTS) frame containing the length of the transmission
  - Receiver respond with a Clear to Send (CTS) frame
  - Sender sends data
  - Receiver sends an ACK; now another sender can send data
- When sender doesn't get a CTS back, it assumes collision

CSMA/CA - Collision Avoidance



- If other nodes hear RTS, but not CTS: send
  - Presumably, destination for first sender is out of node's range …

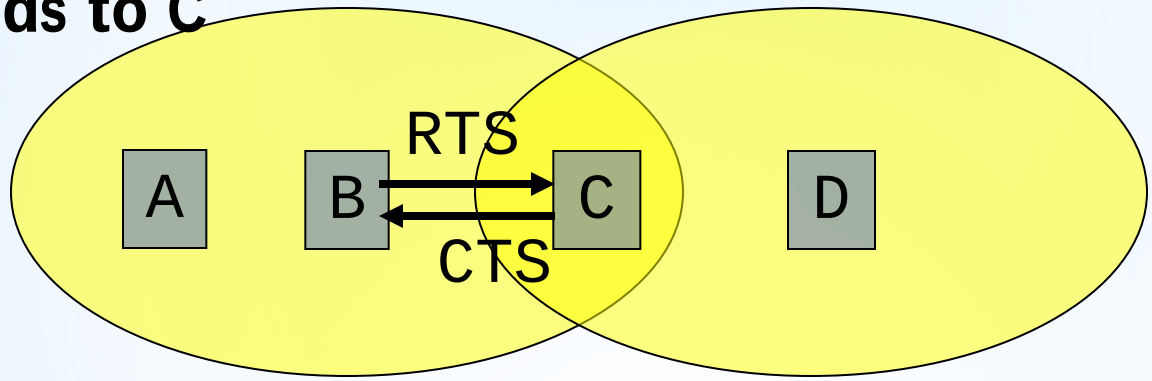
CSMA/CA -MA with Collision Avoidance



- If other nodes hear RTS, but not CTS: send
  - Presumably, destination for first sender is out of node's range …
  - … Can cause problems when a CTS is lost
- When you hear a CTS, you keep quiet until scheduled transmission is over (hear ACK)

RTS / CTS Protocols (CSMA/CA)

B sends to C

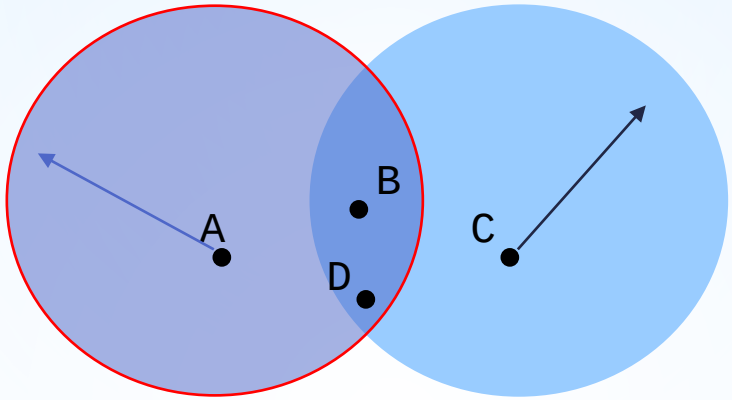


Overcome hidden terminal problems with contention-free protocol

1. B sends to C Request To Send (RTS)
2. A hears RTS and defers (to allow C to answer)
3. C replies to B with Clear To Send (CTS)
4. D hears CTS and defers to allow the data
5. B sends to C

Preventing Collisions Altogether

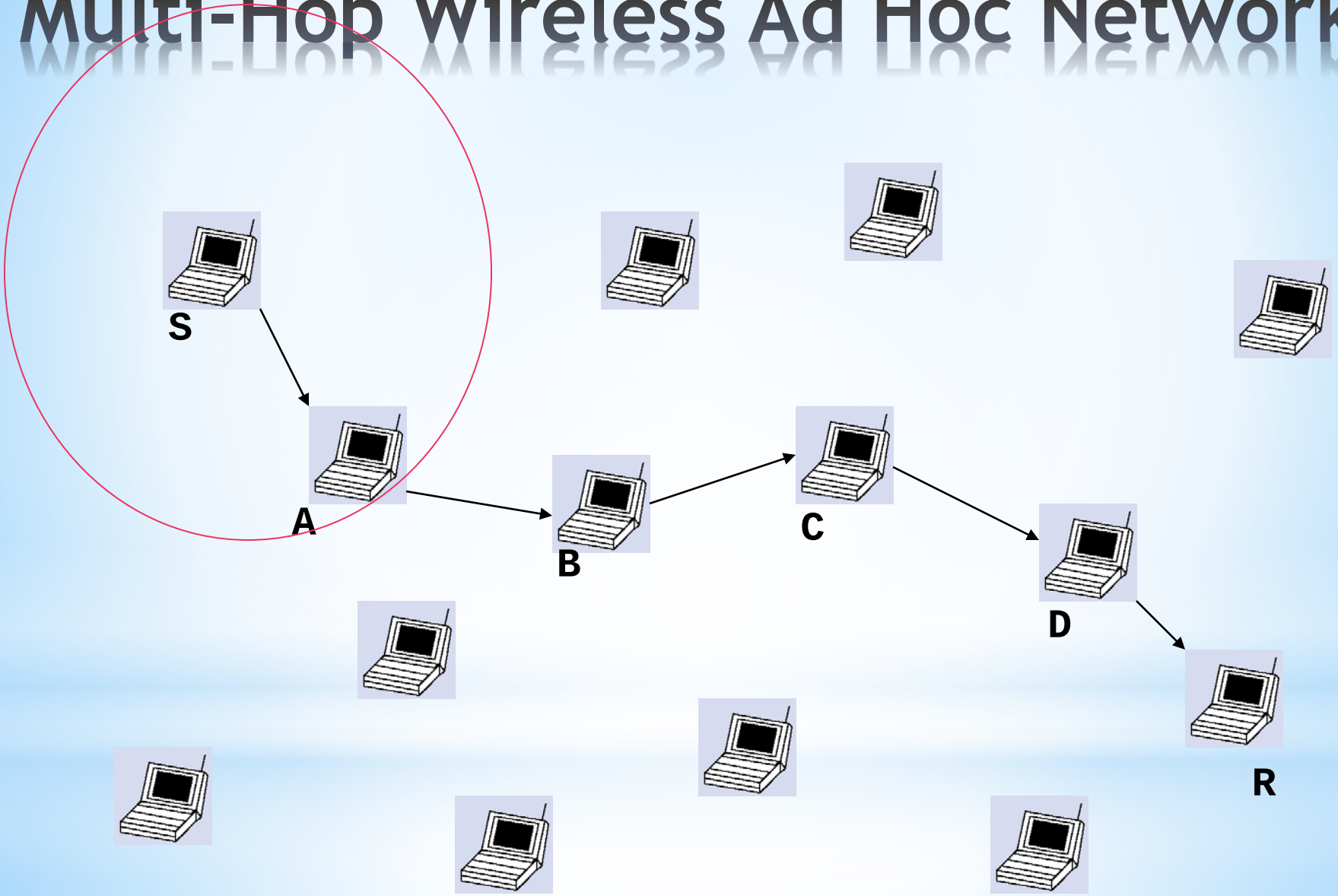
- Frequency Spectrum partitioned into several channels
  - Nodes within interference range can use separate channels



  - Now A and C can send without any interference!
  - Most cards have only 1 transceiver

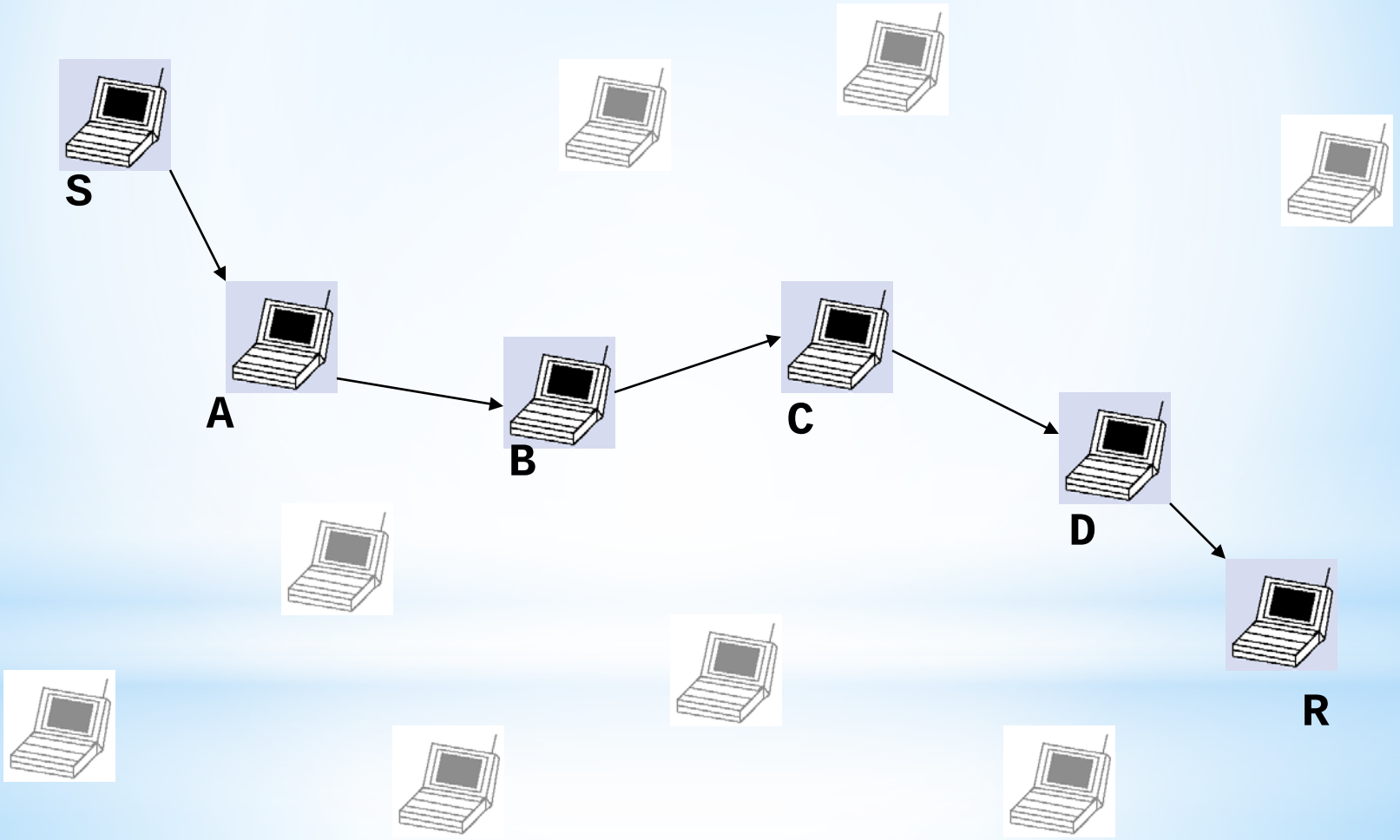
  - Aggregate Network throughput doubles

Multi-Hop Wireless Ad Hoc Networks

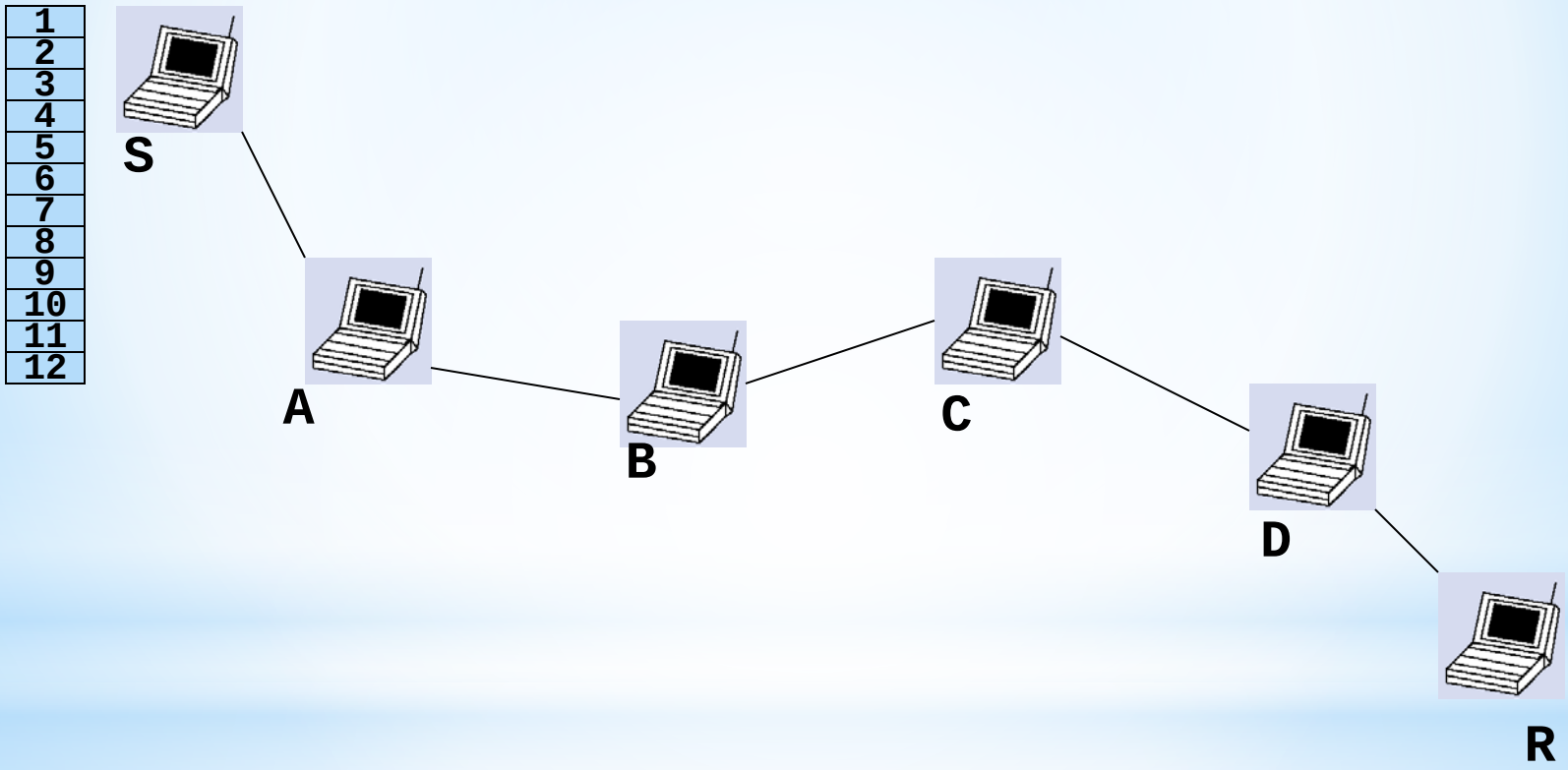


Courtesy of Tianbo Kuang and Carey Williamson University of Calgary)

Multi-Hop Wireless Ad Hoc Networks

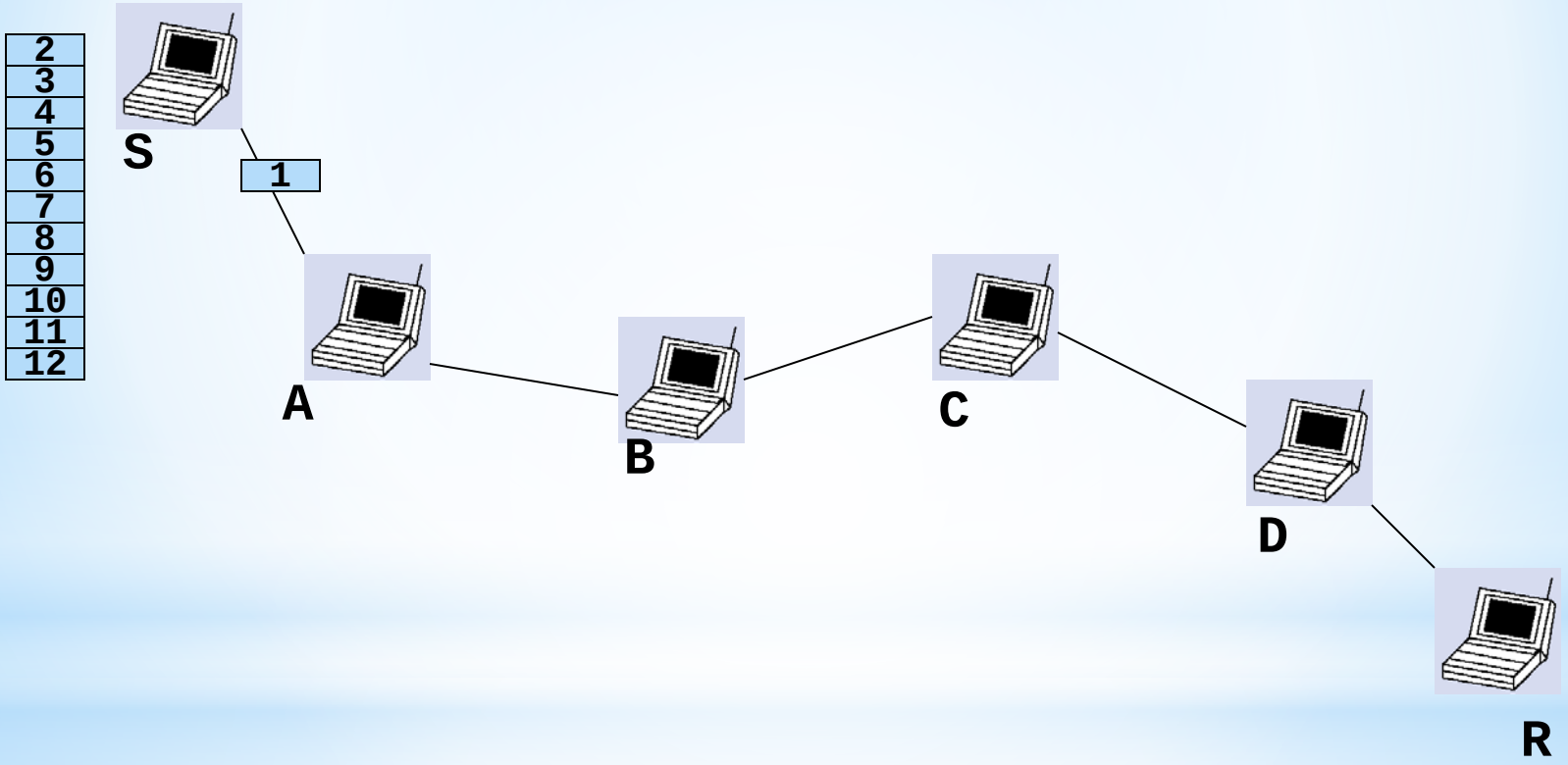


Multi-Hop Wireless Ad Hoc Networks



(Assume ideal world…)

Multi-Hop Wireless Ad Hoc Networks



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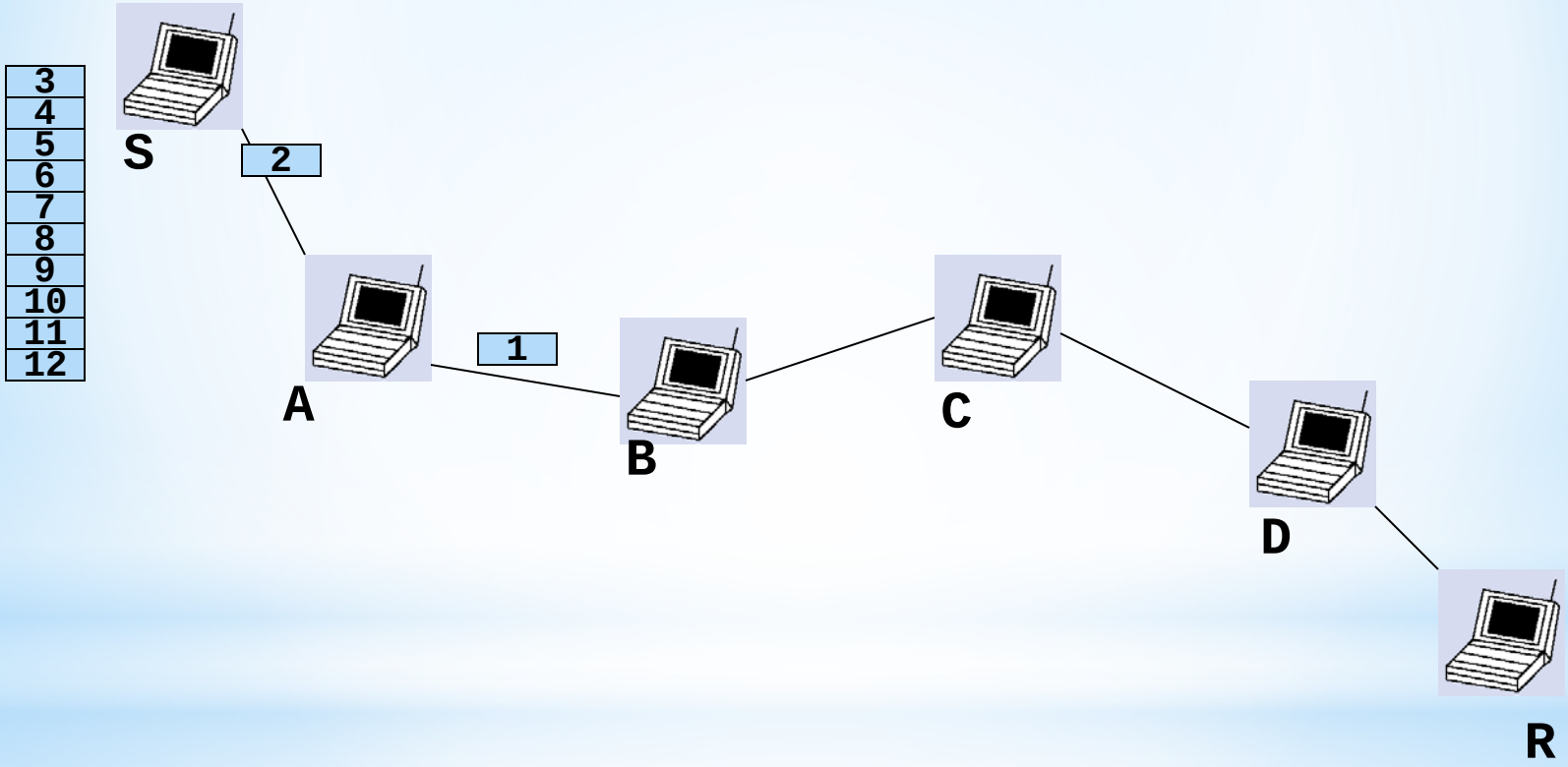

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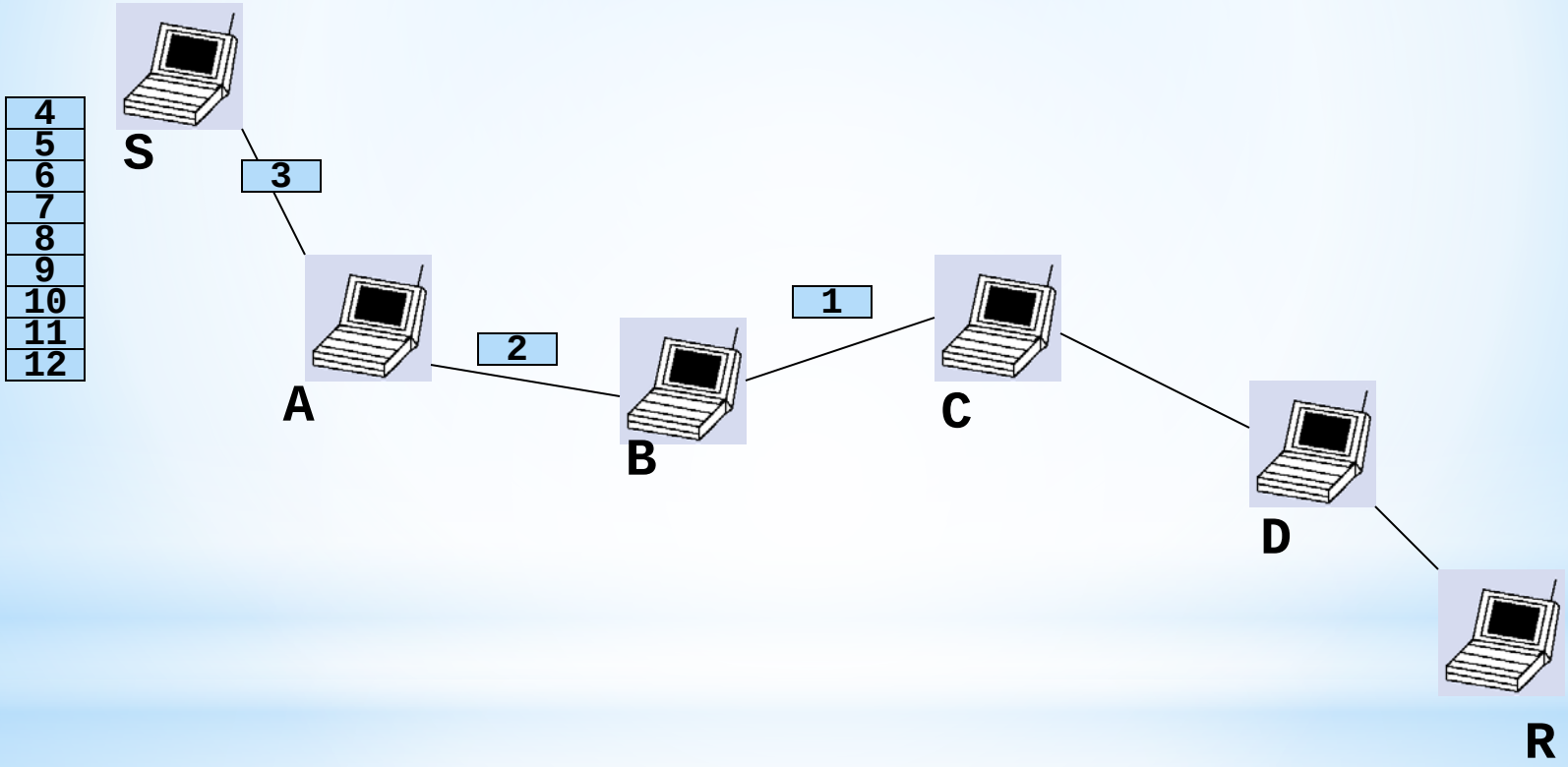

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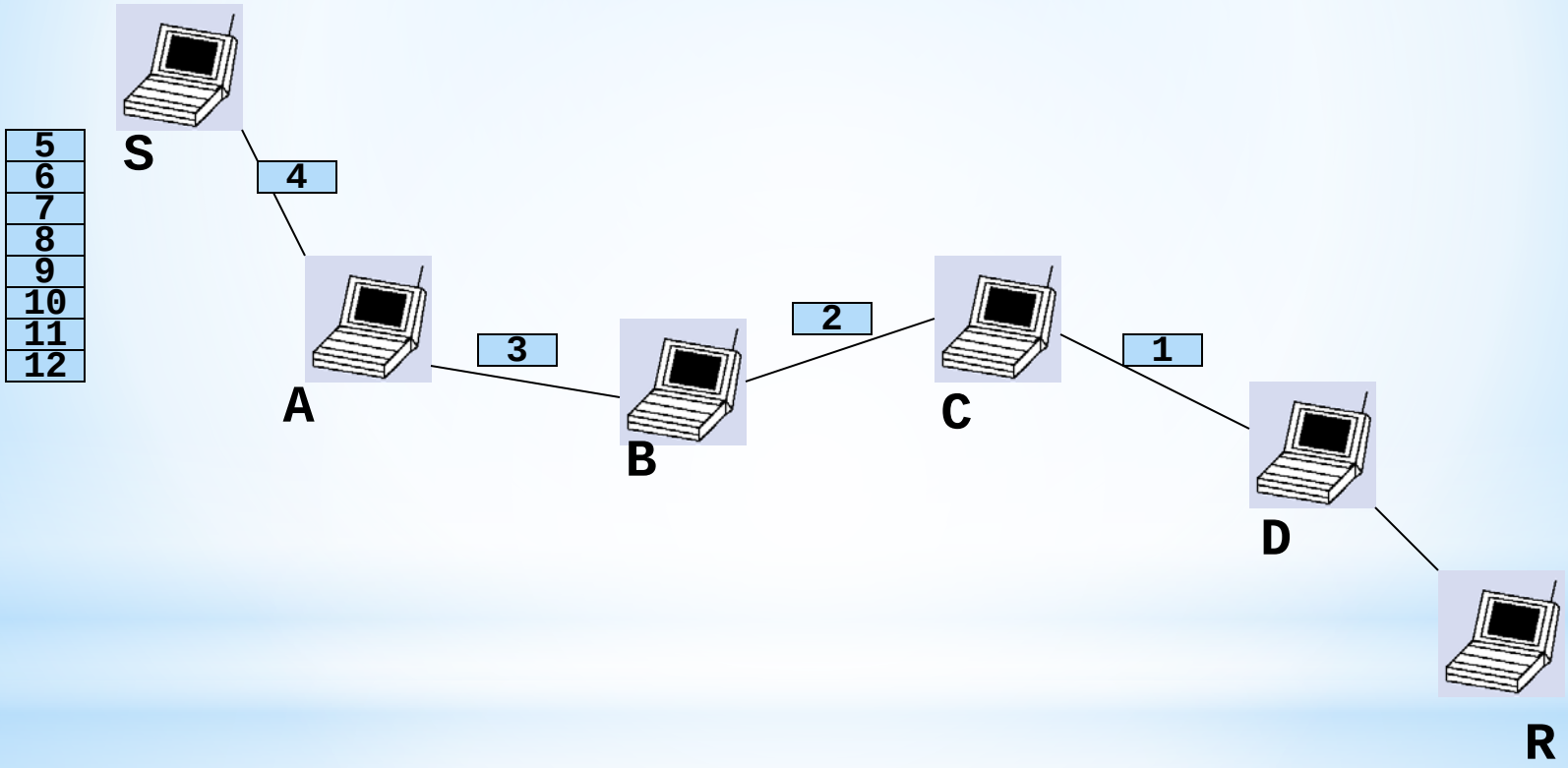
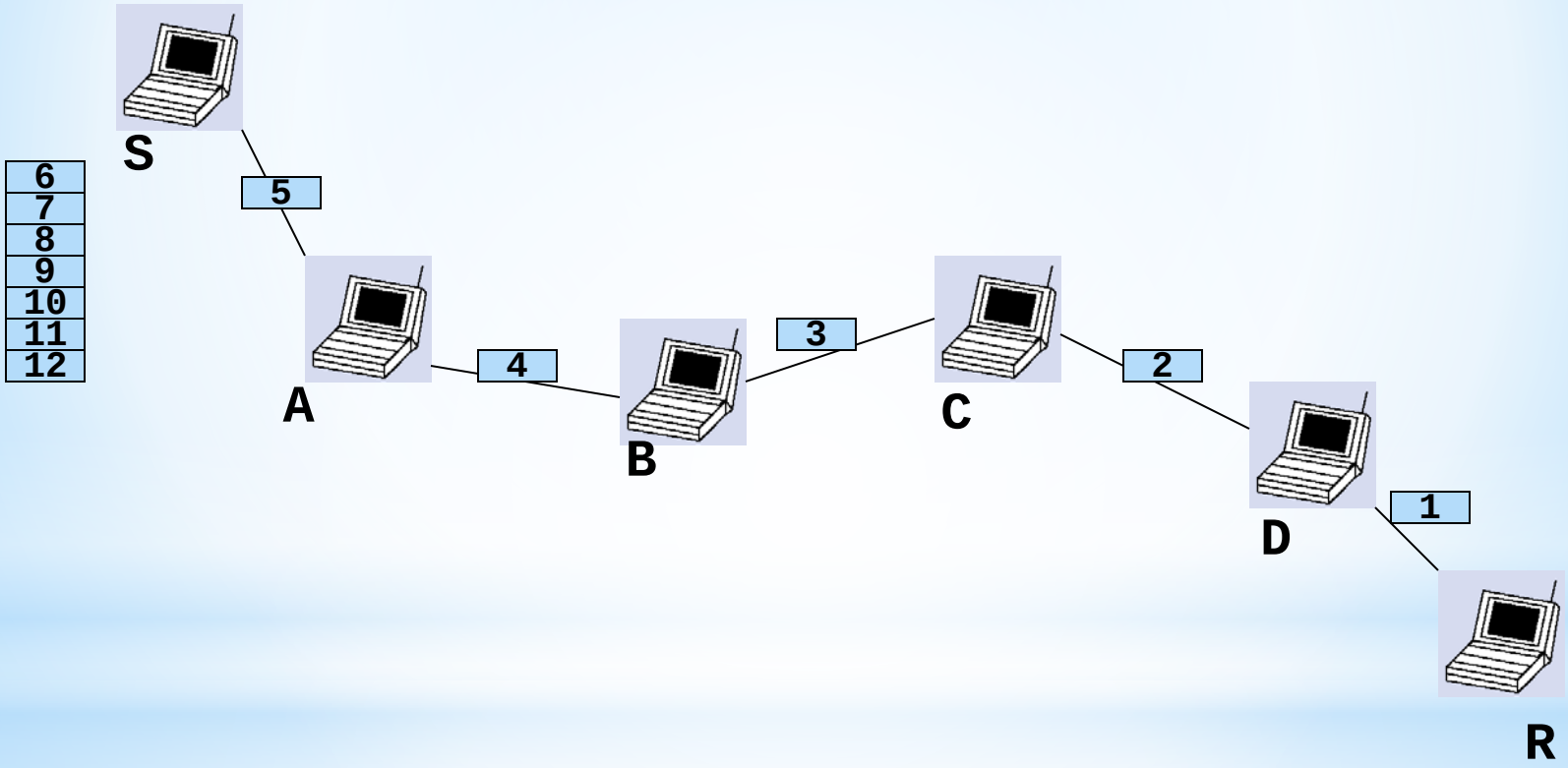
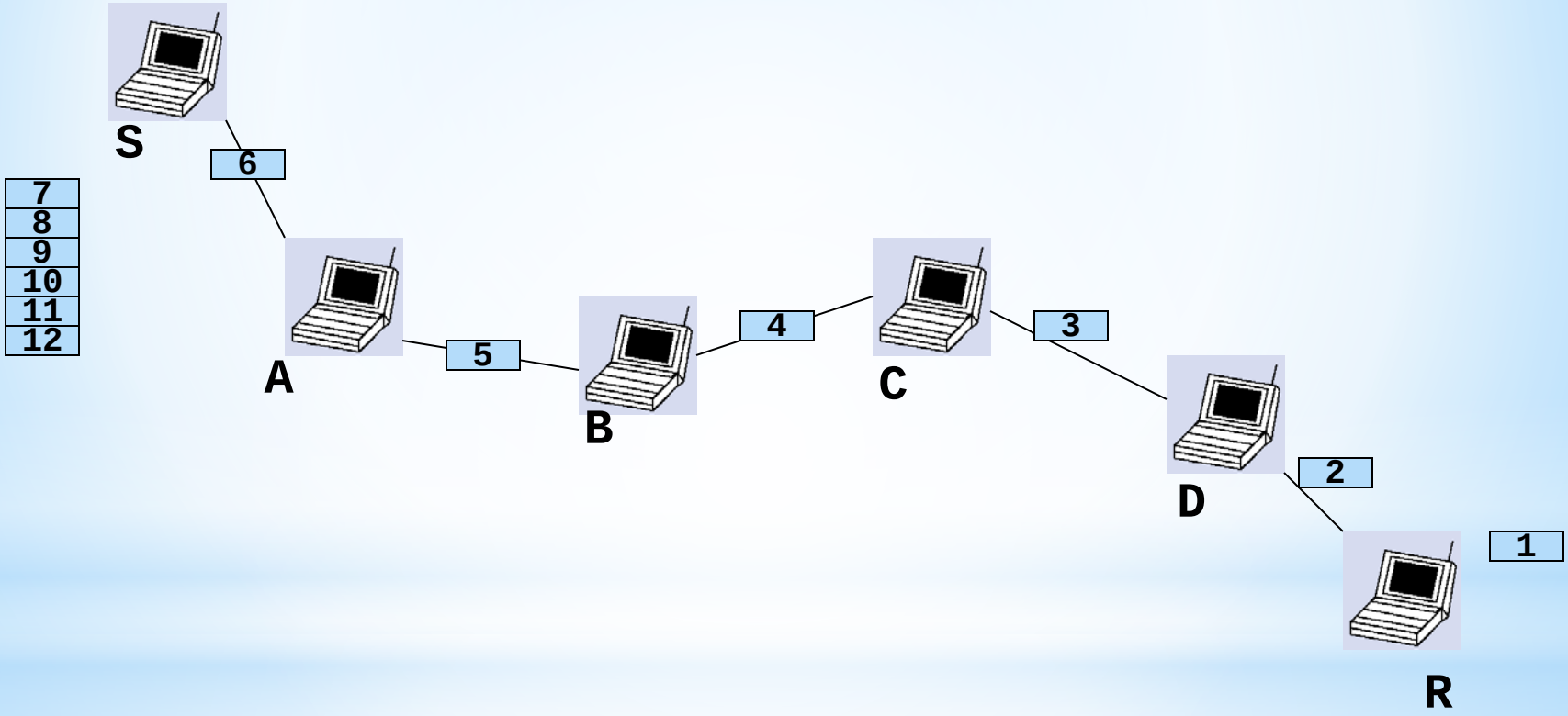


Multi-Hop Wireless Ad Hoc Networks



Multi-Hop Wireless Ad Hoc Networks



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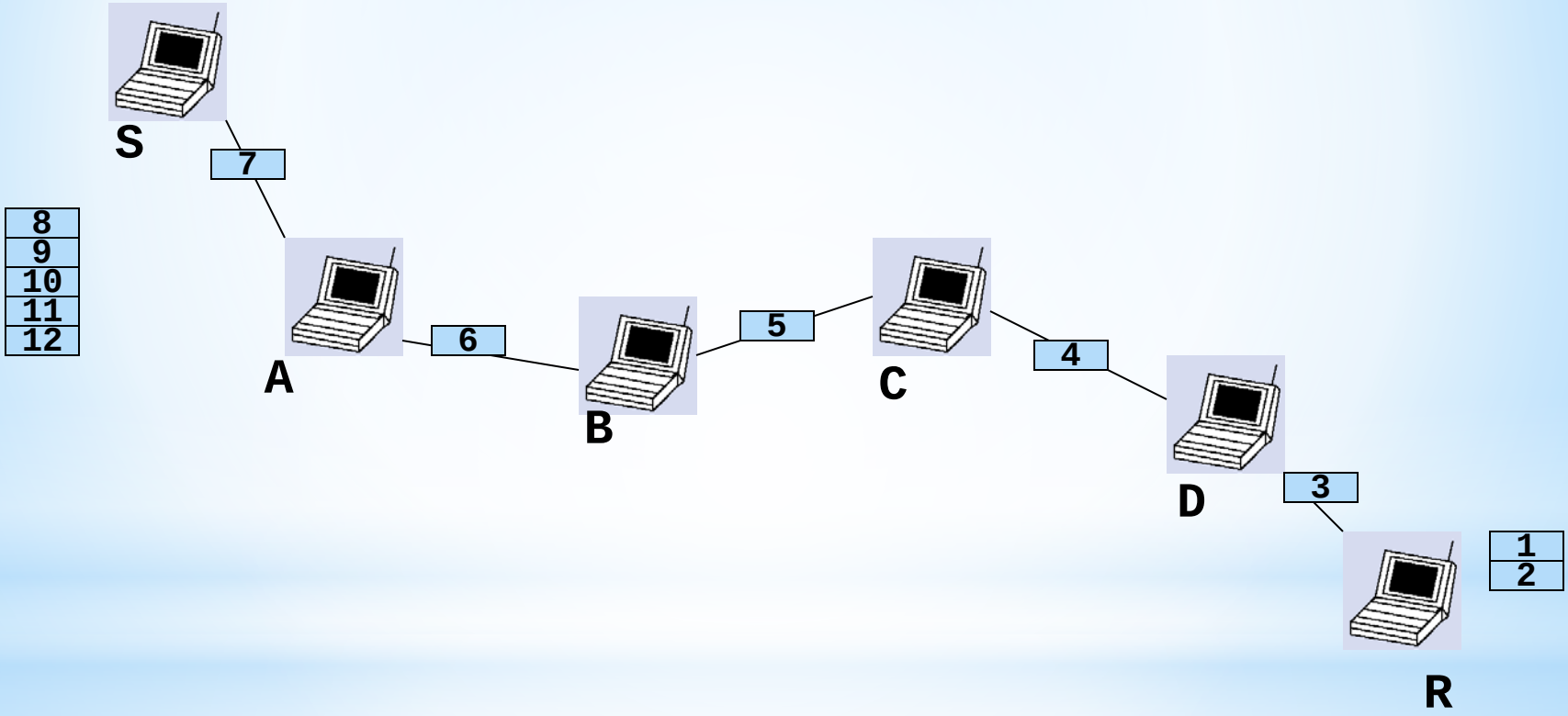
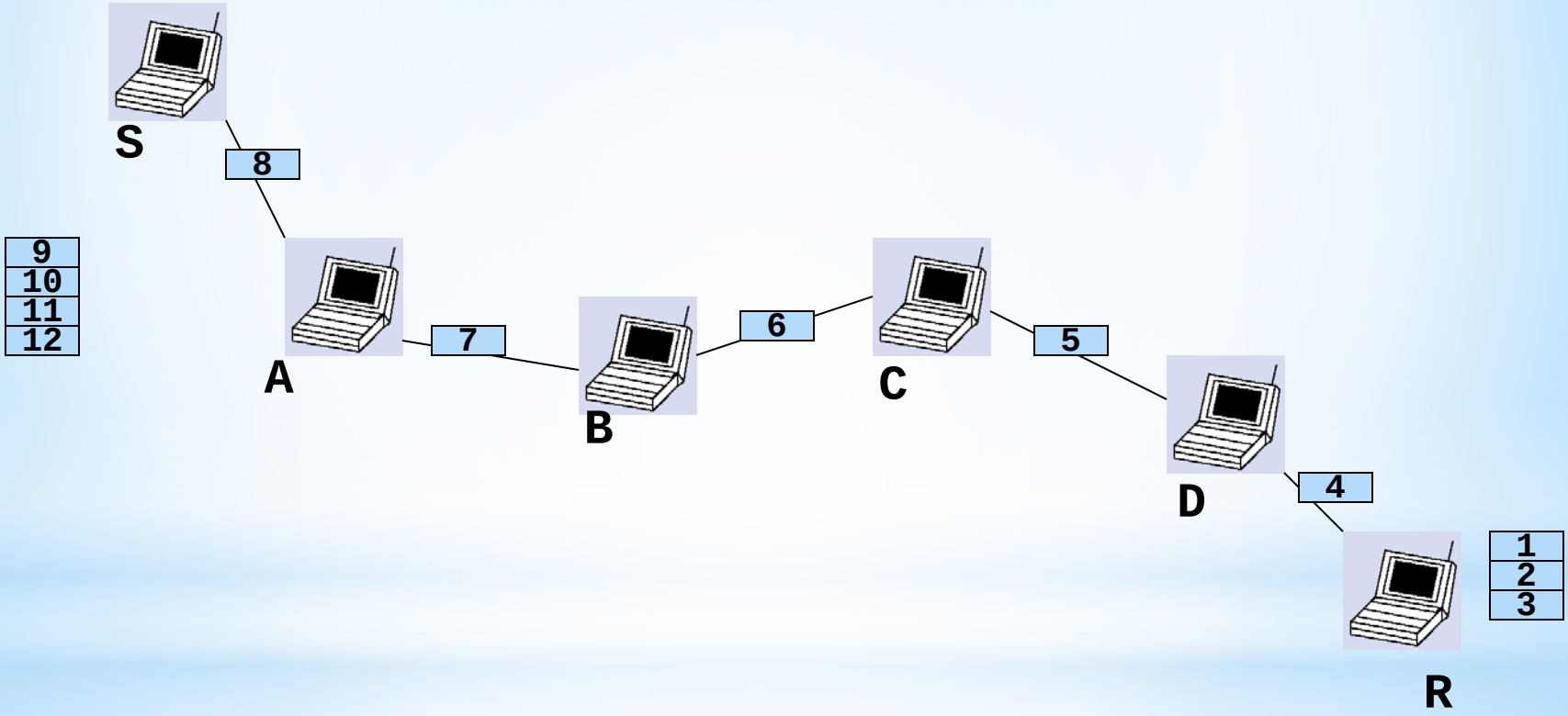


Multi-Hop Wireless Ad Hoc Networks



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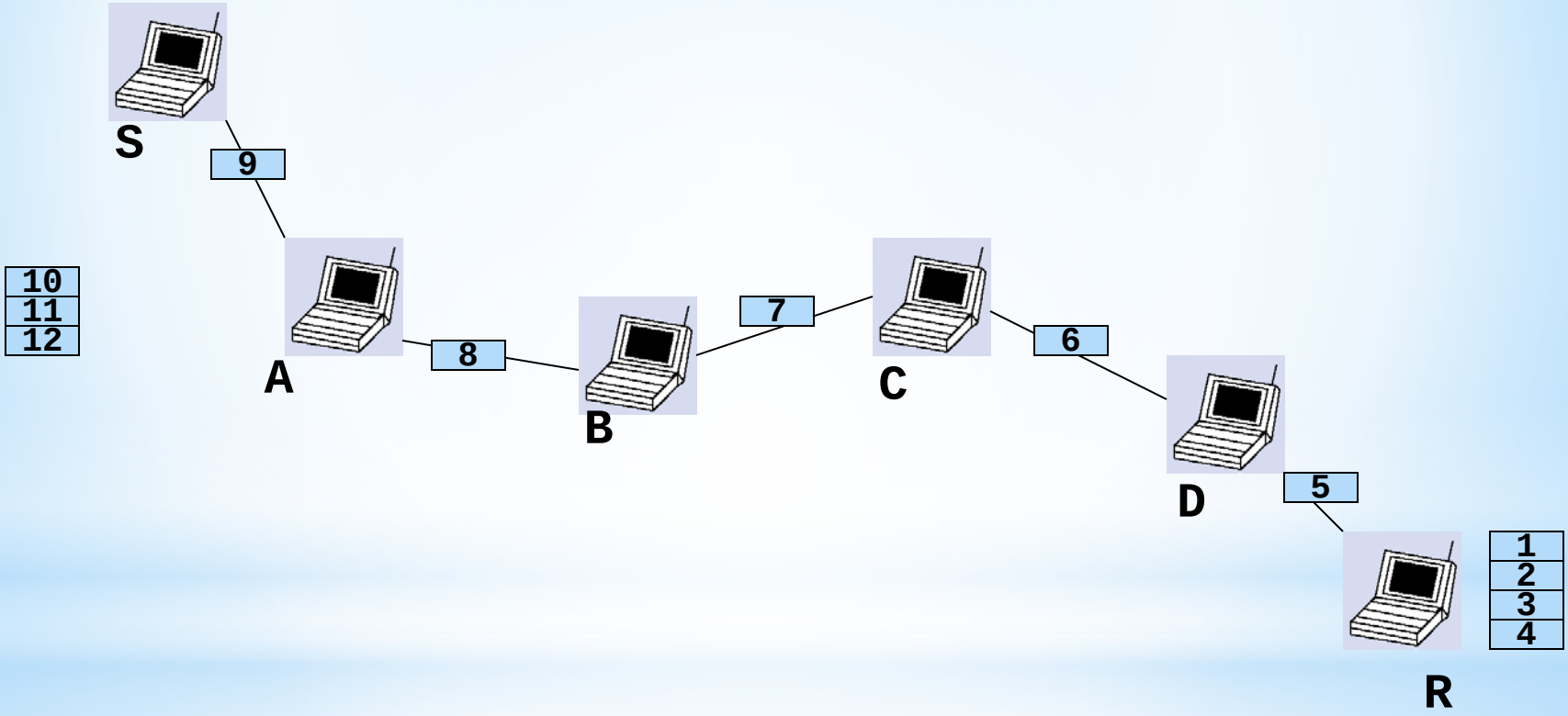

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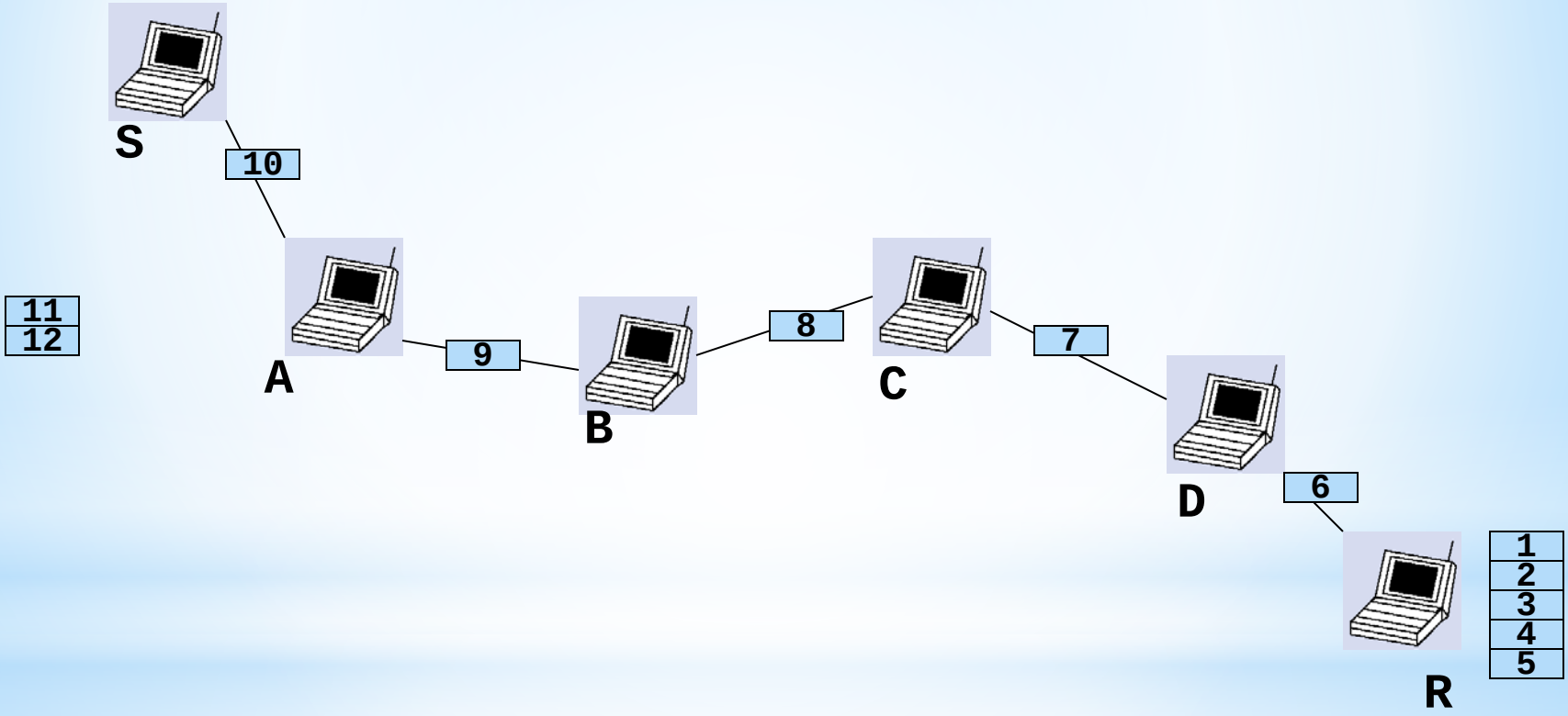

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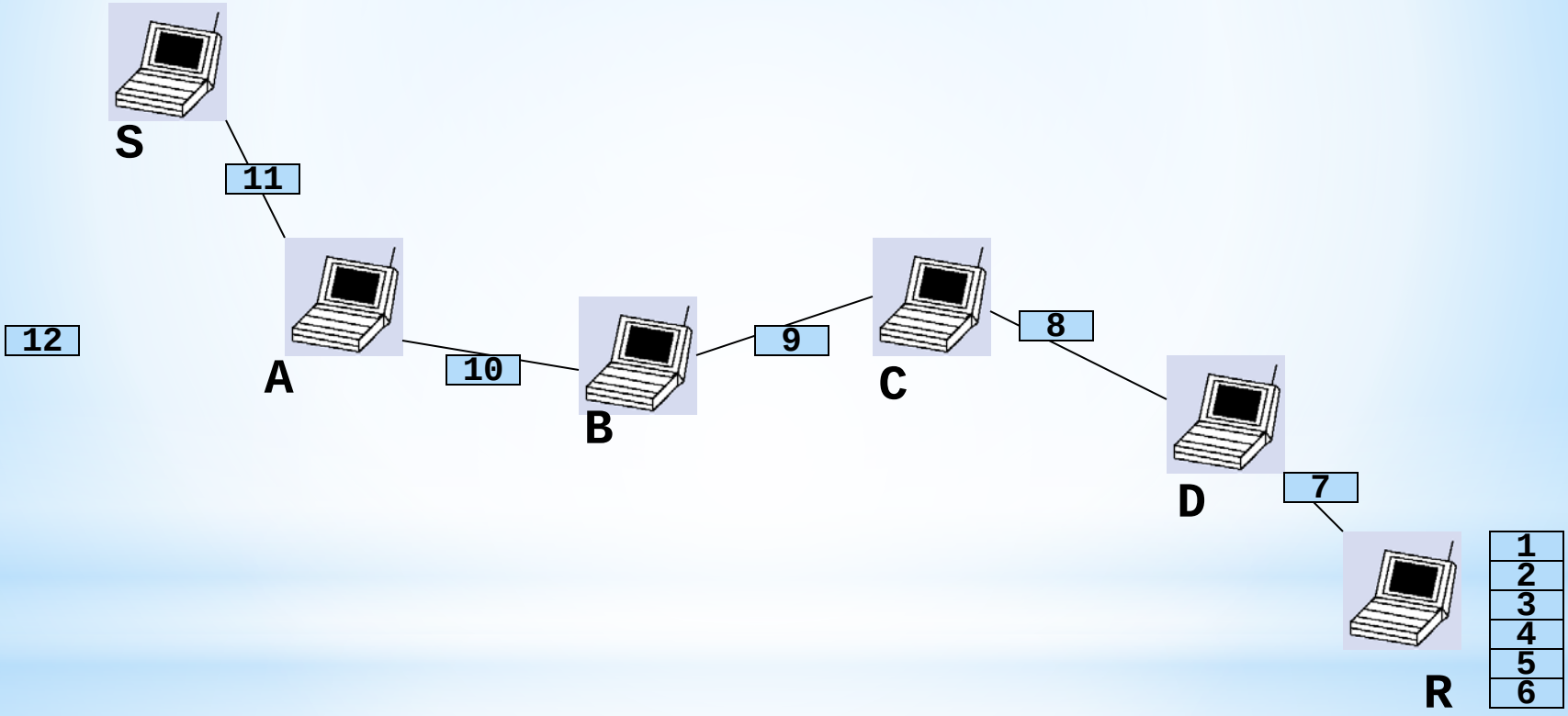

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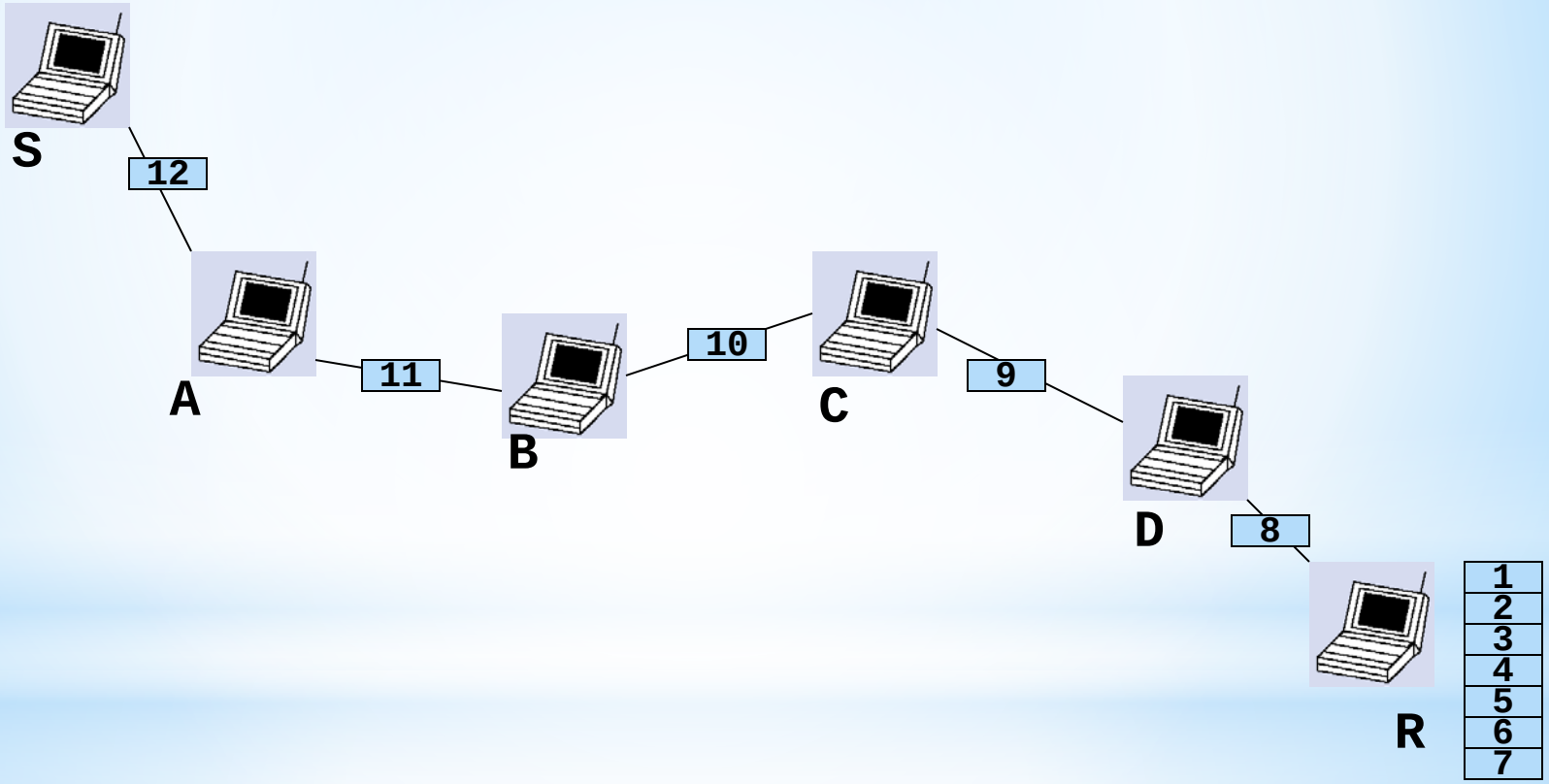

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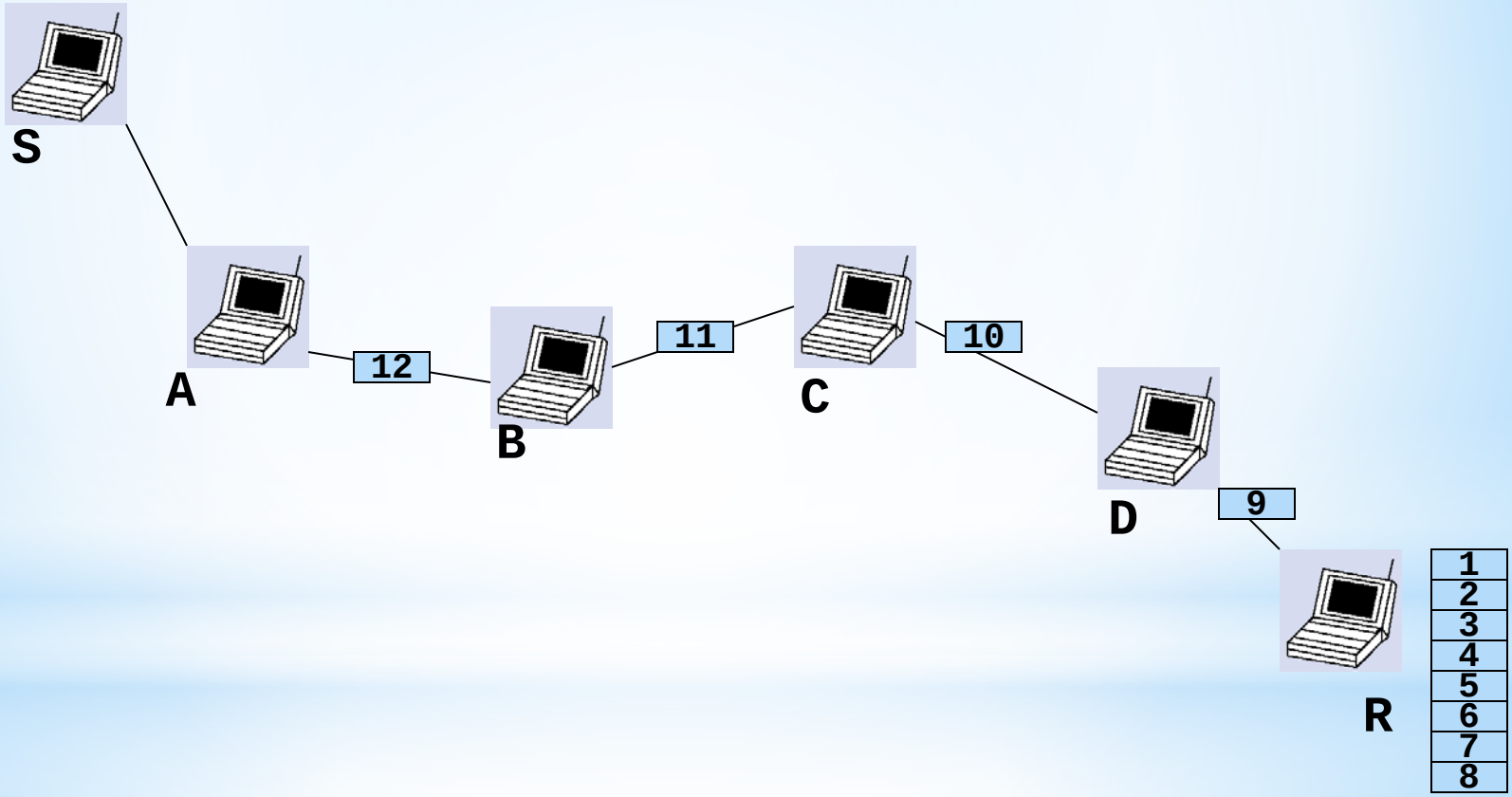

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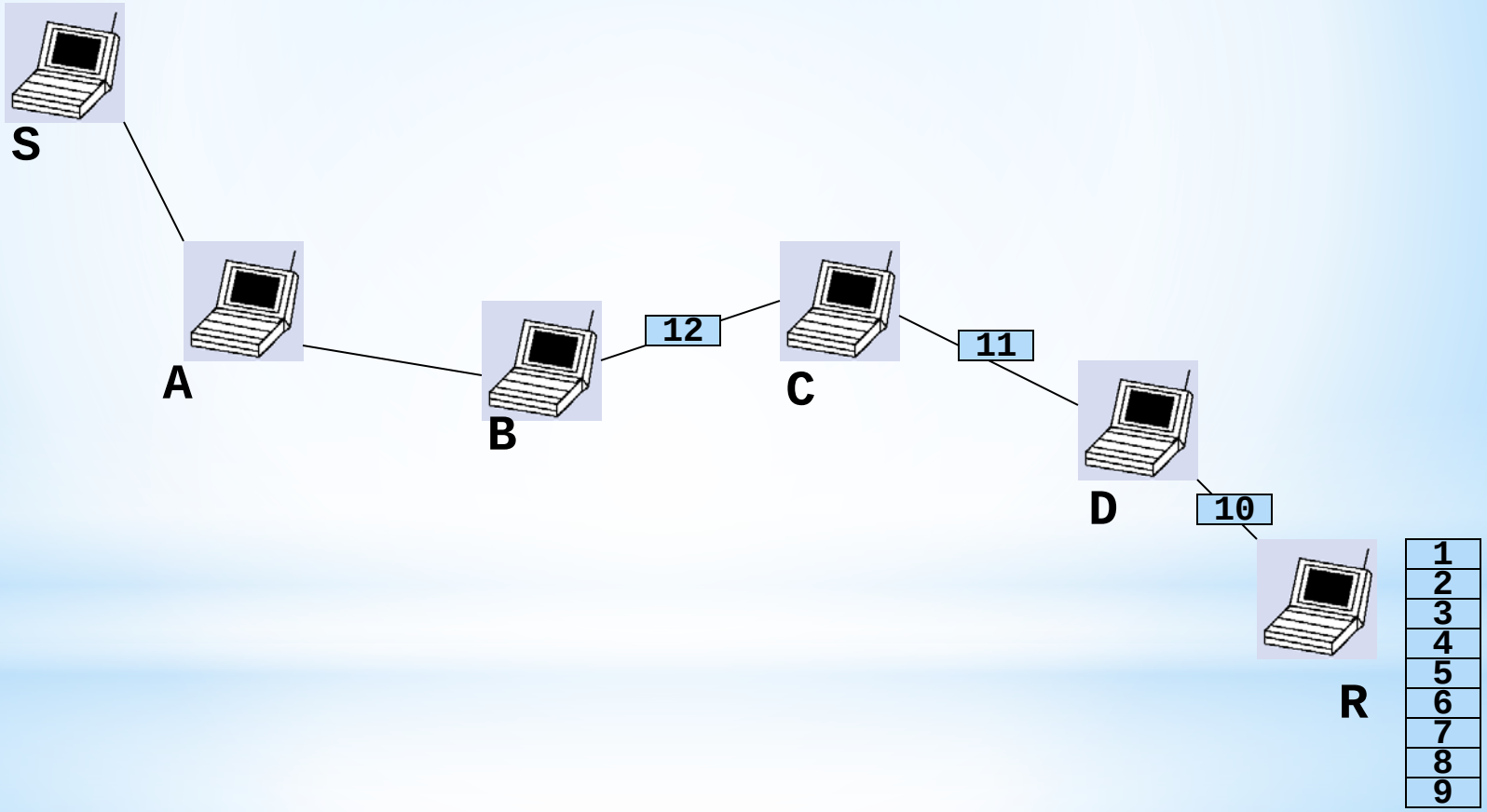

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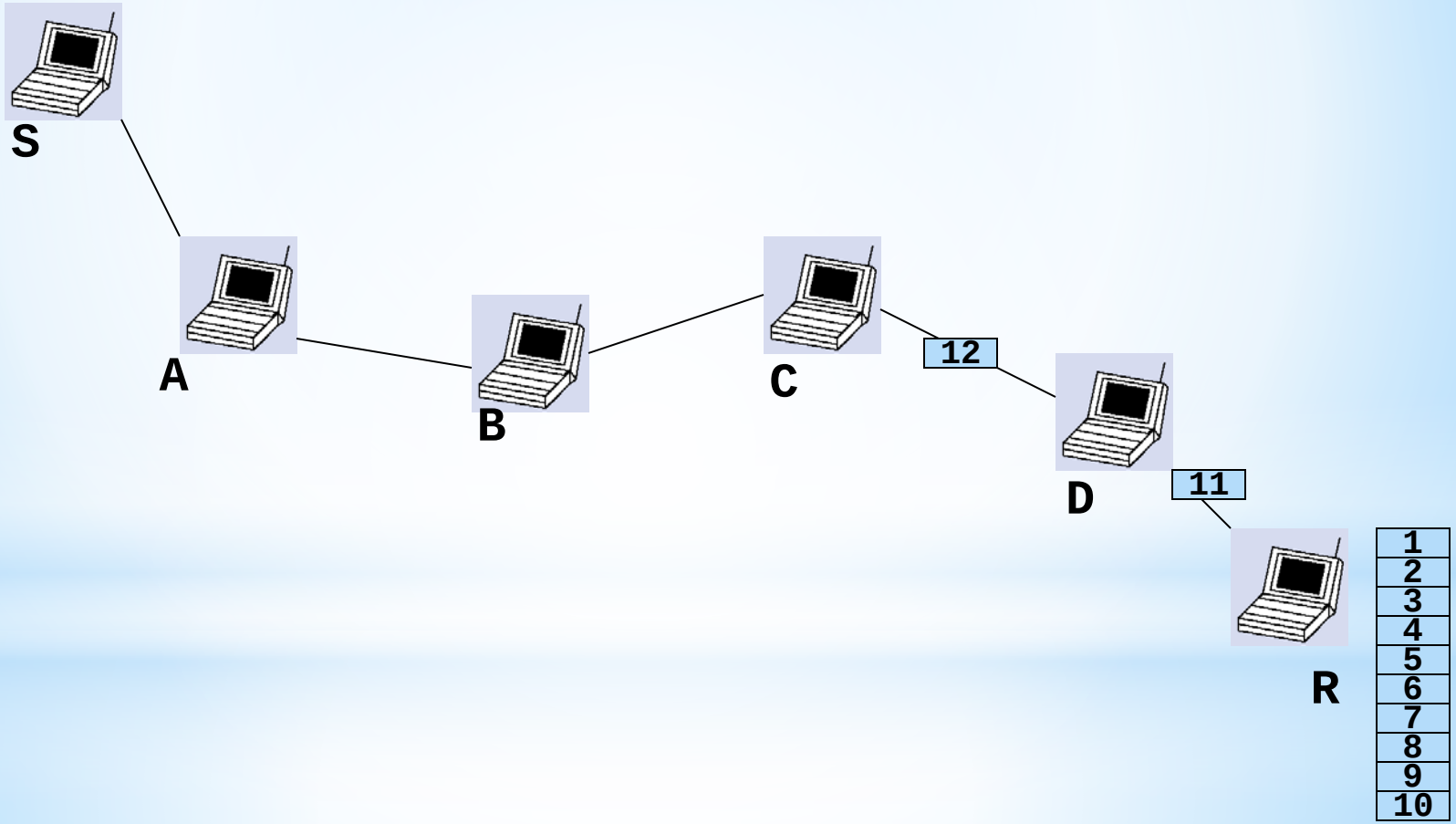

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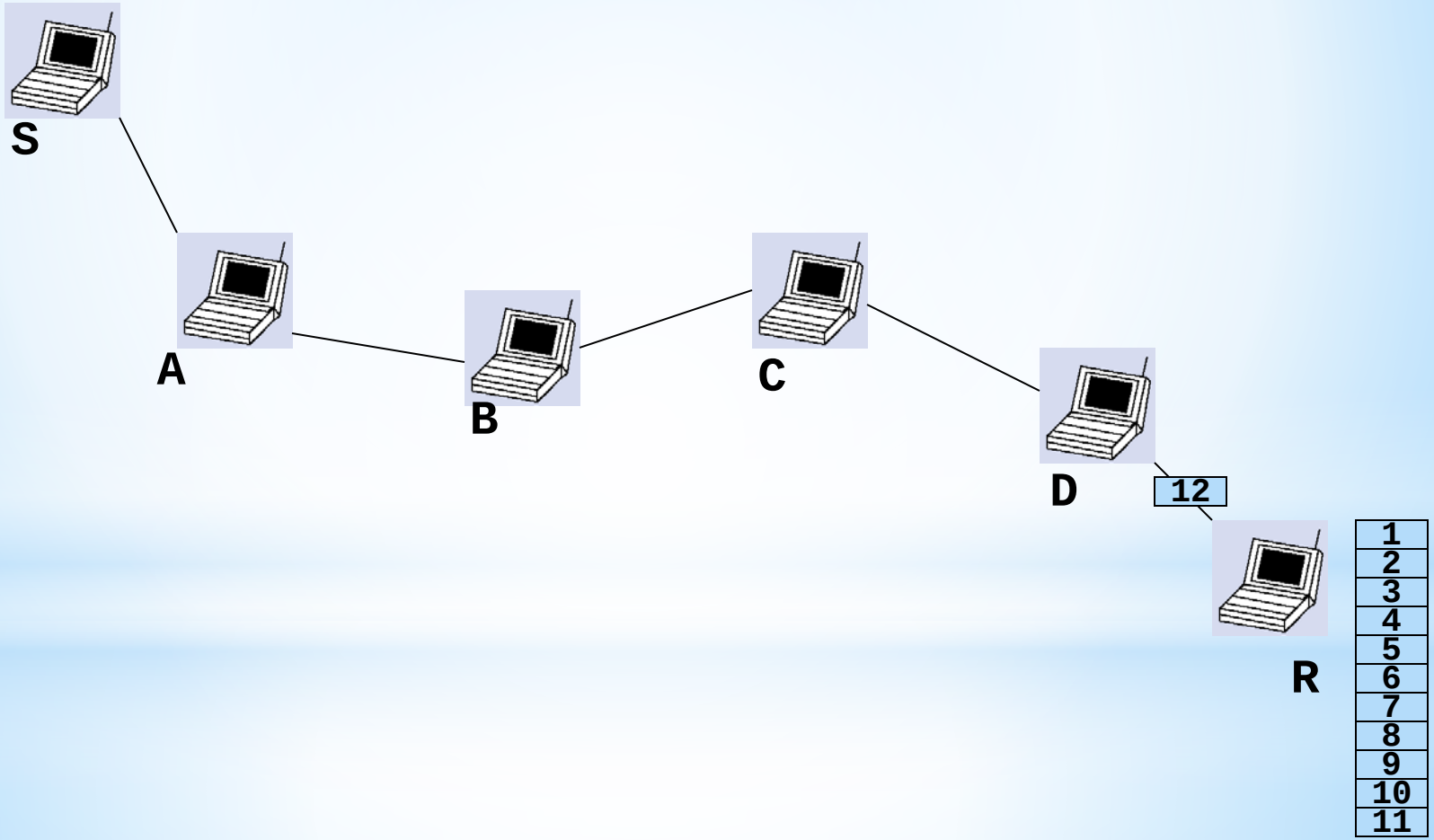
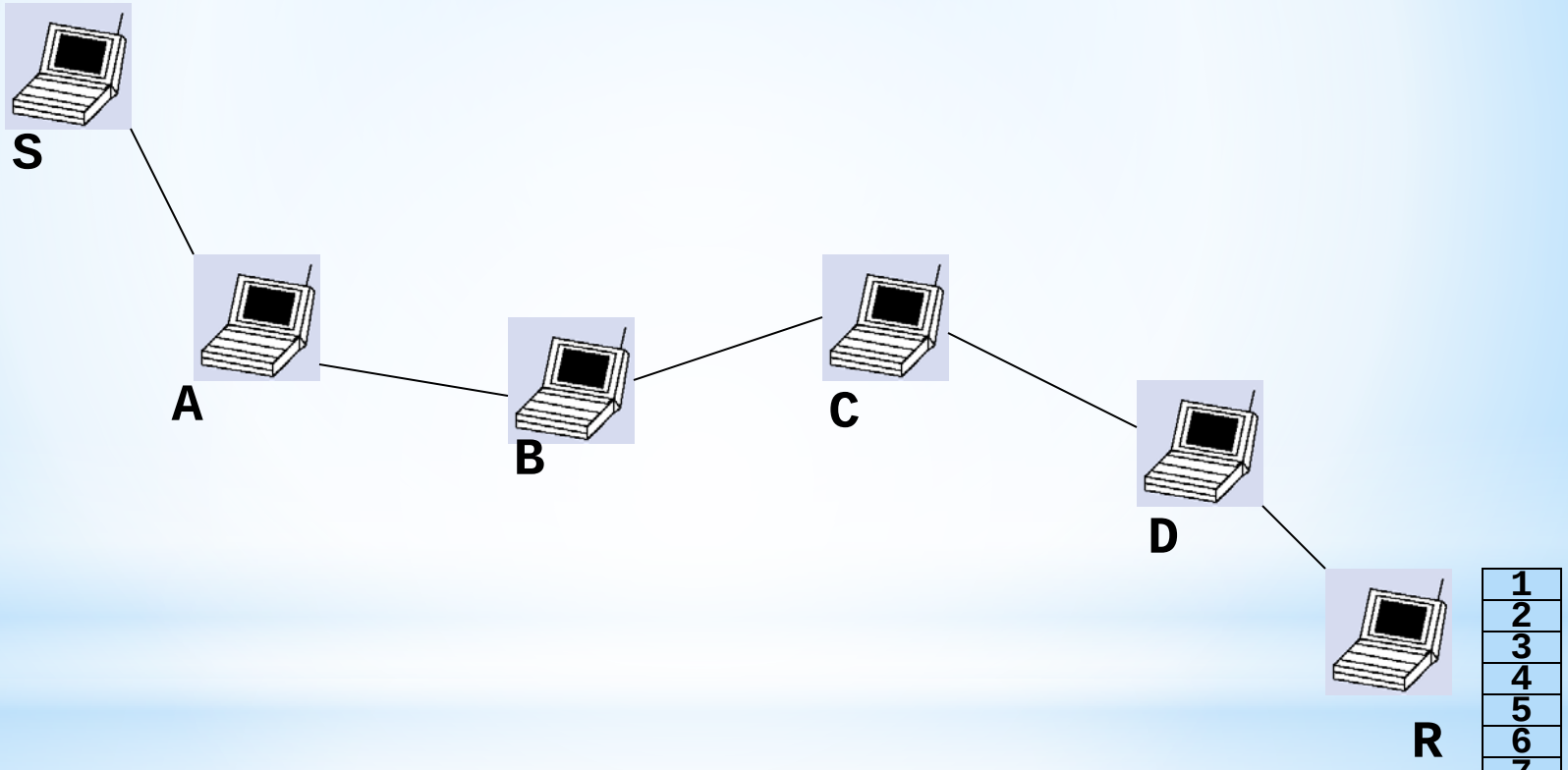
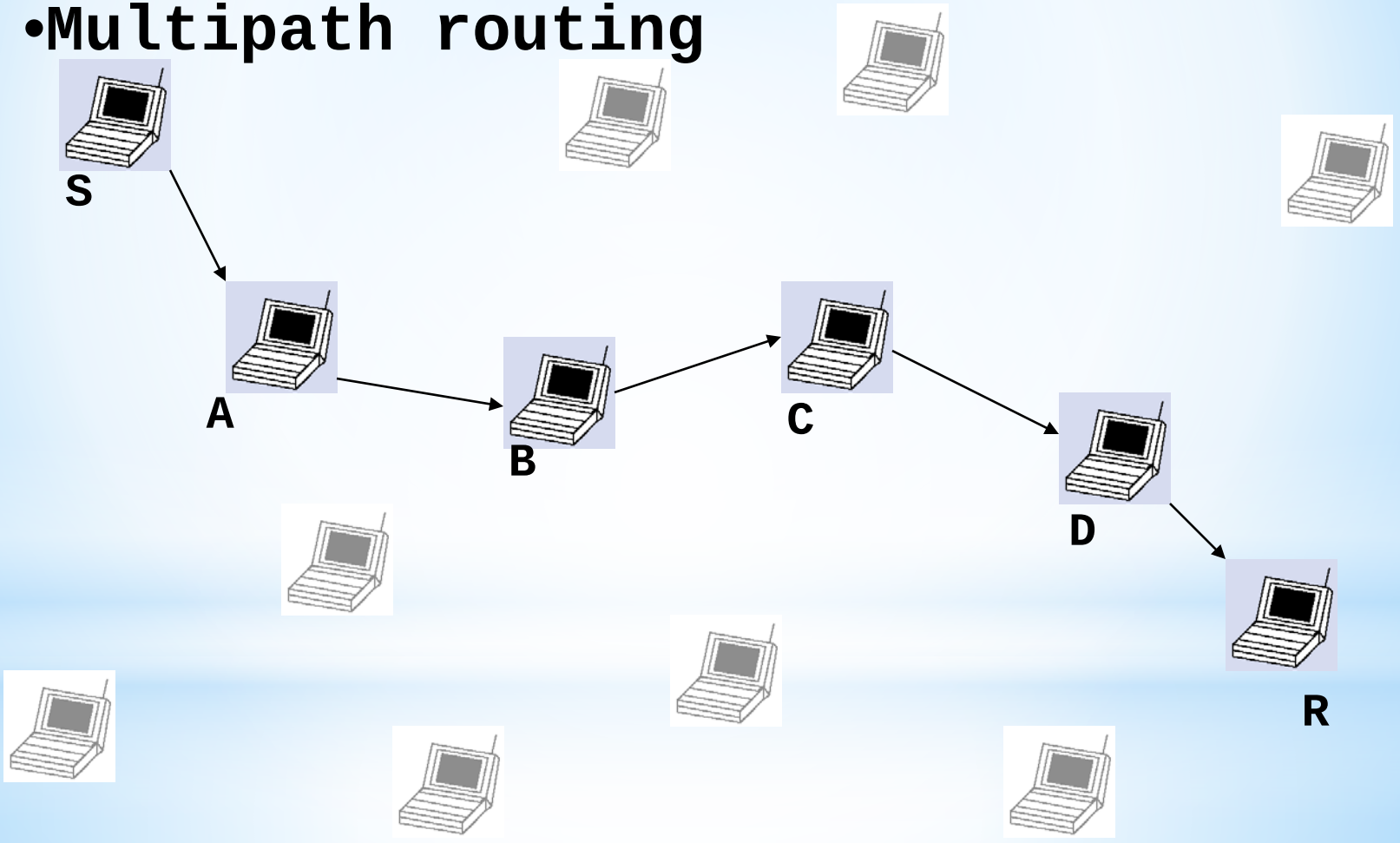


Multi-Hop Wireless Ad Hoc Networks



The end of phone companies & ISPs?

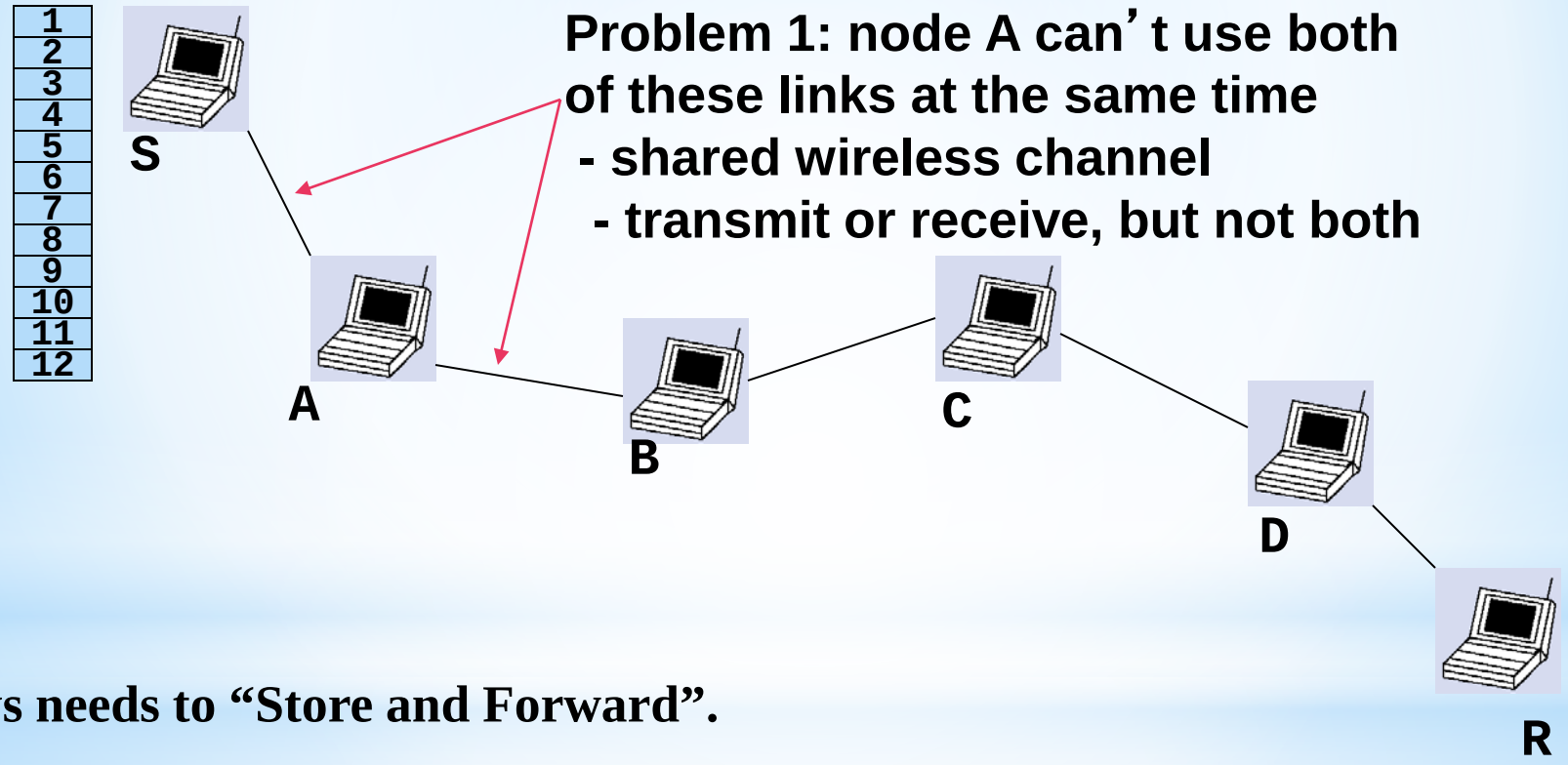
- **Self healing**
- **Multipath routing**



What Do YOU Think Really Happens?

Multi-Hop Wireless Ad Hoc Networks

(Reality check…)



Relays needs to "Store and Forward".

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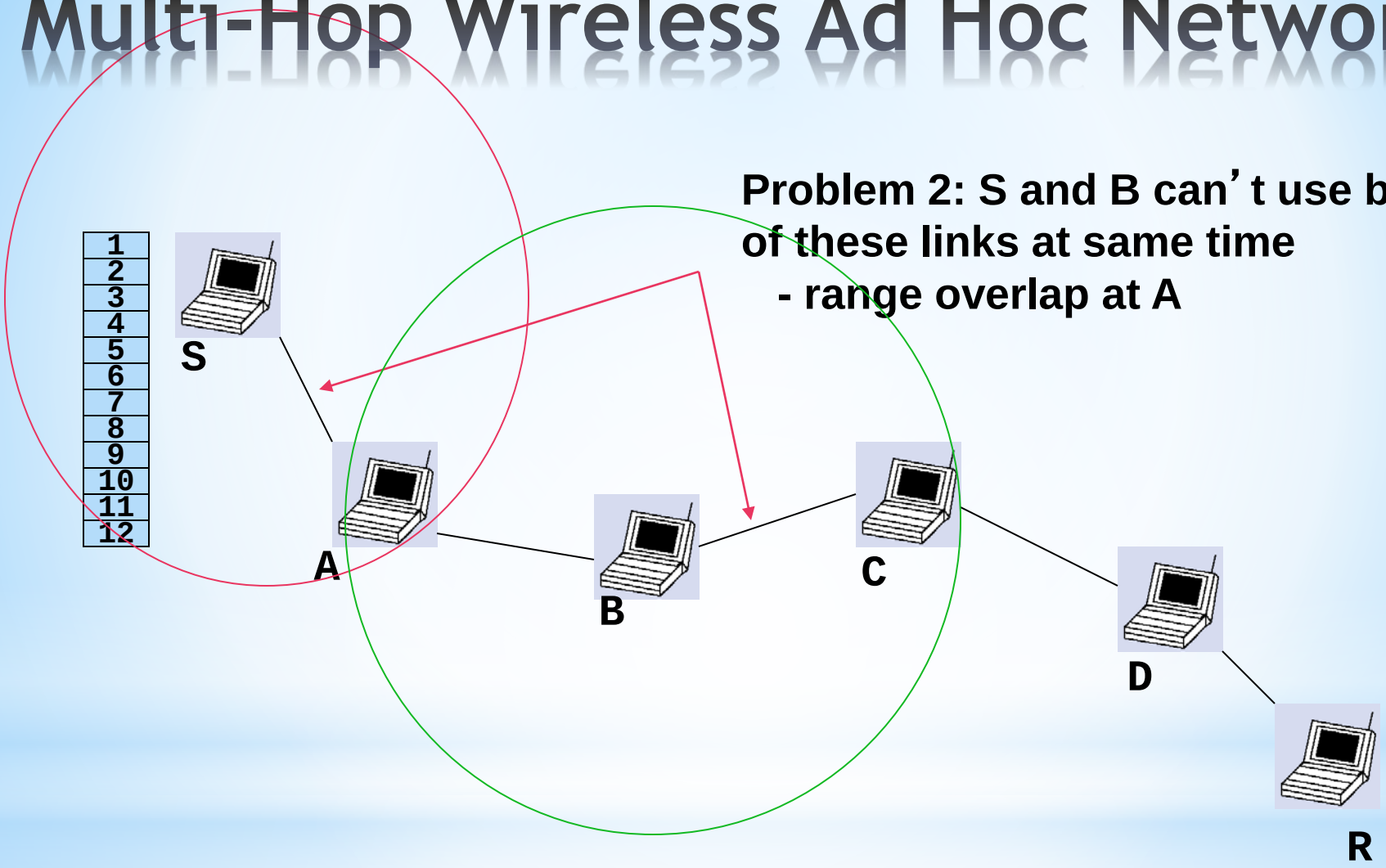

Problem 2: S and B can't use both of these links at same time
- range overlap at A

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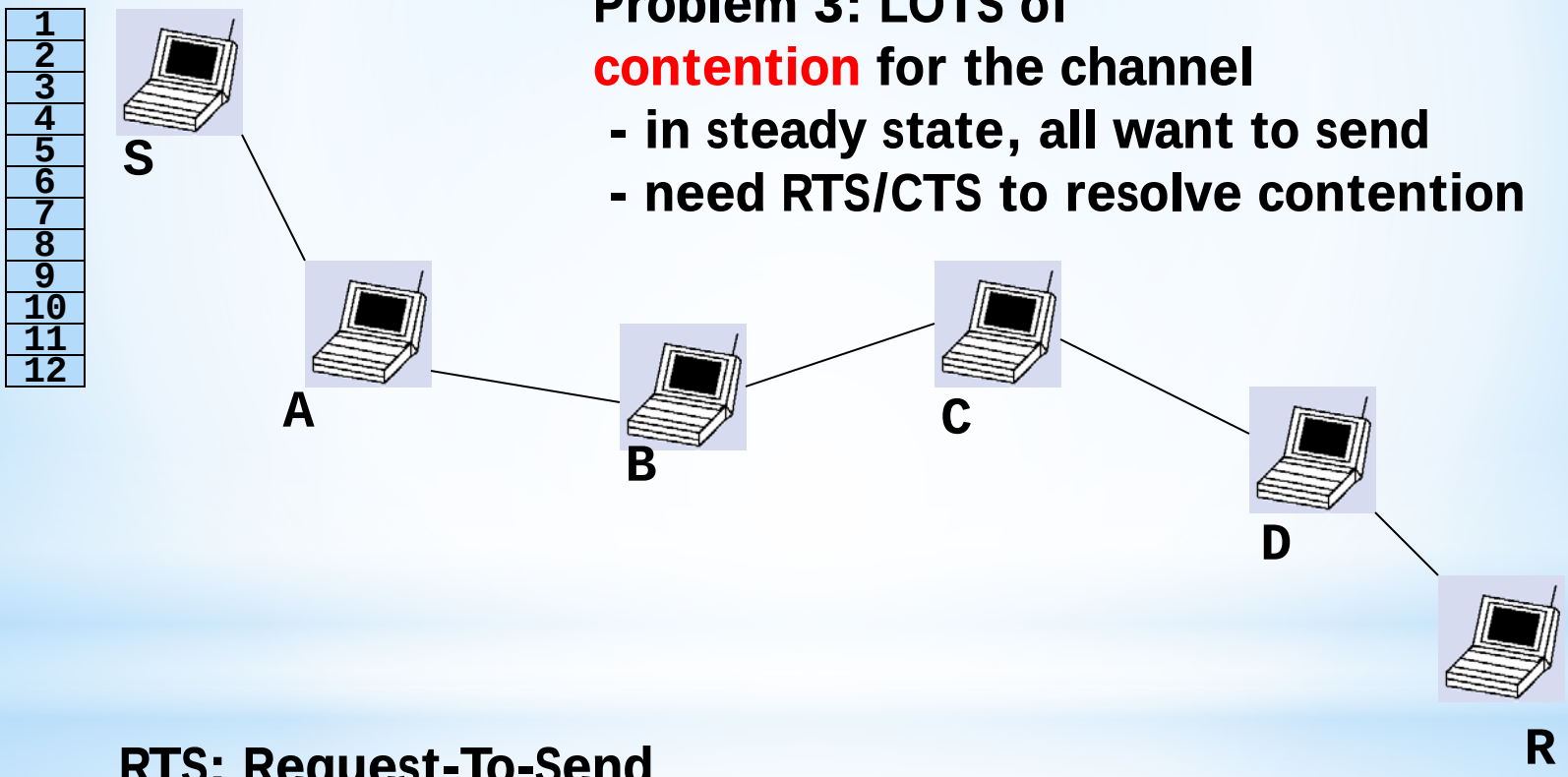
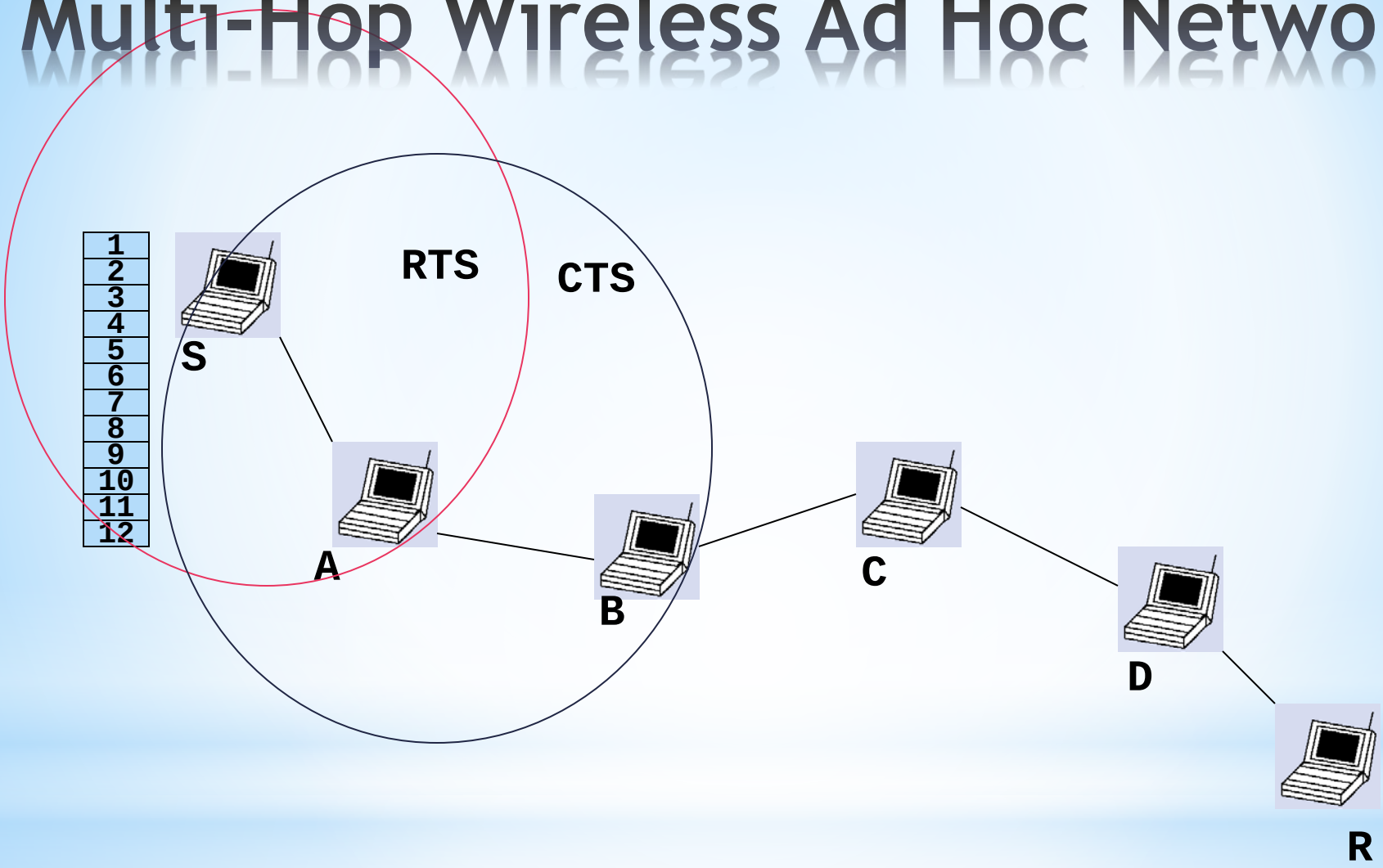


Problem 3: LOTS of contention for the channel
- **in steady state, all want to send**
- **need RTS/CTS to resolve contention**

RTS: Request-To-Send
CTS: Clear-To-Send

Multi-Hop Wireless Ad Hoc Networks



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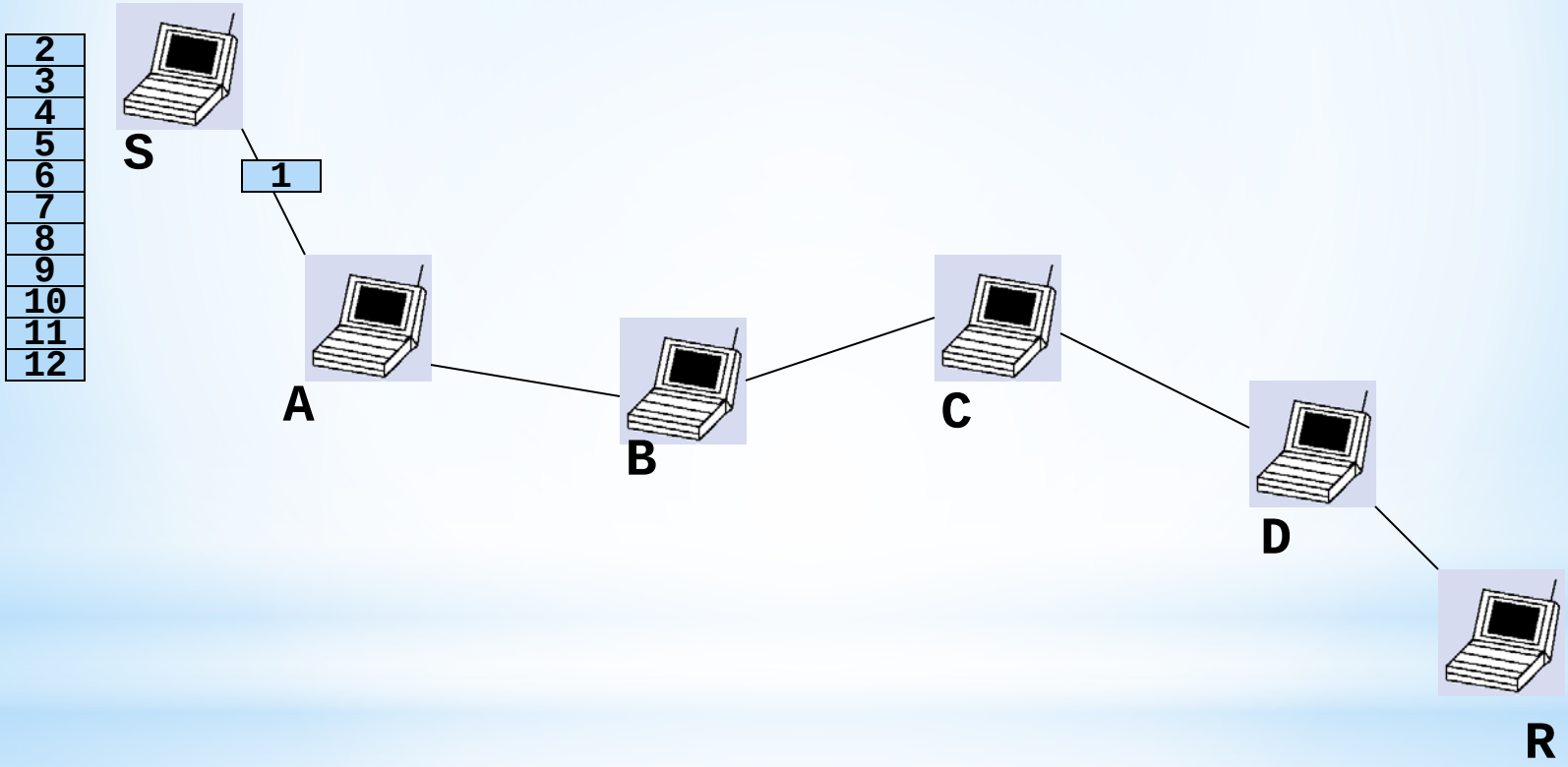

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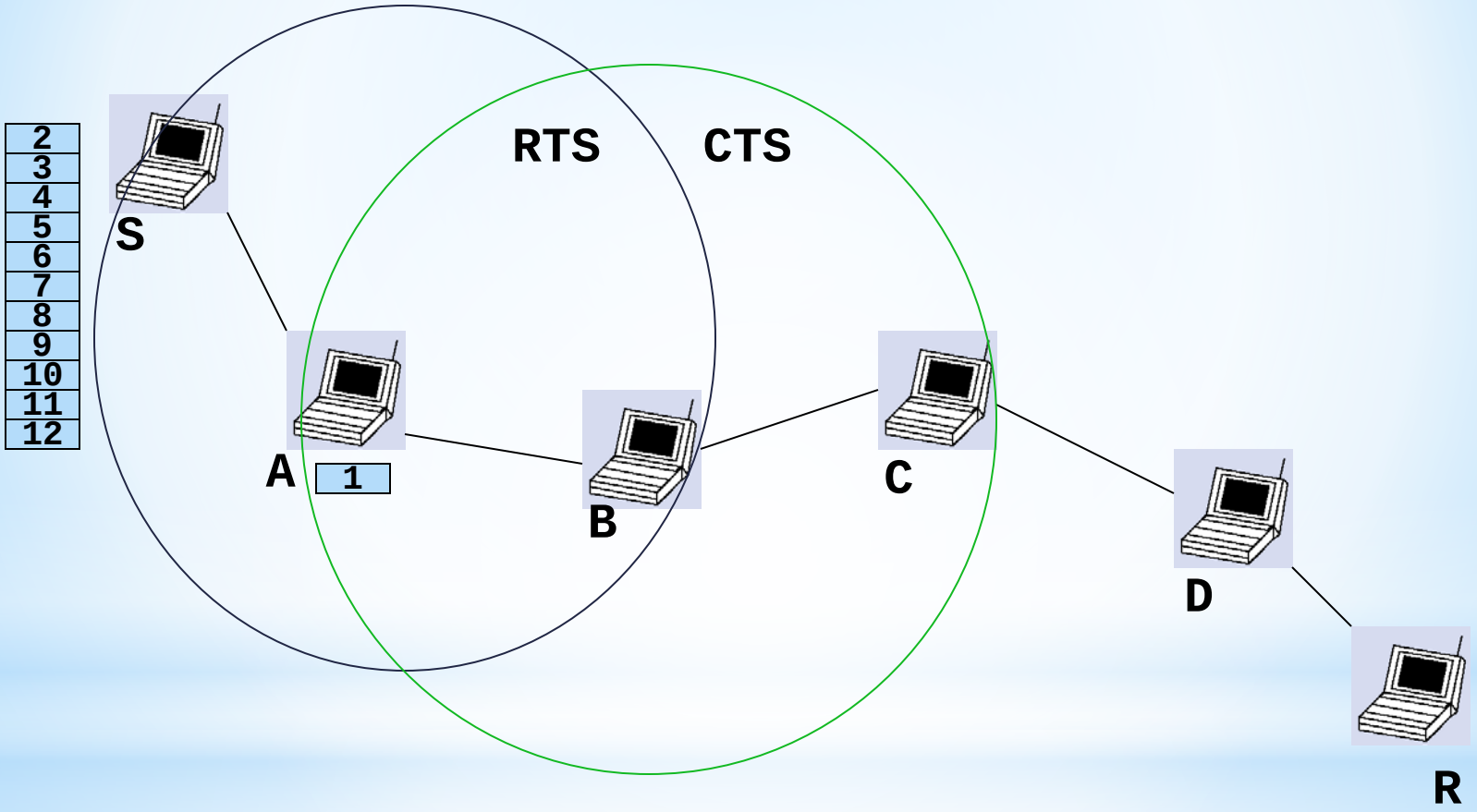

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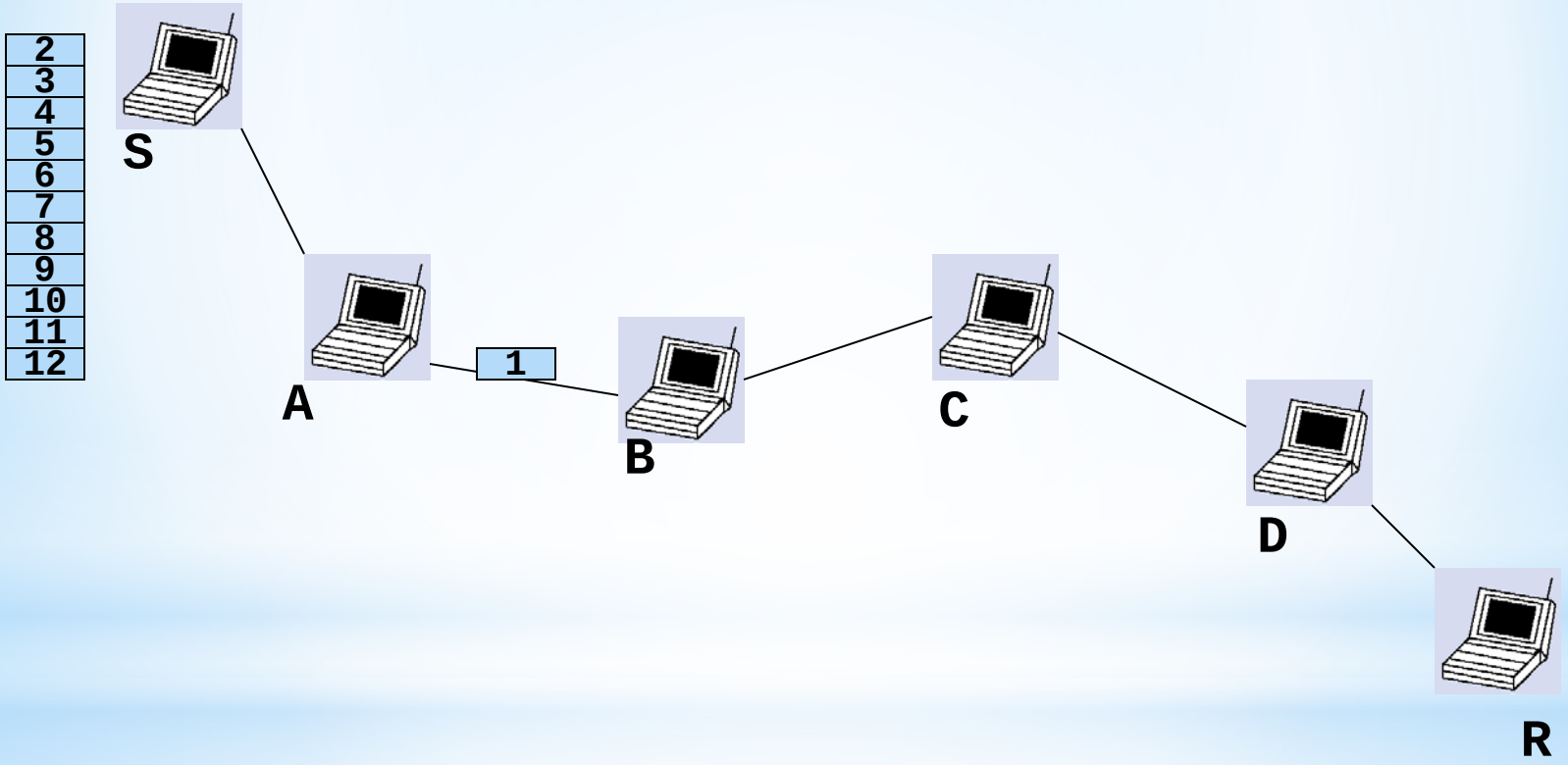

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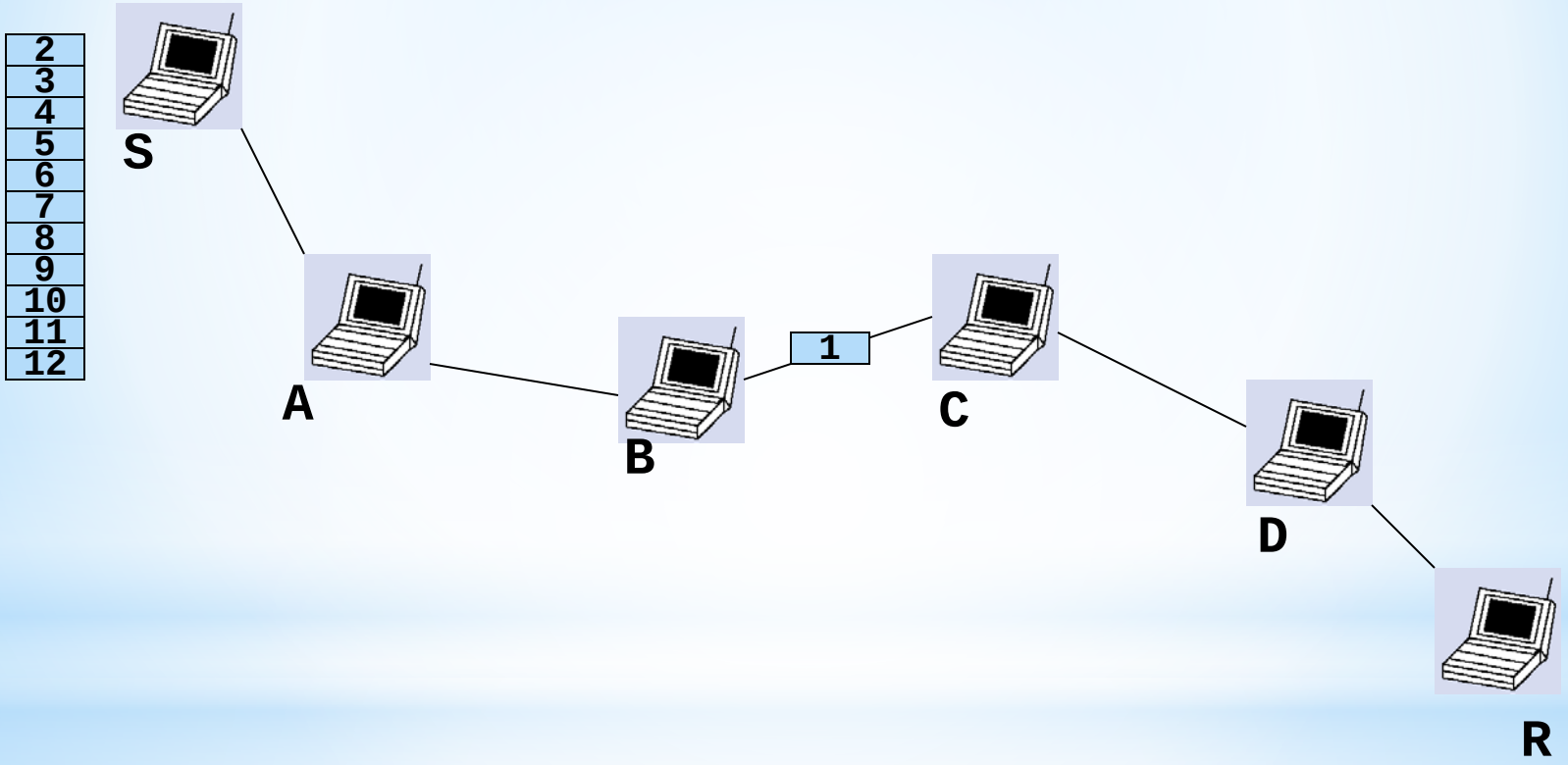

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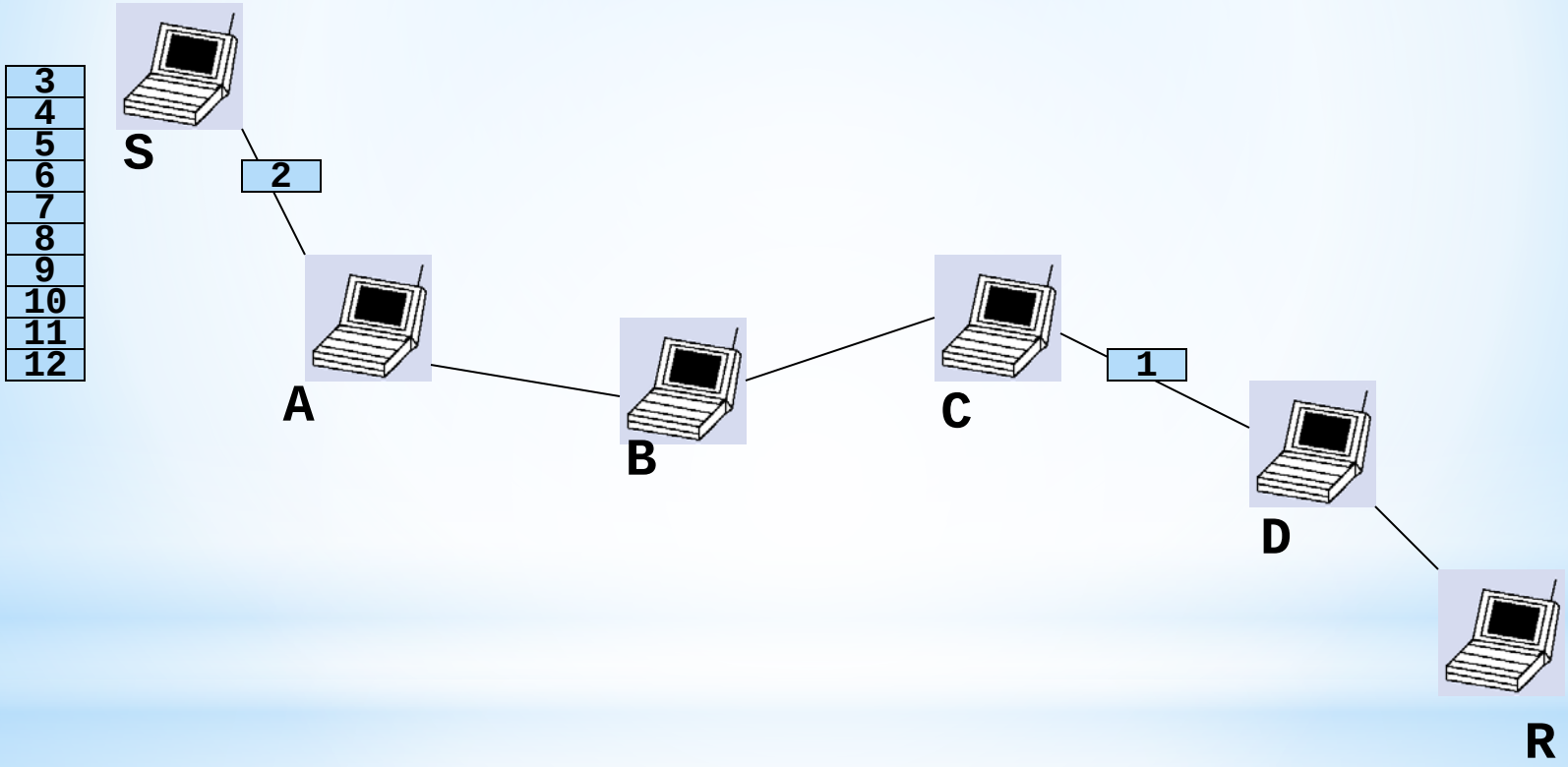

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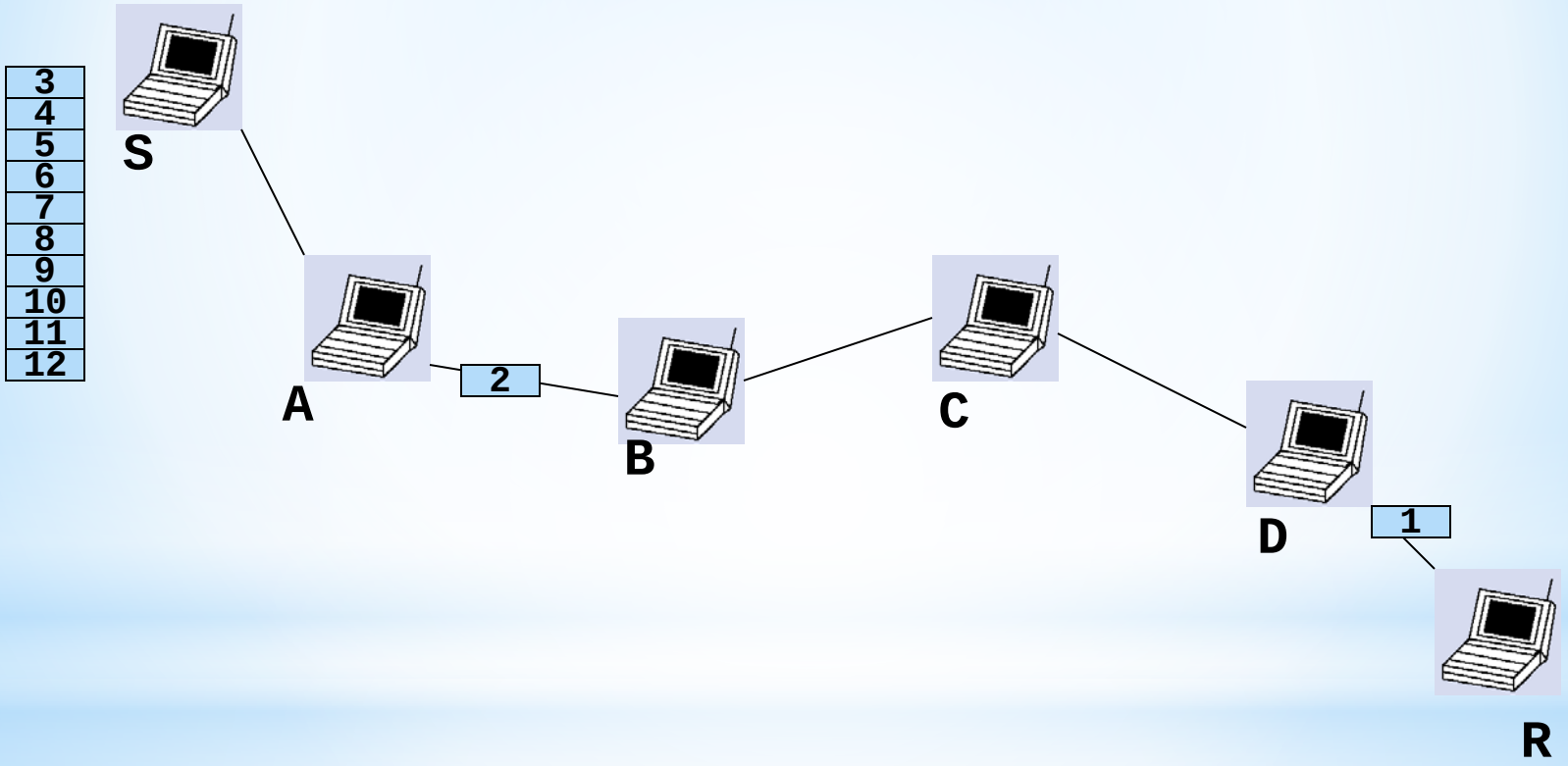

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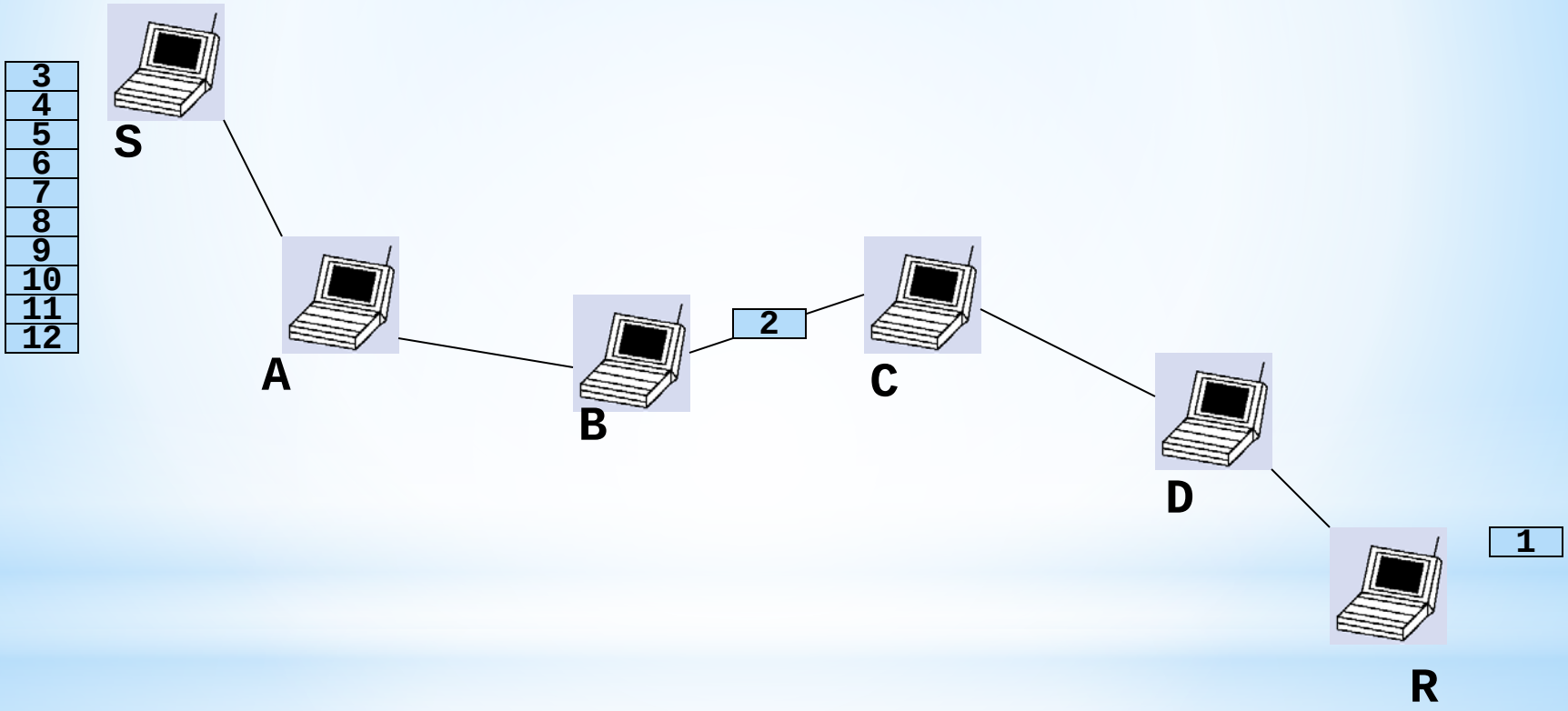

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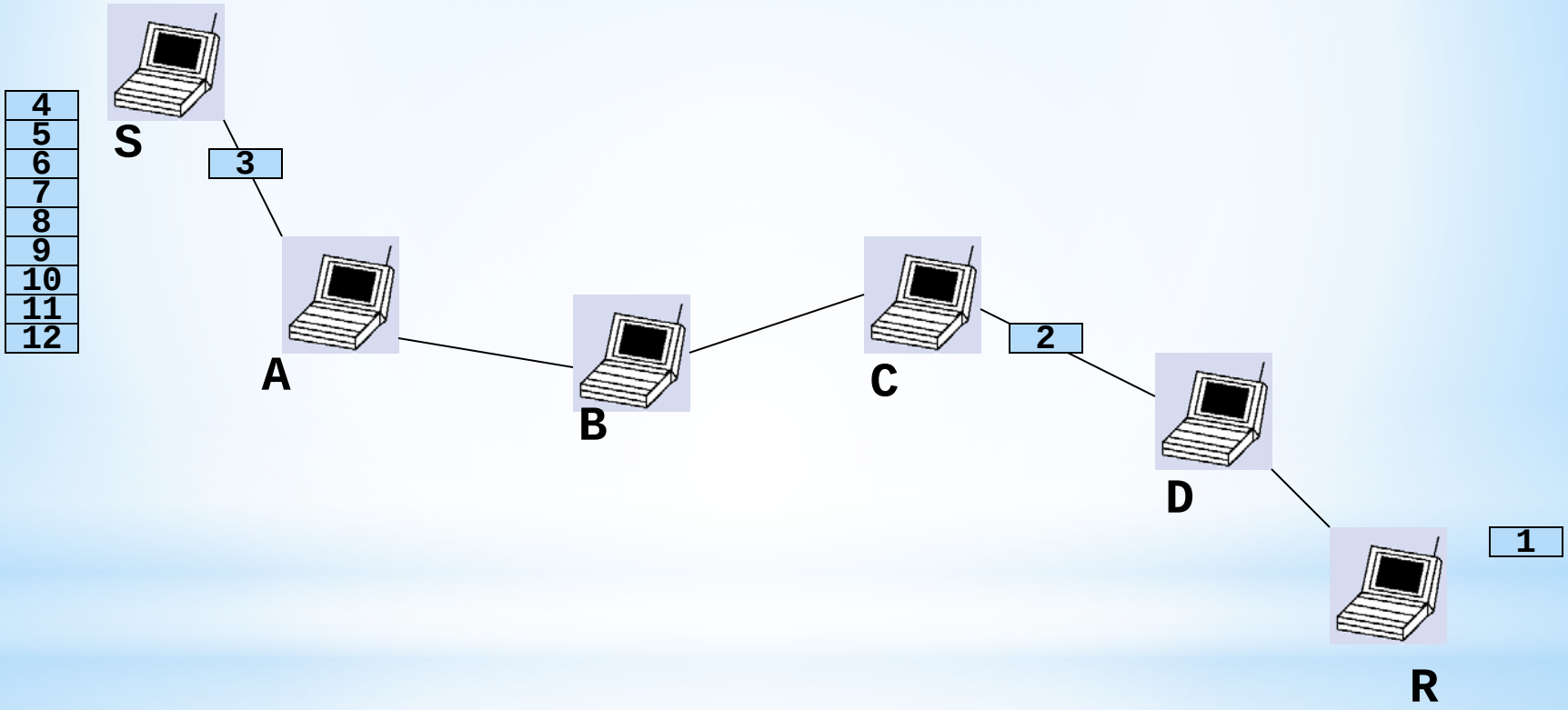

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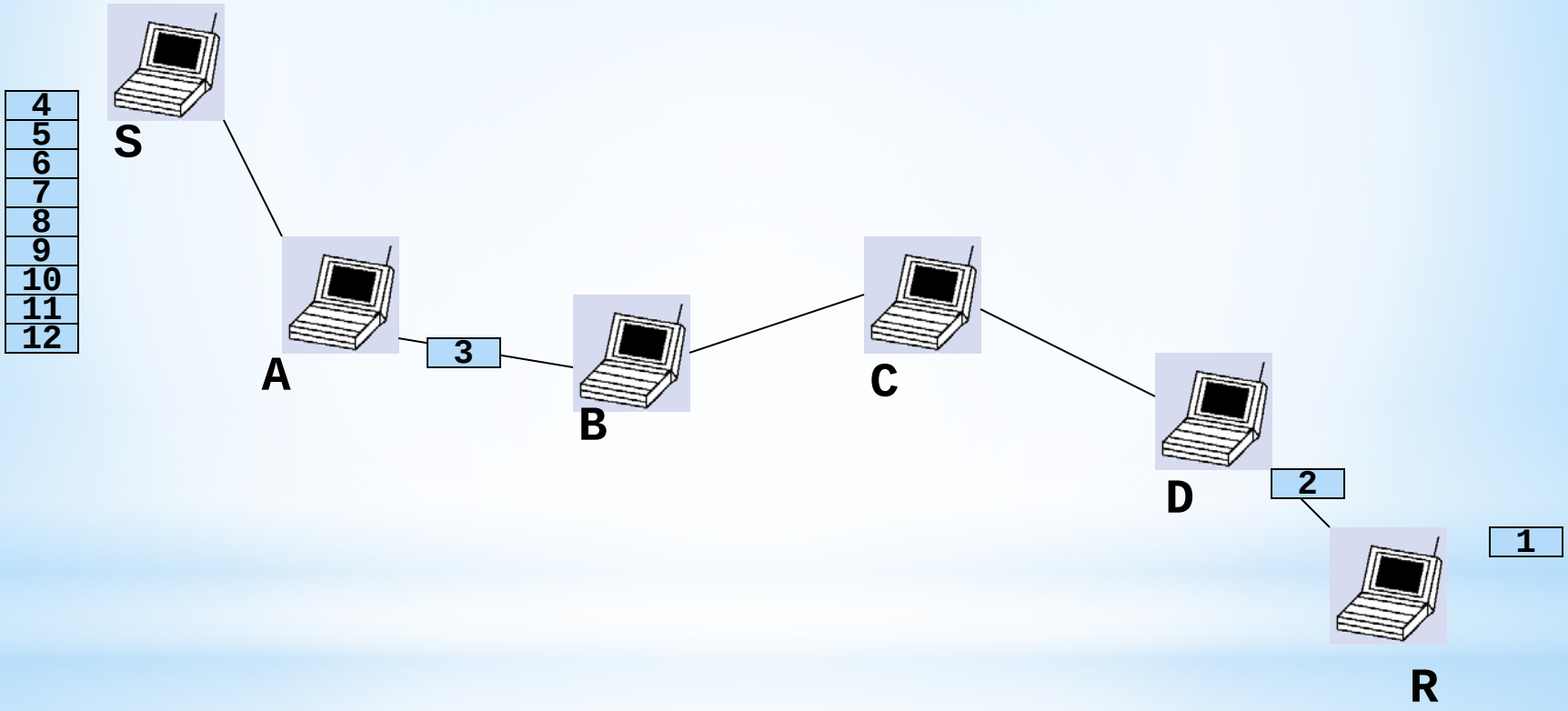

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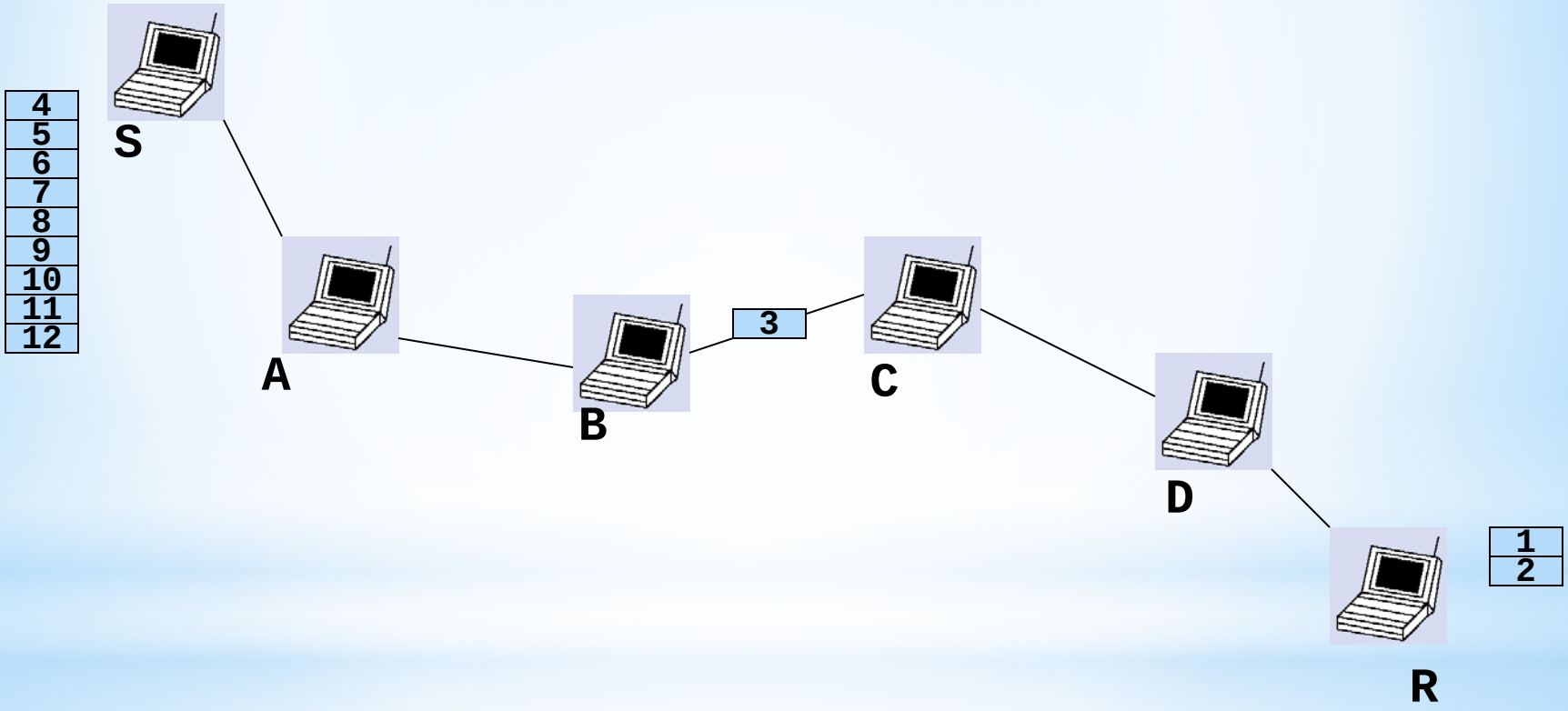

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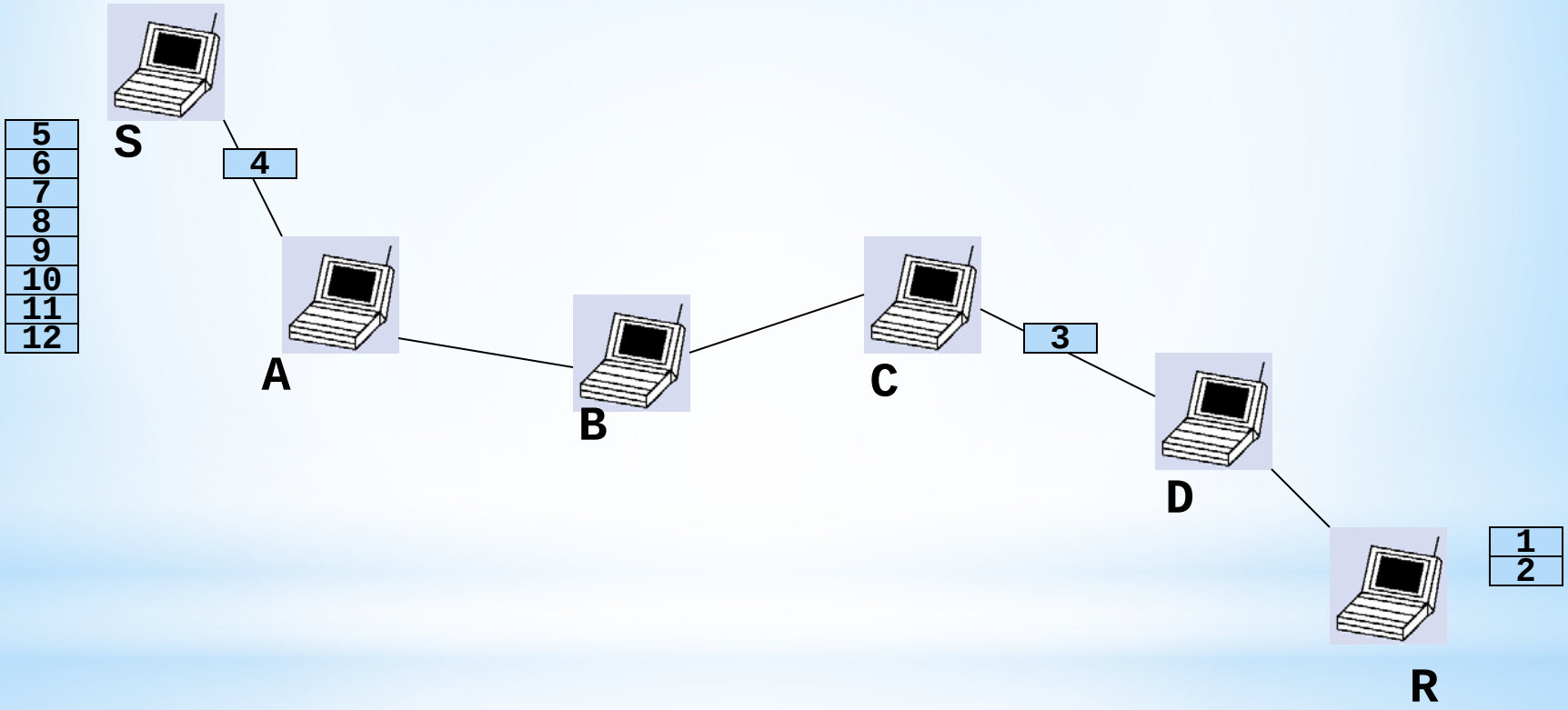

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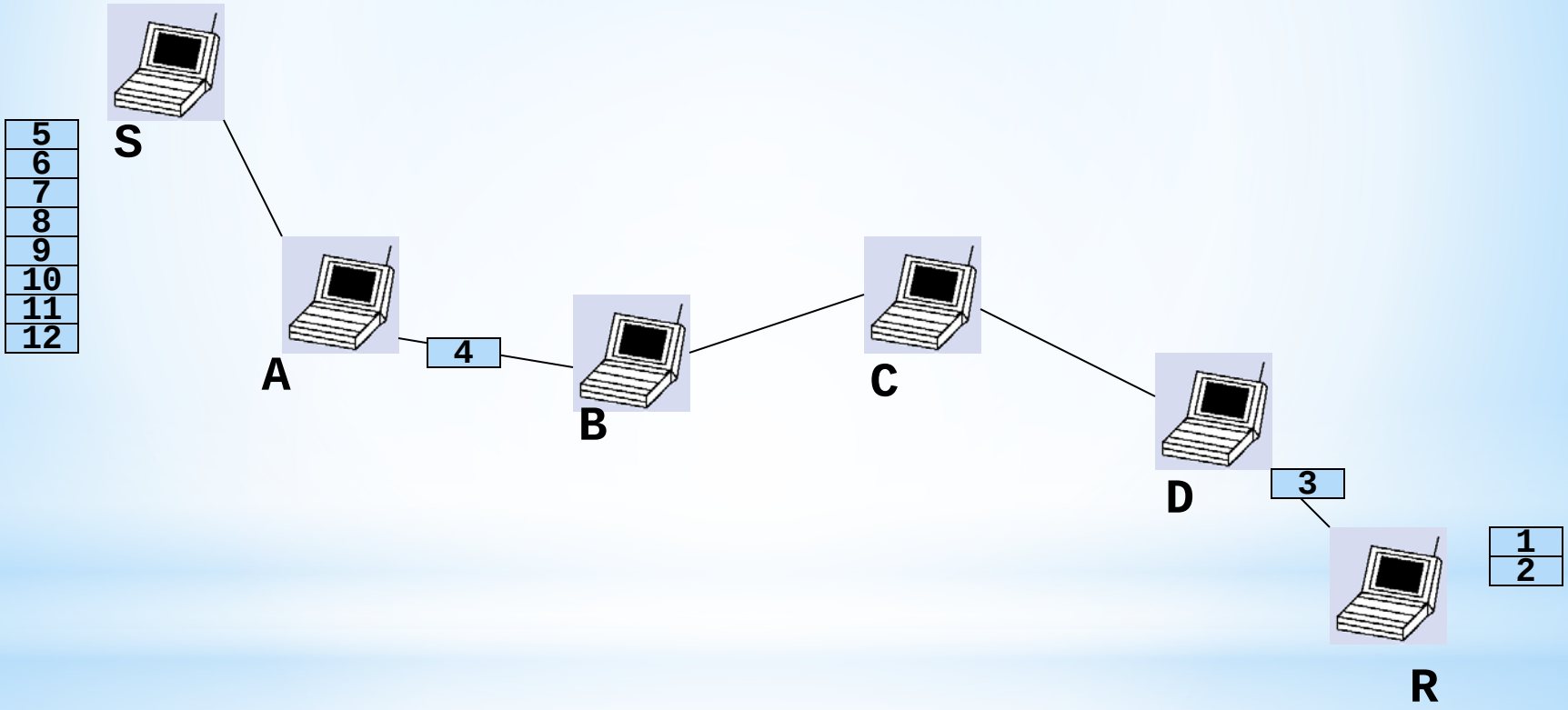

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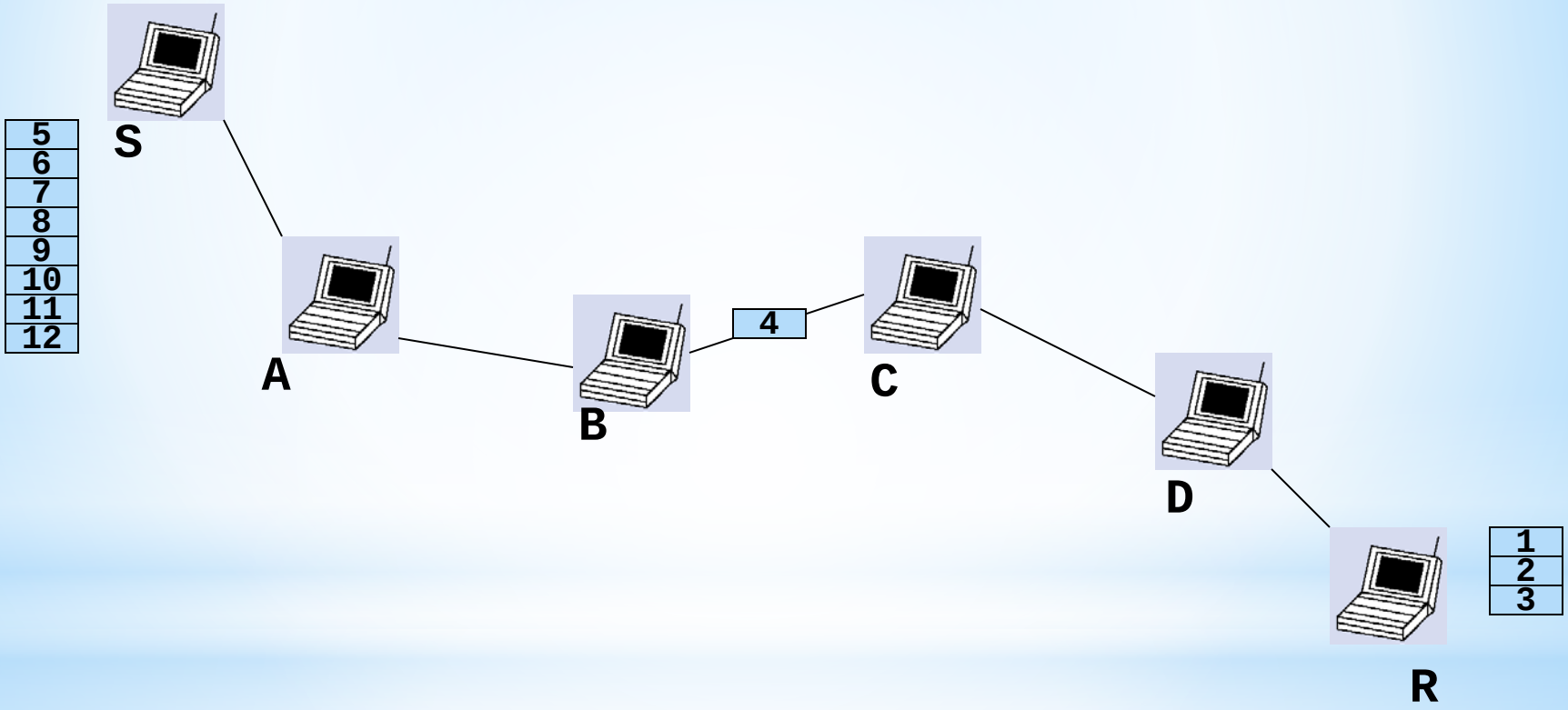

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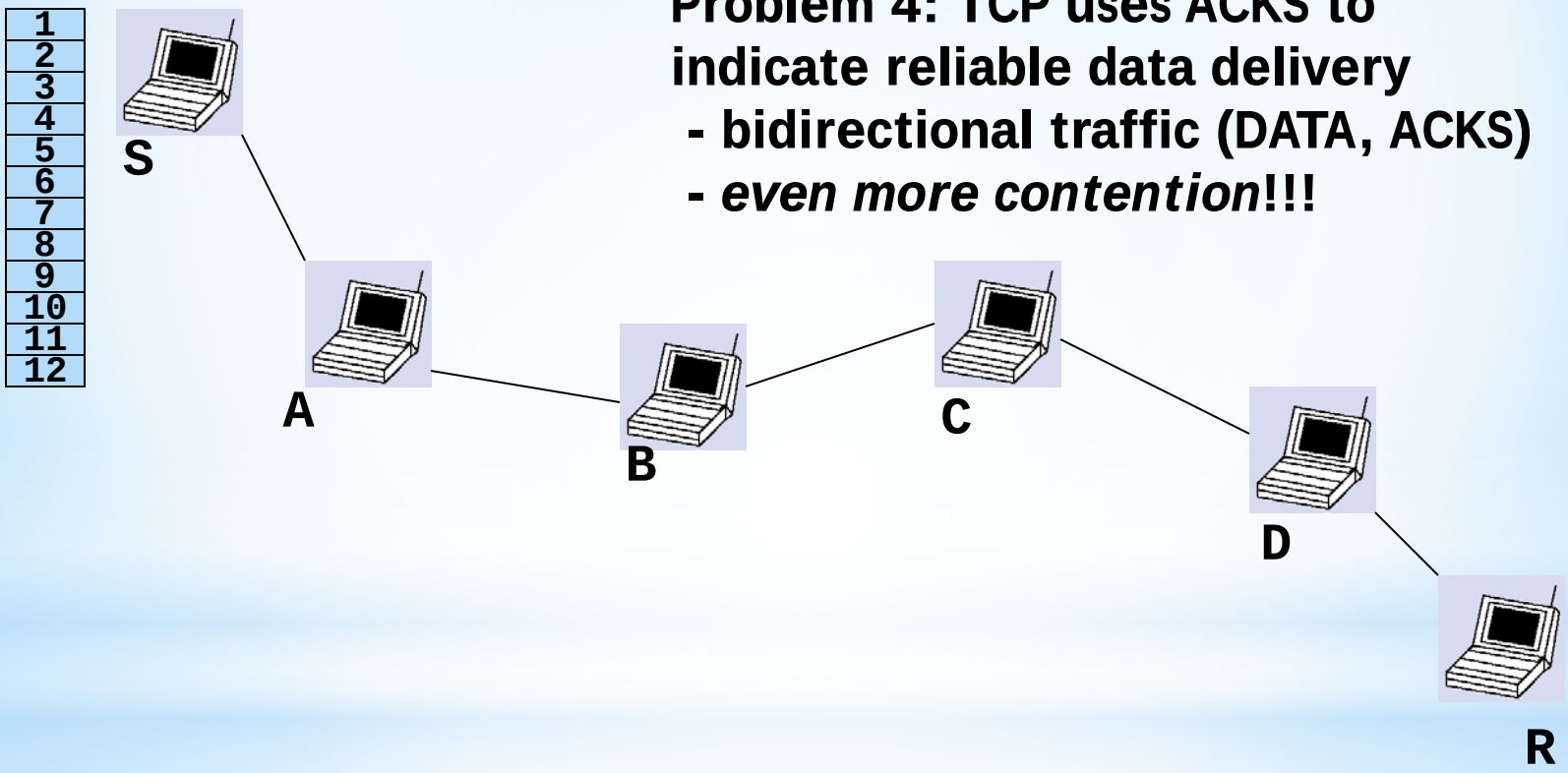
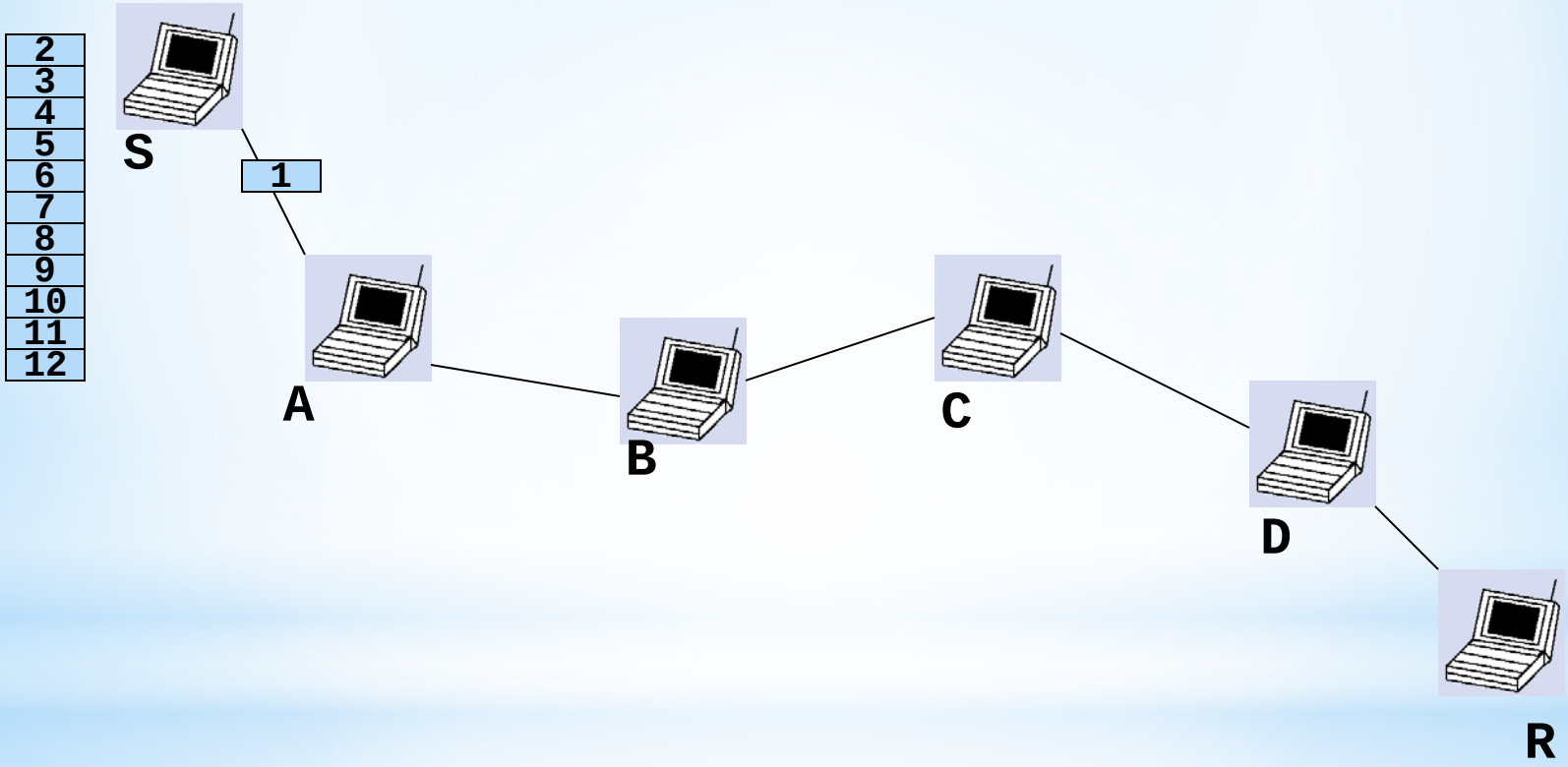


Problem 4: TCP uses ACKS to indicate reliable data delivery

- **bidirectional traffic (DATA, ACKS)**
- ***even more contention*!!!**

Multi-Hop Wireless Ad Hoc Networks



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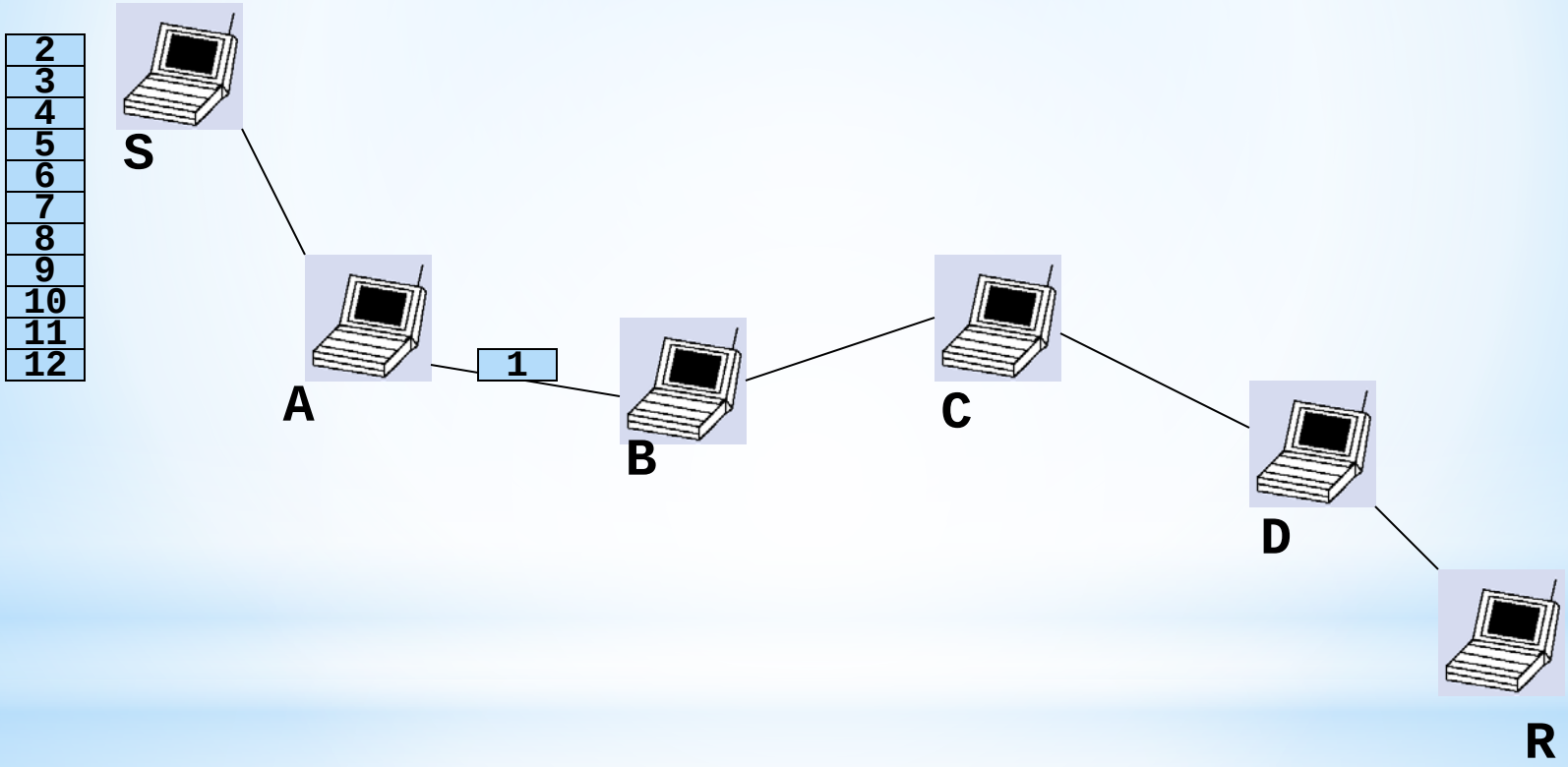

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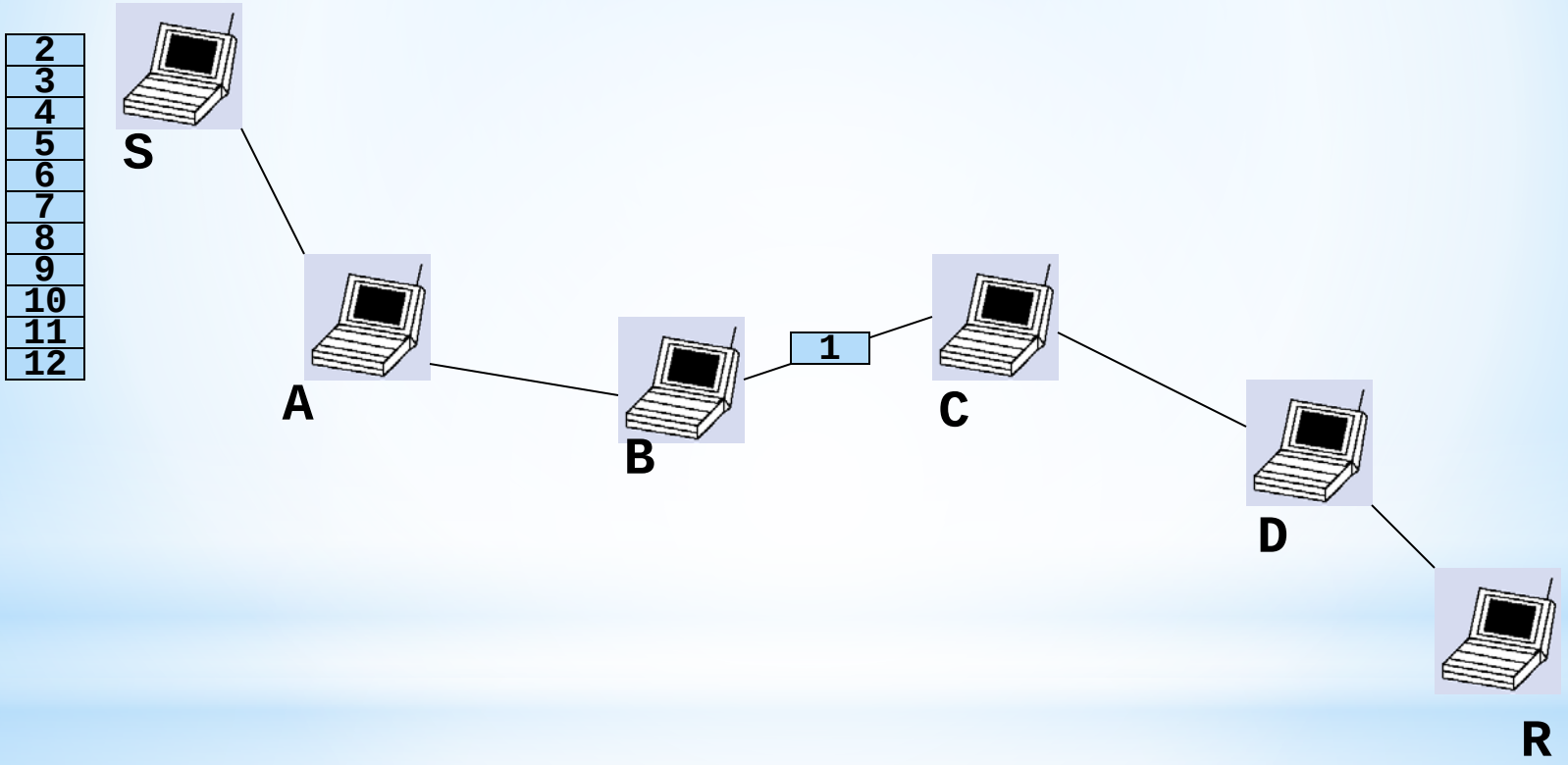

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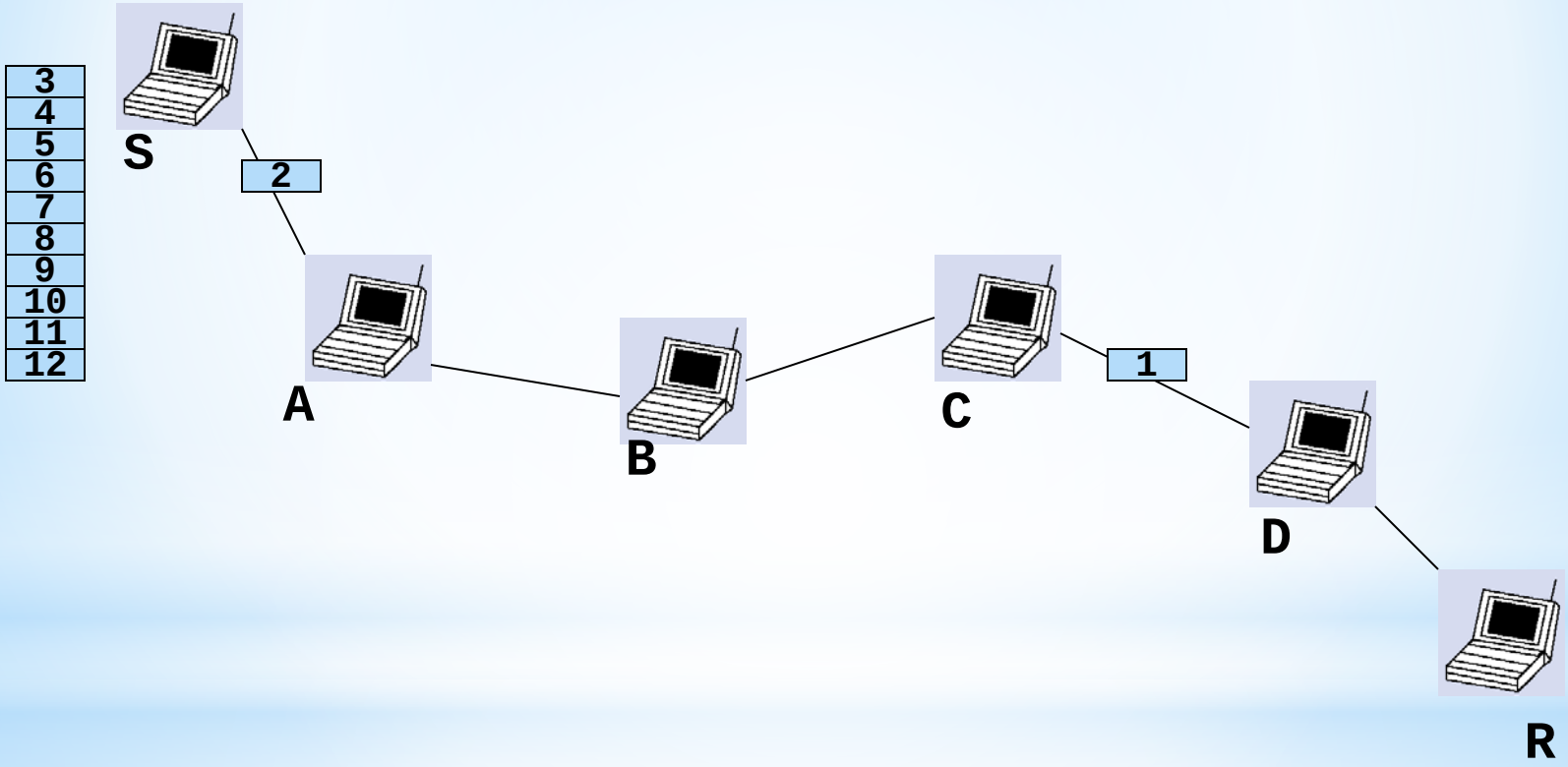

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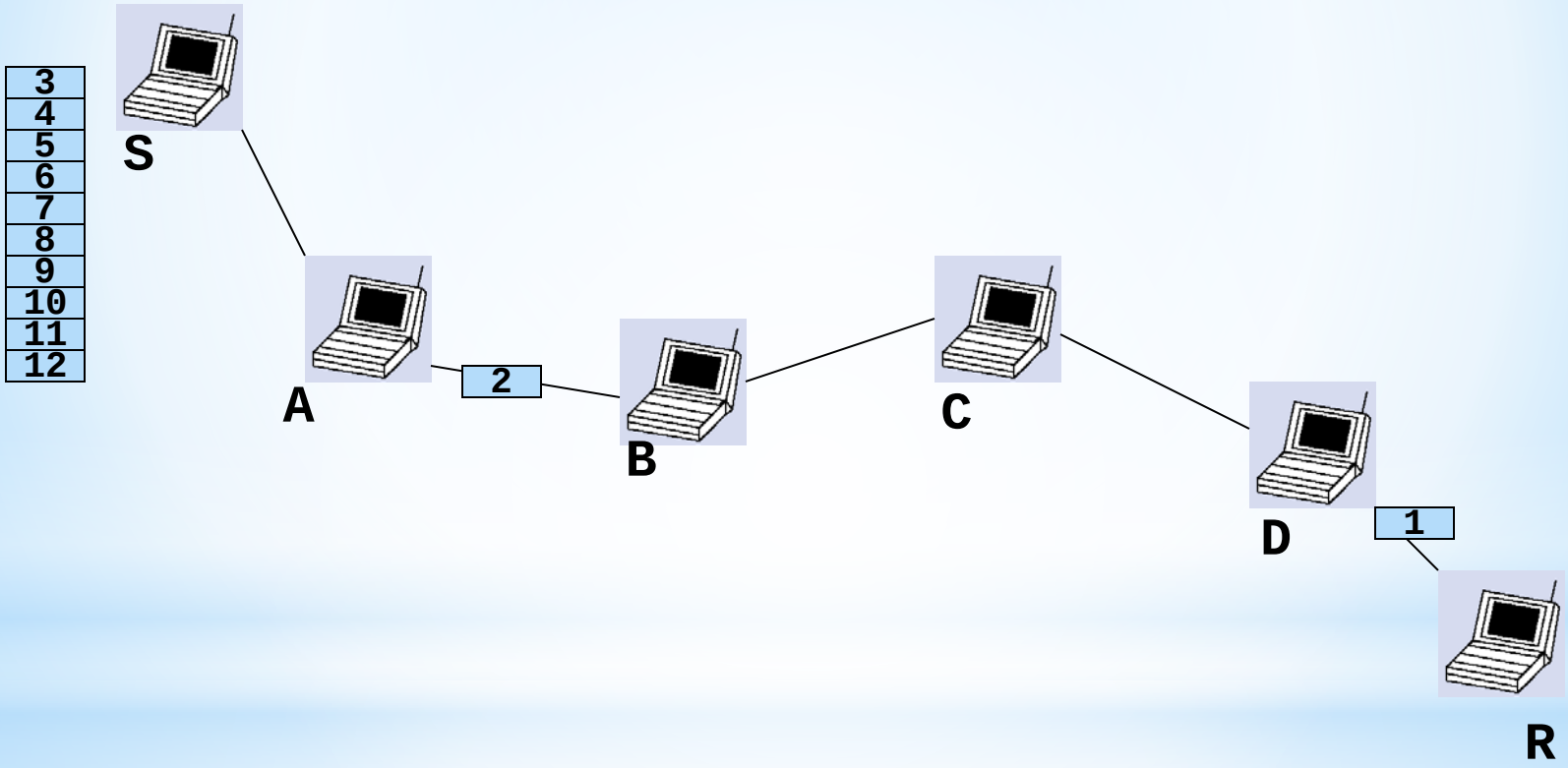

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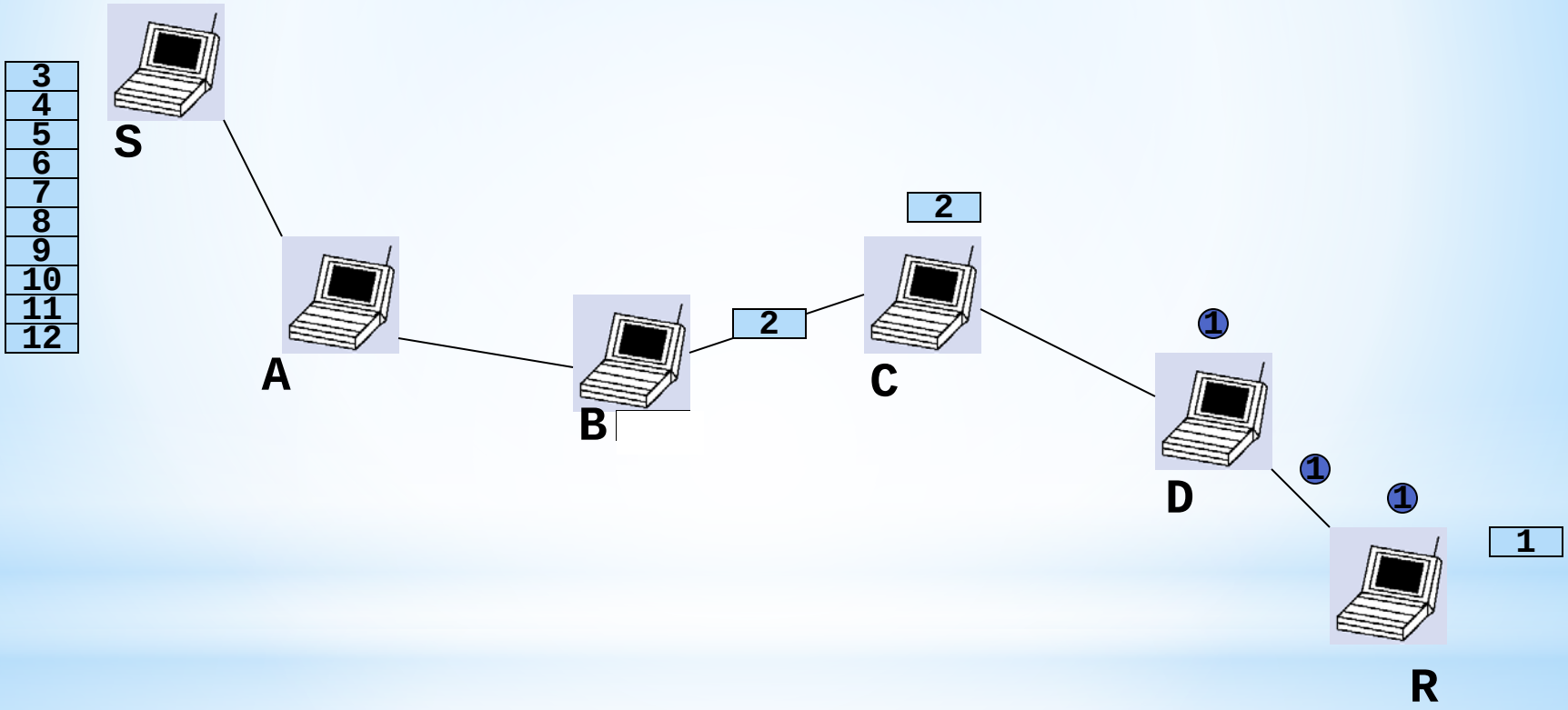

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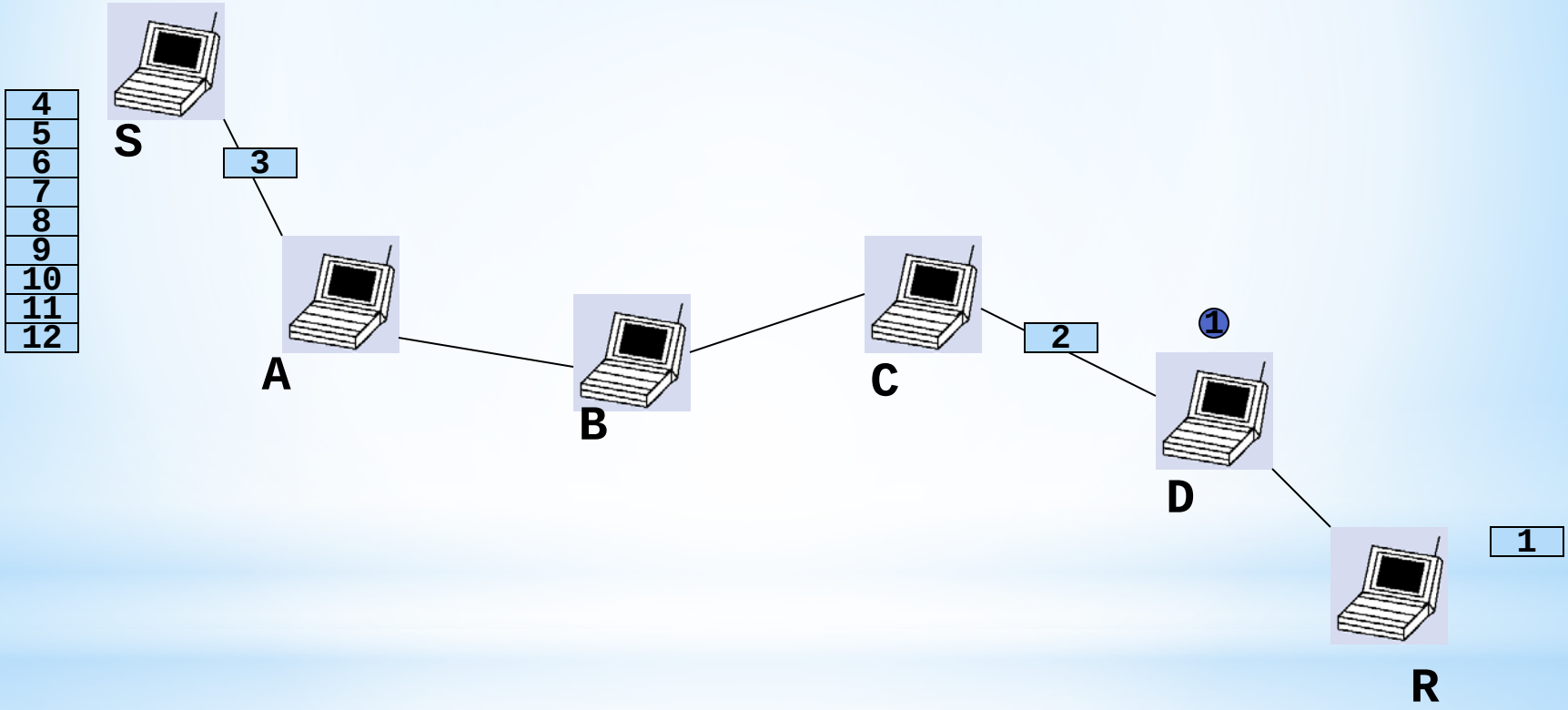

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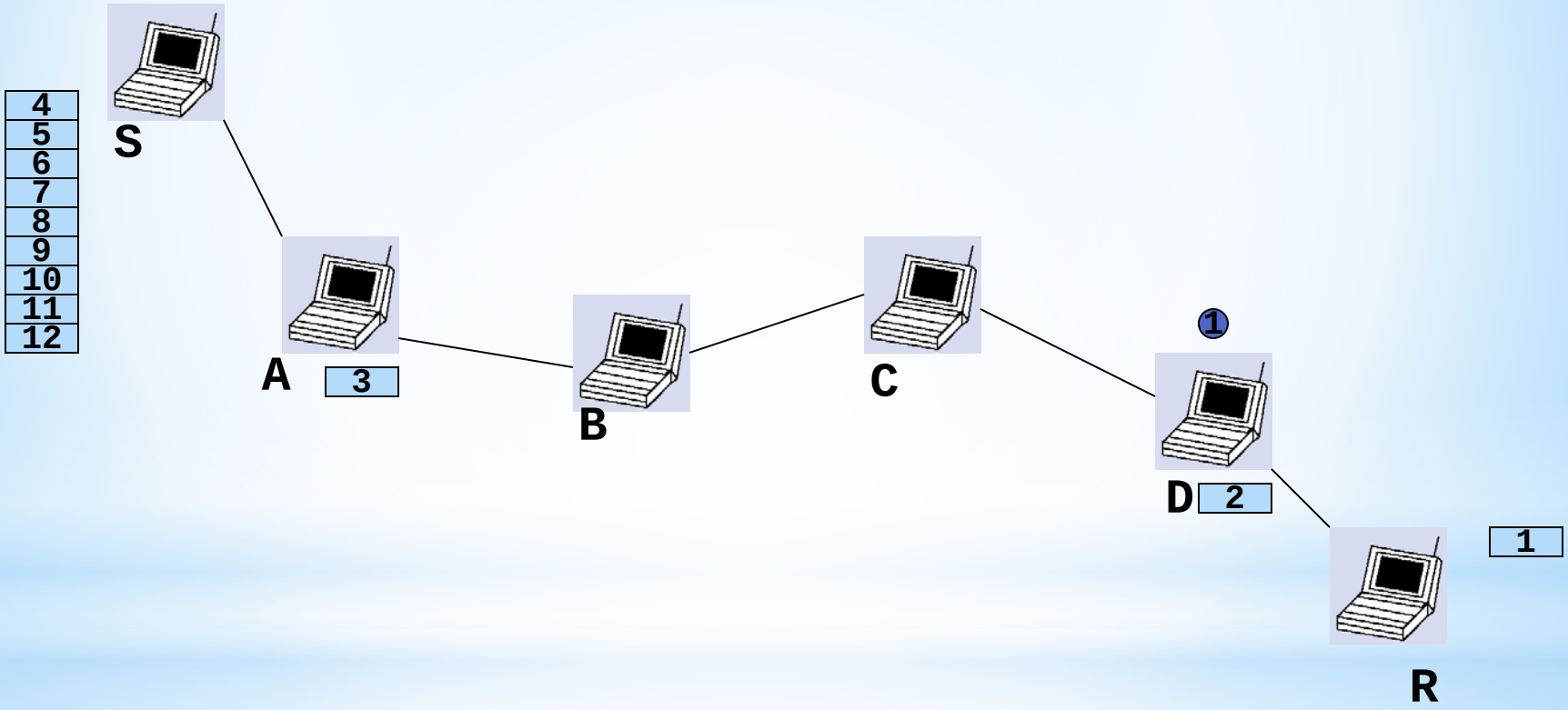

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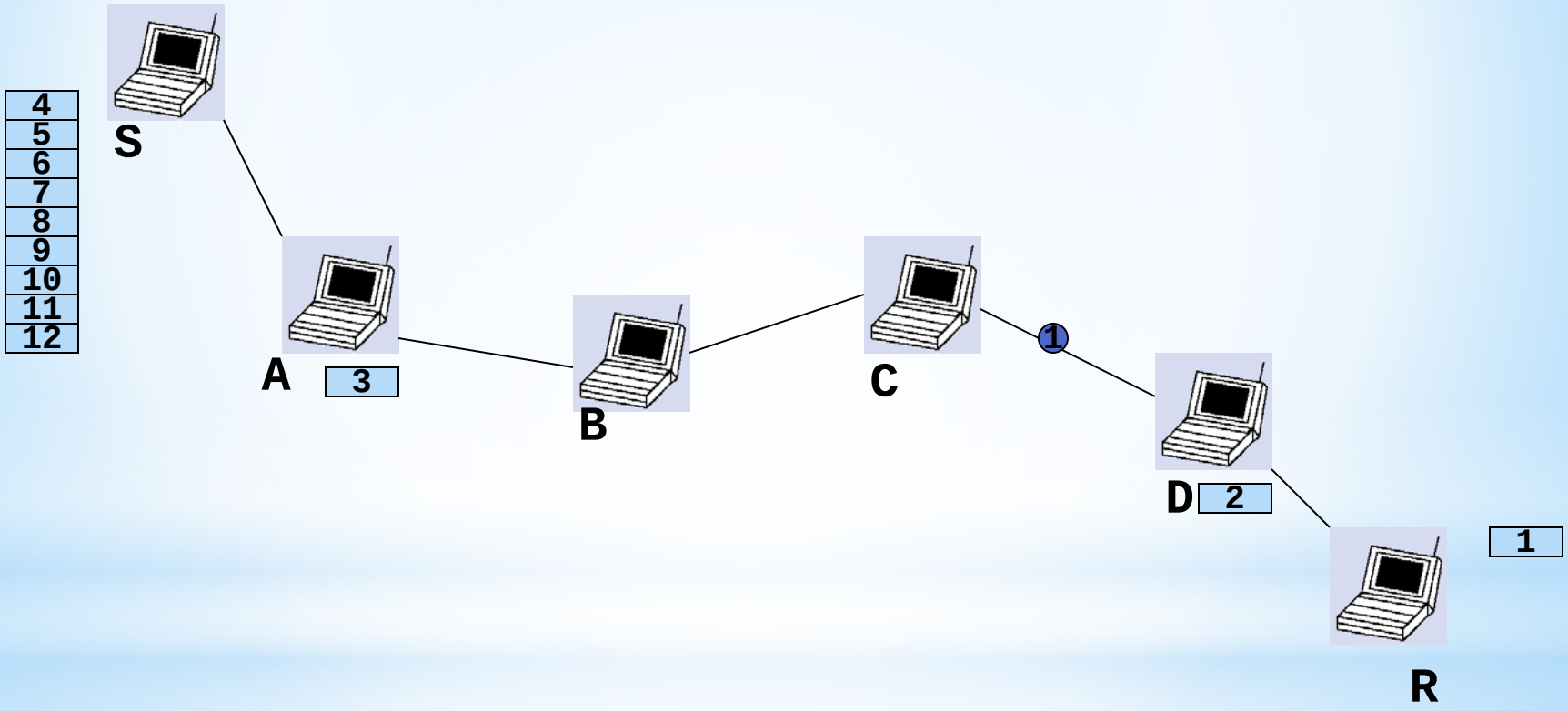

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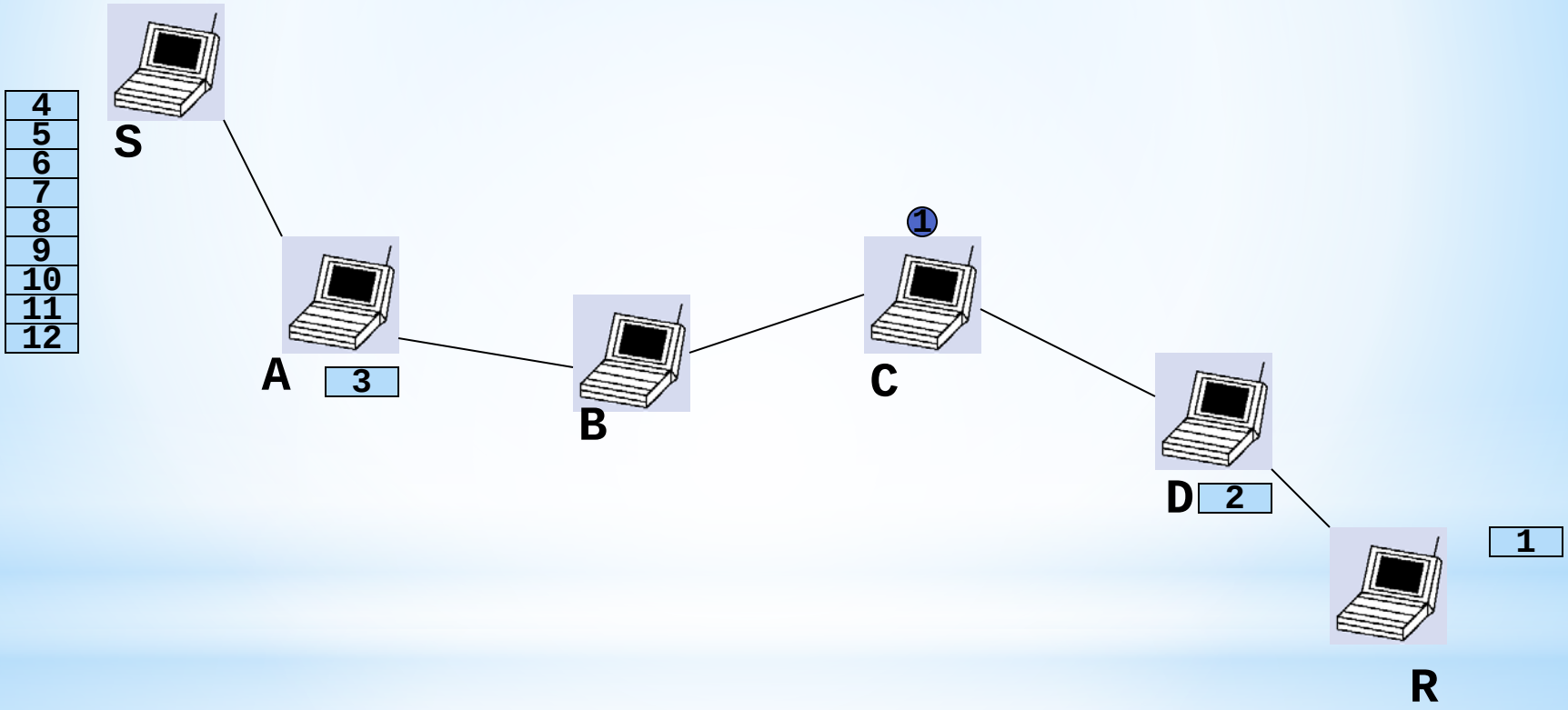

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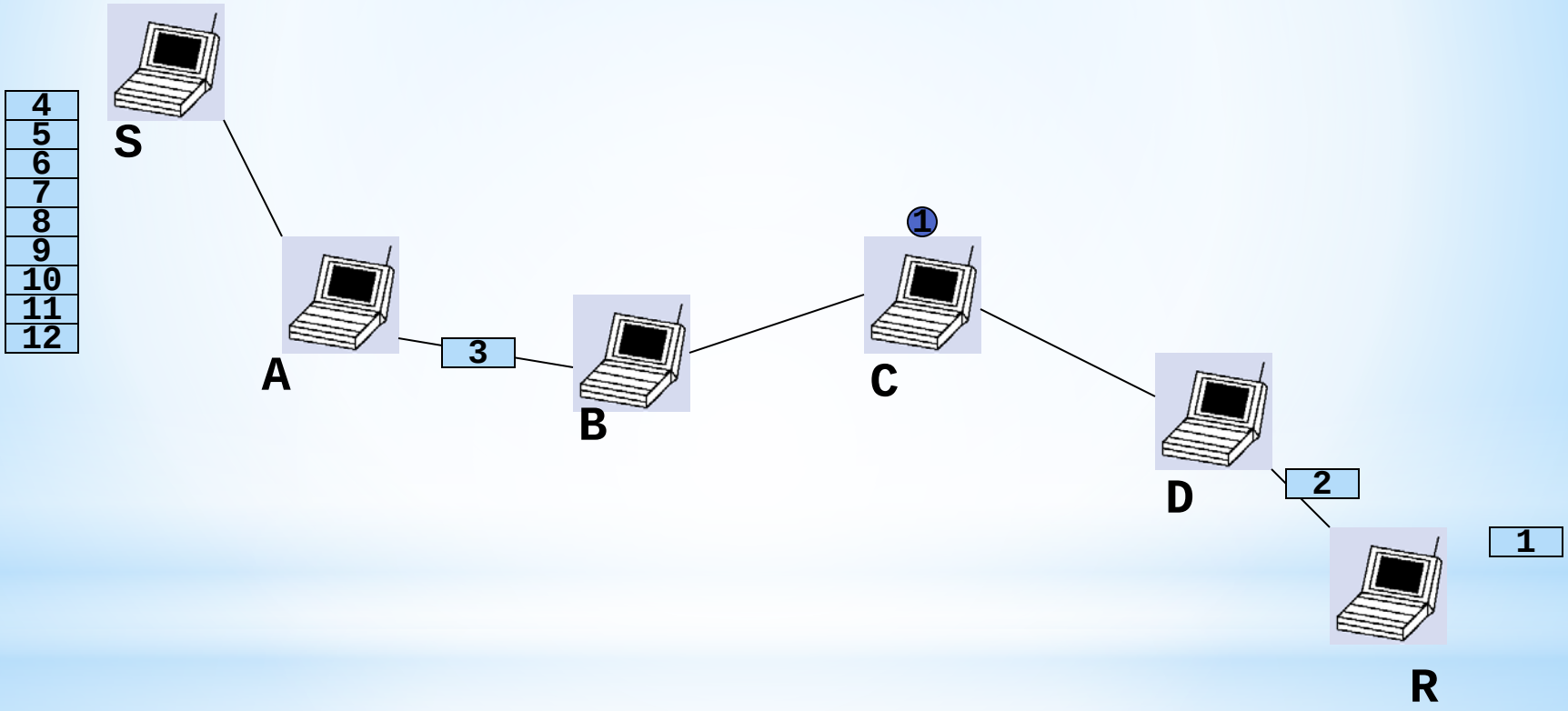

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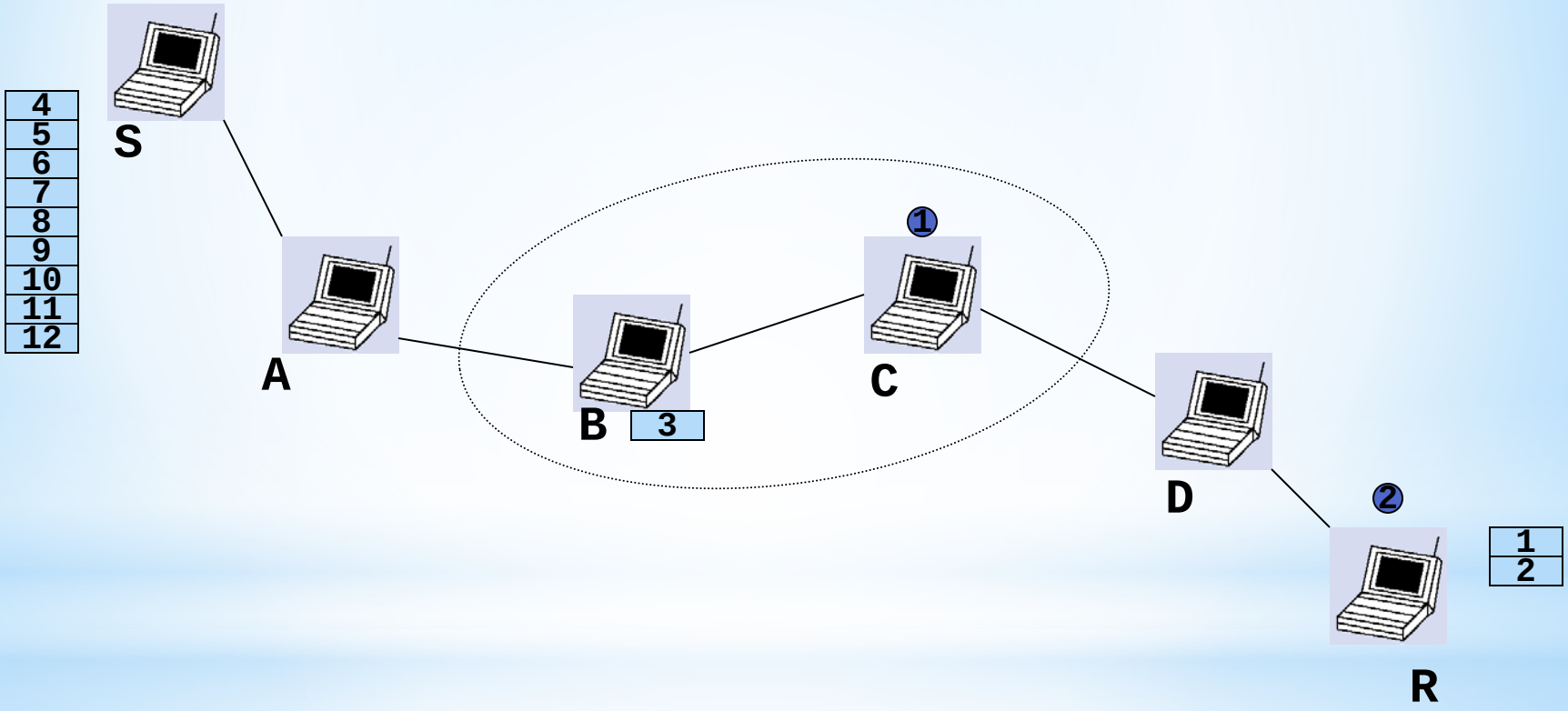

Lesson

- Multi-hop wireless is hard to make efficient
- Store and forward
- Halves the bandwidth for every hop.
- Doubles the latency for every hop.
- Increases Interference.

- Horrible idea for Internet access.
- Even worse for interactive applications (such as video-conferencing).

Summary

- Wireless is a tricky beast
  - Distributed multiple access problem
  - Hidden terminals
  - Exposed terminals
  - Current protocols sufficient, given overprovisioning
- Multihop even more complicated

Questions ?

- Thank you -