15-441: Networking
Virtual Circuits, ATM, MPLS

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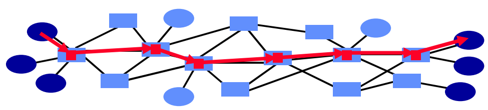
Outline

- Circuit switching refresher
- Virtual Circuits - general
  - » Why virtual circuits?
  - » How virtual circuits? -- tag switching!
- Two modern implementations
  - » ATM - teleco-style virtual circuits
  - » MPLS - IP-style virtual circuits

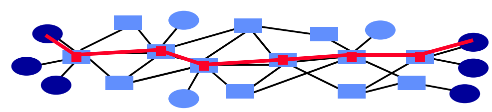
Packet Switching

- Source sends information as self-contained packets that have an address.
  - » Source may have to break up single message in multiple
- Each packet travels independently to the destination host.
  - » Routers and switches use the address in the packet to determine how to forward the packets
- Destination recreates the message.
- Analogy: a letter in surface mail.



Circuit Switching

- Source first establishes a connection (circuit) to the destination.
  - » Each router or switch along the way may reserve some bandwidth for the data flow
- Source sends the data over the circuit.
  - » No need to include the destination address with the data since the routers know the path
- The connection is torn down.
- Example: telephone network.

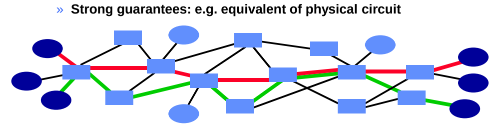


Circuit Switching Discussion

- Traditional circuits: on each hop, the circuit has a dedicated wire or slice of bandwidth.
  - » Physical connection - clearly no need to include addresses with the data
- Advantages, relative to packet switching:
  - » Implies guaranteed bandwidth, predictable performance
  - » Simple switch design: only remembers connection information, no longest-prefix destination address look up
- Disadvantages:
  - » Inefficient for bursty traffic (wastes bandwidth)
  - » Delay associated with establishing a circuit
- Can we get the advantages without (all) the disadvantages?

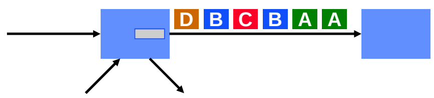
Virtual Circuits

- Each wire carries many “virtual” circuits.
  - » Forwarding based on virtual circuit (VC) identifier
    - – IP header: src, dst, etc.
    - – Virtual circuit header: just “VC”
  - » A path through the network is determined for each VC when the VC is established
  - » Use statistical multiplexing for efficiency
- Can support wide range of quality of service.
  - » No guarantees: best effort service
  - » Weak guarantees: delay < 300 msec, …
  - » Strong guarantees: e.g. equivalent of physical circuit



Packet Switching and Virtual Circuits: Similarities

- "Store and forward" communication based on an address.
  - » Address is either the destination address or a VC identifier
- Must have buffer space to temporarily store packets.
  - » E.g. multiple packets for some destination arrive simultaneously
- Multiplexing on a link is similar to time sharing.
  - » No reservations: multiplexing is statistical, i.e. packets are interleaved without a fixed pattern
  - » Reservations: some flows are guaranteed to get a certain number of "slots"



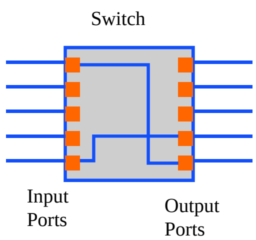
7

Virtual Circuits Versus Packet Switching

- Circuit switching:
  - » Uses short connection identifiers to forward packets
  - » Switches know about the connections so they can more easily implement features such as quality of service
  - » Virtual circuits form basis for traffic engineering: VC identifies long-lived stream of data that can be scheduled
- Packet switching:
  - » Use full destination addresses for forwarding packets
  - » Can send data right away: no need to establish a connection first
  - » Switches are stateless: easier to recover from failures
  - » Adding QoS is hard
  - » Traffic engineering is hard: too many packets!

8

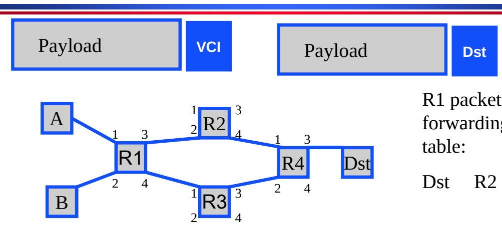
Circuit Switching



Connects (electrons, light, or bits) ports to ports

9

Packet switched vs. VC



R1 packet forwarding table:

Dst R2

Different paths to same destination!

(useful for traffic engineering!)

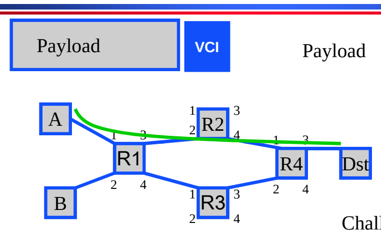
R1 VC table:

VC 1 R2

VC 2 R3

10

Virtual Circuit



Challenges:

- How to set up path?

- How to assign IDs??

R1 VC table:

VC 5 R2

R2 VC table:

VC 5 R4

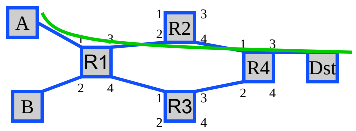
11

Connections and Signaling

- Permanent vs. switched virtual connections (PVCs, SVCs)
  - » static vs. dynamic. PVCs last "a long time"
    - – E.g., connect two bank locations with a PVC
    - – SVCs are more like a phone call
  - » PVCs administratively configured (but not "manually")
  - » SVCs dynamically set up on a "per-call" basis
- Topology
  - » point to point
  - » point to multipoint
  - » multipoint to multipoint
- Challenges: How to configure these things?
  - – What VCI to use?
  - – Setting up the path

12

Virtual Circuit Switching: Label ("tag") Swapping



- Global VC ID allocation -- ICK! Solution: Per-link uniqueness. *Change VCI each hop.*

	Input Port	Input VCI	Output Port	Output VCI
R1:	1	5	3	9
R2:	2	9	4	2
R4:	1	2	3	5

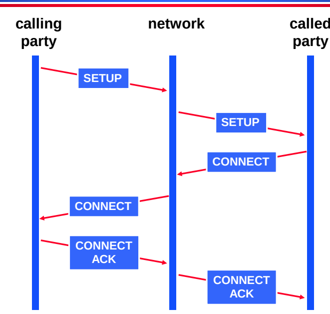
Label ("tag") Swapping

- Result: Signalling protocol must only find per-link unused VCIs.
  - » "Link-local scope"
  - » Connection setup can proceed hop-by-hop.
    - – Good news for our setup protocols!

PVC connection setup

- Manual?
  - » Configure each switch by hand. Ugh.
- Dedicated signalling protocol
  - » E.g., what ATM uses
- Piggyback on routing protocols
  - » Used in MPLS. E.g., use BGP to set up

SVC Connection Setup



Virtual Circuits In Practice

- ATM: Teleco approach
  - » Kitchen sink. Based on voice, support file transfer, video, etc., etc.
  - » Intended as IP replacement. That didn't happen. :)
  - » Today: Underlying network protocol in many teleco networks. E.g., DSL speaks ATM. IP over ATM in some cases.
- MPLS: The "IP Heads" answer to ATM
  - » Stole good ideas from ATM
  - » Integrates well with IP
  - » Today: Used inside some networks to provide VPN support, traffic engineering, simplify core.
- Other nets just run IP.
- Older tech: Frame Relay
  - » Only provided PVCs. Used for quasi-dedicated 56k/T1 links between offices, etc. Slower, less flexible than ATM.

Asynchronous Transfer Mode: ATM

- Connection-oriented, packet-switched
  - » (e.g., virtual circuits).
- Teleco-driven. Goals:
  - » Handle voice, data, multimedia
  - » Support both PVCs and SVCs
  - » Replace IP. (didn't happen...)
- Important feature: Cell switching

Cell Switching

- Small, fixed-size cells
  [Fixed-length data][header]
- Why?
  - Efficiency: All packets the same
    - Easier hardware parallelism, implementation
  - Switching efficiency:
    - Lookups are easy -- table index.
  - Result: Very high cell switching rates.
  - Initial ATM was 155Mbit/s. Ethernet was 10Mbit/s at the same time. (!)
- How do you pick the cell size?

19

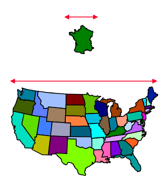
ATM Features

- Fixed size cells (53 bytes).
  - Why 53?
- Virtual circuit technology using hierarchical virtual circuits (VP,VC).
- PHY (physical layer) processing delineates cells by frame structure, cell header error check.
- Support for multiple traffic classes by adaptation layer.
  - E.g. voice channels, data traffic
- Elaborate signaling stack.
  - Backwards compatible with respect to the telephone standards
- Standards defined by ATM Forum.
  - Organization of manufacturers, providers, users

20

Why 53 Bytes?

- Small cells favored by voice applications
  - delays of more than about 10 ms require echo cancellation
  - each payload byte consumes 125 µs (8000 samples/sec)
- Large cells favored by data applications
  - Five bytes of each cell are overhead
- France favored 32 bytes
  - 32 bytes = 4 ms packetization delay.
  - France is 3 ms wide.
  - Wouldn't need echo cancellers!
- USA, Australia favored 64 bytes
  - 64 bytes = 8 ms
  - USA is 16 ms wide
  - Needed echo cancellers anyway, wanted less overhead
- Compromise



21

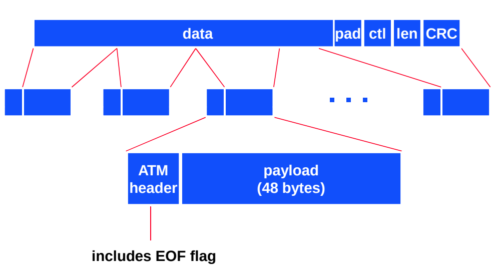
ATM Adaptation Layers

1	2	3	4	5
synchronous		asynchronous		
constant	variable bit rate			
connection-oriented			connectionless	

- AAL 1: audio, uncompressed video
- AAL 2: compressed video
- AAL 3: long term connections
- AAL 4/5: data traffic
  - AAL5 is most relevant to us…

22

AAL5 Adaptation Layer



Pertinent part: Packets are spread across multiple ATM cells. Each packet is delimited by EOF flag in cell.

23

ATM Packet Shredder Effect

- Cell loss results in packet loss.
  - Cell from middle of packet: lost packet
  - EOF cell: lost two packets
  - Just like consequence of IP fragmentation, but VERY small fragments!
- Even low cell loss rate can result in high packet loss rate.
  - E.g. 0.2% cell loss -> 2 % packet loss
  - Disaster for TCP
- Solution: drop remainder of the packet, i.e. until EOF cell.
  - Helps a lot: dropping useless cells reduces bandwidth and lowers the chance of later cell drops
  - Slight violation of layers
  - Discovered after early deployment experience with IP over ATM.

24

ATM Traffic Classes

- Constant Bit Rate (CBR) and Variable Bit Rate (VBR).
  - » Guaranteed traffic classes for different traffic types.
- Unspecified Bit Rate (UBR).
  - » Pure best effort with no help from the network
- Available Bit Rate (ABR).
  - » Best effort, but network provides support for congestion control and fairness
  - » Congestion control is based on explicit congestion notification
    - – Binary or multi-valued feedback
  - » Fairness is based on Max-Min Fair Sharing.

    (small demands are satisfied, unsatisfied demands share equally)

25

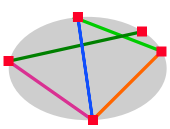
IP over ATM

- When sending IP packets over an ATM network, set up a VC to destination.
  - » ATM network can be end to end, or just a partial path
  - » ATM is just another link layer
- Virtual connections can be cached.
  - » After a packet has been sent, the VC is maintained so that later packets can be forwarded immediately
  - » VCs eventually times out
- Properties.
  - – Overhead of setting up VCs (delay for first packet)
  - – Complexity of managing a pool of VCs
  - \+ Flexible bandwidth management
  - \+ Can use ATM QoS support for individual connections (with appropriate signaling support)

26

IP over ATM Permanent VCs

- Establish a set of “ATM pipes” that defines connectivity between routers.
- Routers simply forward packets through the pipes.
  - » Each statically configured VC looks like a link
- Properties.
  - – Some ATM benefits are lost (per flow QoS)
  - \+ Flexible but static bandwidth management
  - \+ No set up overheads



27

ATM Discussion

- At one point, ATM was viewed as a replacement for IP.
  - » Could carry both traditional telephone traffic (CBR circuits) and other traffic (data, VBR)
  - » Better than IP, since it supports QoS
- Complex technology.
  - » Switching core is fairly simple, but
  - » Support for different traffic classes
  - » Signaling software is very complex
  - » Technology did not match people’s experience with IP
    - – deploying ATM in LAN is complex (e.g. broadcast)
    - – supporting connection-less service model on connection-based technology
  - » With IP over ATM, a lot of functionality is replicated
- Currently used as a datalink layer supporting IP.

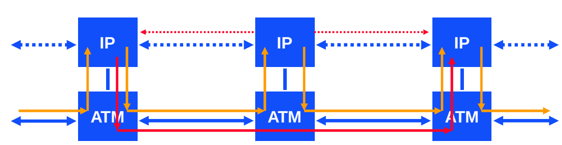
28

IP Switching

- How to use ATM hardware without the software.
  - » ATM switches are very fast data switches
  - » software adds overhead, cost
- The idea is to identify flows at the IP level and to create specific VCs to support these flows.
  - » flows are identified on the fly by monitoring traffic
  - » flow classification can use addresses, protocol types, ...
  - » can distinguish based on destination, protocol, QoS
- Once established, data belonging to the flow bypasses level 3 routing.
  - » never leaves the ATM switch
- Interoperates fine with “regular” IP routers.
  - » detects and collaborates with neighboring IP switches

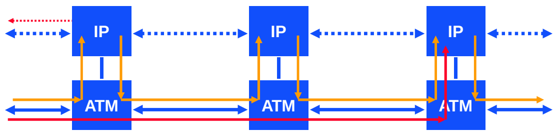
29

IP Switching Example



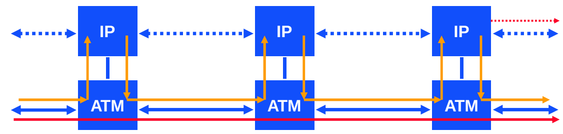
30

IP Switching Example



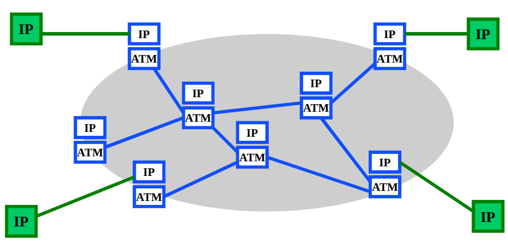
31

IP Switching Example



32

Another View



33

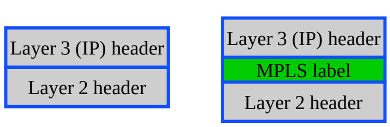
IP Switching Discussion

- IP switching selectively optimizes the forwarding of specific flows.
  - » Offloads work from the IP router, so for a given size router, a less powerful forwarding engine can be used
  - » Can fall back on traditional IP forwarding if there are failures
- IP switching couples a router with an ATM switching using the GSMP protocol.
  - » General Switch Management Protocol
- IP switching can be used for flows with different granularity.
  - » Flows belonging to an application .. Organization
  - » Controlled by the classifier

34

Multi Protocol Label Switching - MPLS

- Selective combination of VCs + IP
  - » Today: MPLS useful for traffic engineering, reducing core complexity, and VPNs
- Core idea: Layer 2 carries VC label
  - » Could be ATM (which has its own tag)
  - » Could be a “shim” on top of Ethernet/etc.:
  - » Existing routers could act as MPLS switches just by examining that shim -- no radical re-design. Gets flexibility benefits, though not cell switching advantages



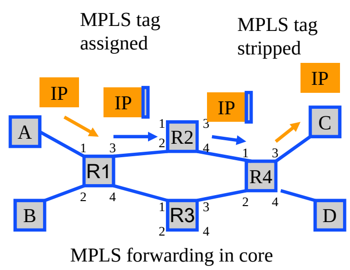
35

MPLS + IP

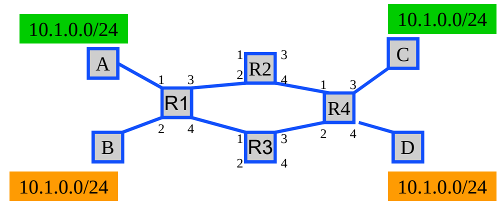
- Map packet onto Forward Equivalence Class (FEC)
  - » Simple case: longest prefix match of destination address
  - » More complex if QoS of policy routing is used
- In MPLS, a label is associated with the packet when it enters the network and forwarding is based on the label in the network core.
  - » Label is swapped (as ATM VCIs)
- Potential advantages.
  - » Packet forwarding can be faster
  - » Routing can be based on ingress router and port
  - » Can use more complex routing decisions
  - » Can force packets to followed a pinned route

36

MPLS core, IP interface

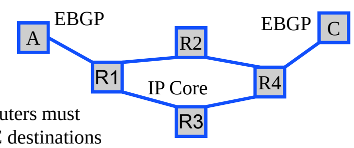


MPLS use case #1: VPNs



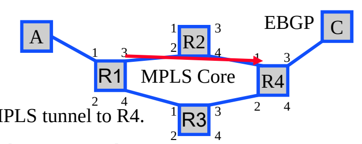
MPLS tags can differentiate green VPN from orange VPN.

MPLS use case #2: Reduced State Core



A-> C pkt

Internal routers must know all C destinations



R1 uses MPLS tunnel to R4.

R1 and R4 know routes, but R2 and R3 don't.

MPLS use case #3: Traffic Engineering

- **As discussed earlier -- can pick routes based upon more than just destination**
- **Used in practice by many ISPs, though certainly not all.**

MPLS Mechanisms

- **MPLS packet forwarding: implementation of the label is technology specific.**
  - » Could be ATM VCI or a short extra "MPLS" header
- **Supports stacked labels.**
  - » Operations can be "swap" (normal label swapping), "push" and "pop" labels.
    - – VERY flexible! Like creating tunnels, but much simpler -- only adds a small label.

Label	CoS	S	TTL
20	3	1	8

MPLS Discussion

- **Original motivation.**
  - » Fast packet forwarding:
    - – Use of ATM hardware
    - – Avoid complex "longest prefix" route lookup
    - – Limitations of routing table sizes
  - » Quality of service
- **Currently mostly used for traffic engineering and network management.**
  - » LSPs can be thought of as "programmable links" that can be set up under software control
  - » on top of a simple, static hardware infrastructure

Take Home Points

- Costs/benefits/goals of virtual circuits
- Cell switching (ATM)
  - » Fixed-size pkts: Fast hardware
  - » Packet size picked for low voice jitter. Understand trade-offs.
  - » Beware packet shredder effect (drop entire pkt)
- Tag/label swapping
  - » Basis for most VCs.
  - » Makes label assignment link-local. Understand mechanism.
- MPLS - IP meets virtual circuits
  - » MPLS tunnels used for VPNs, traffic engineering, reduced core routing table sizes

43