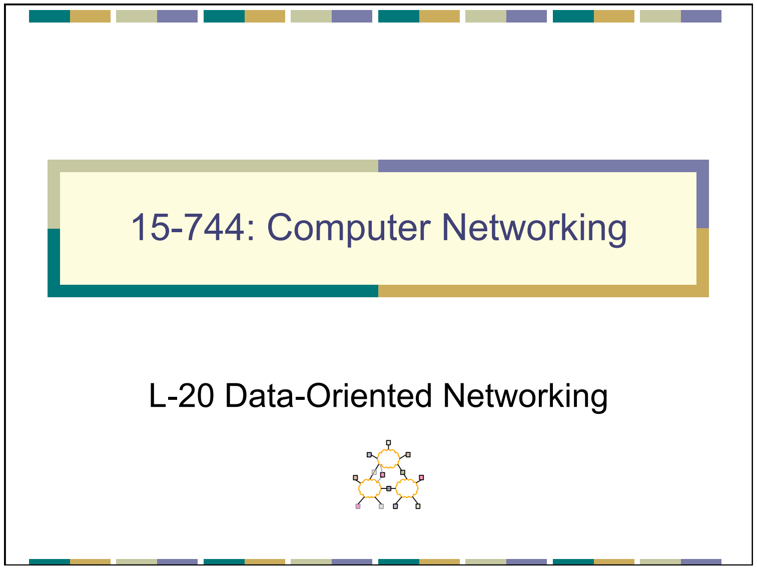
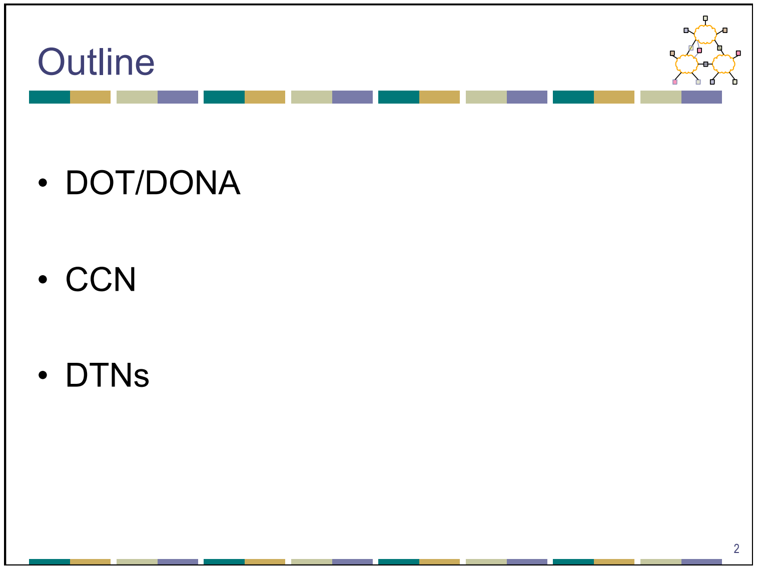


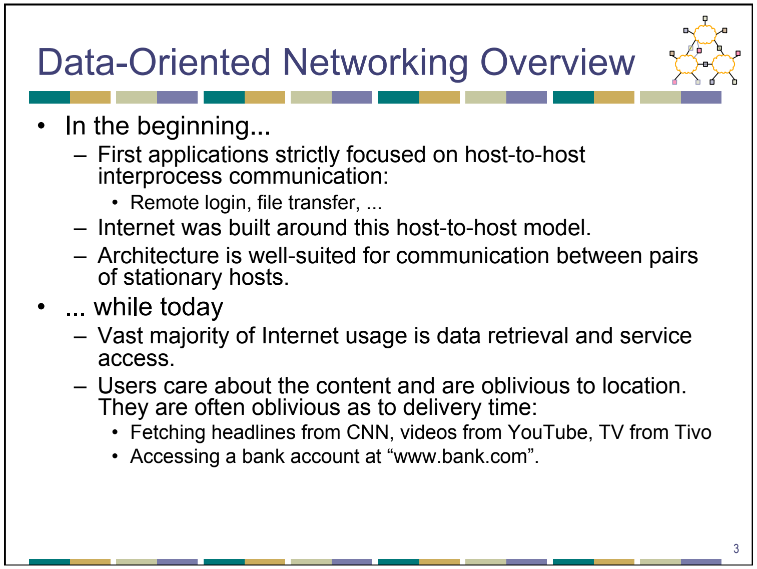
15-744: Computer Networking

L-20 Data-Oriented Networking



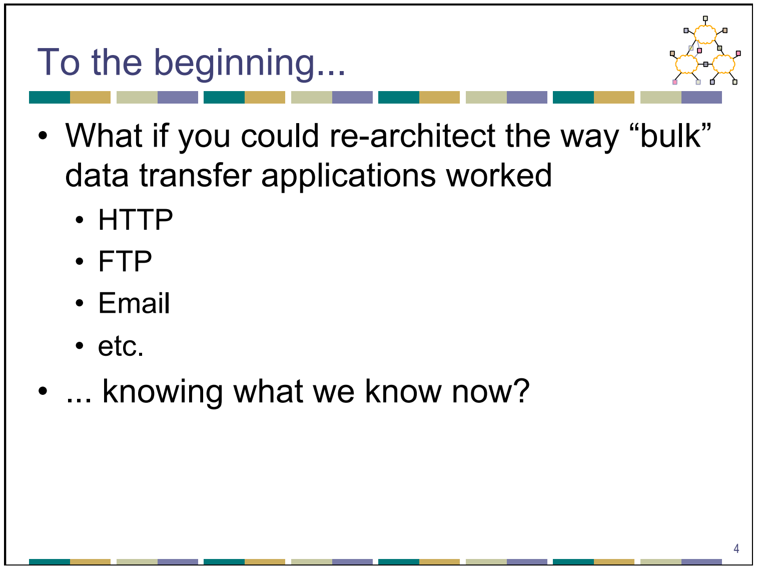
Outline

- DOT/DONA
- CCN
- DTNs



Data-Oriented Networking Overview

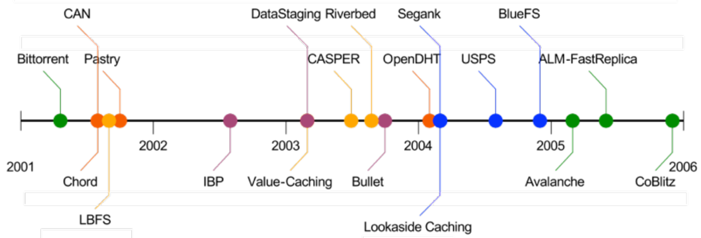
- In the beginning...
  - First applications strictly focused on host-to-host interprocess communication:
    - Remote login, file transfer, ...
  - Internet was built around this host-to-host model.
  - Architecture is well-suited for communication between pairs of stationary hosts.
- ... while today
  - Vast majority of Internet usage is data retrieval and service access.
  - Users care about the content and are oblivious to location. They are often oblivious as to delivery time:
    - Fetching headlines from CNN, videos from YouTube, TV from Tivo
    - Accessing a bank account at “www.bank.com”.



To the beginning...

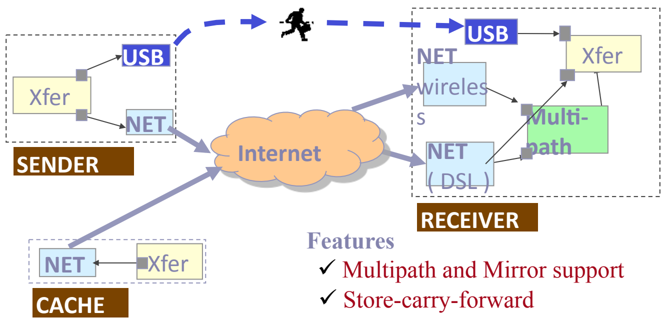
- What if you could re-architect the way “bulk” data transfer applications worked
  - HTTP
  - FTP
  - Email
  - etc.
- ... knowing what we know now?

Innovation in Data Transfer is Hard



- Imagine: You have a novel data transfer technique
- How do you deploy?
  - Update HTTP. Talk to IETF. Modify Apache, IIS, Firefox, Netscape, Opera, IE, Lynx, Wget, …
  - Update SMTP. Talk to IETF. Modify Sendmail, Postfix, Outlook…
  - Give up in frustration

Data-Oriented Network Design

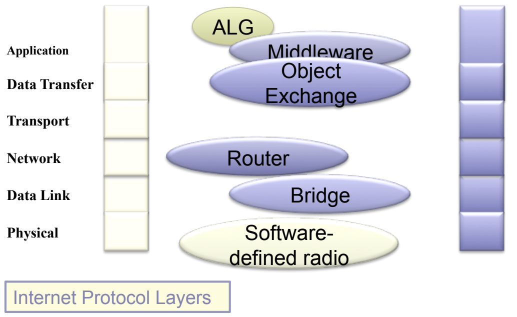


Features

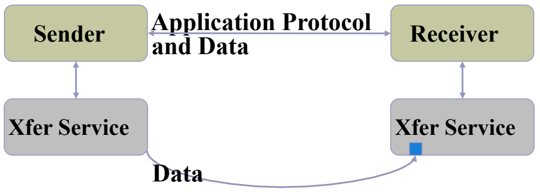
✓ Multipath and Mirror support

✓ Store-carry-forward

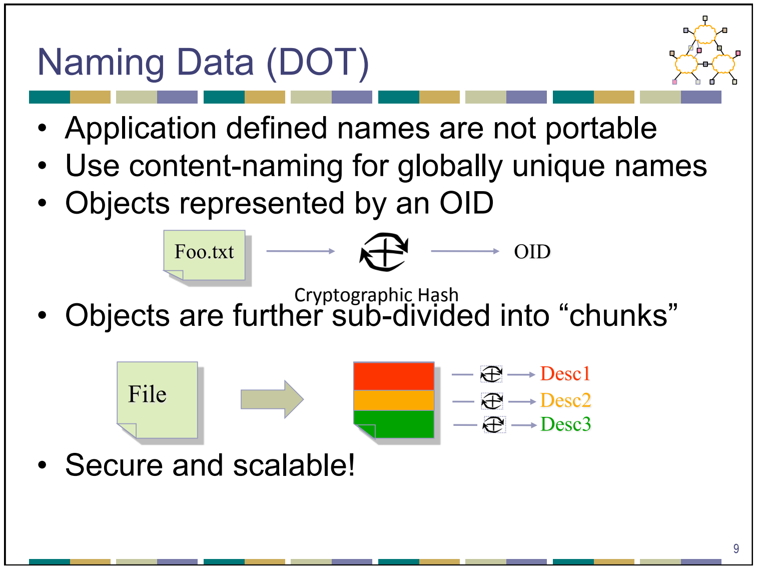
New Approach: Adding to the Protocol Stack



Data Transfer Service



- Transfer Service responsible for finding/transferring data
  - Transfer Service is shared by applications
- How are users, hosts, services, and data named?
- How is data secured and delivered reliably?
- How are legacy systems incorporated?

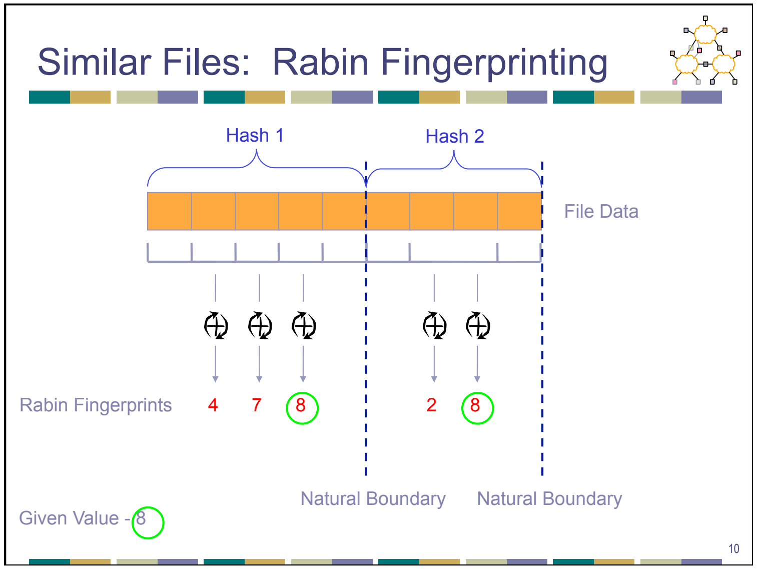


Naming Data (DOT)

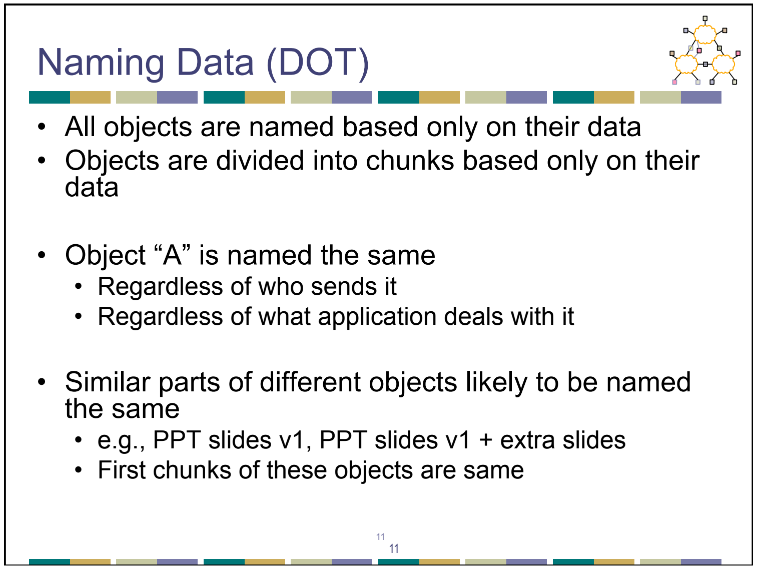
- Application defined names are not portable
- Use content-naming for globally unique names
- Objects represented by an OID

- Objects are further sub-divided into “chunks”

- Secure and scalable!



Similar Files: Rabin Fingerprinting

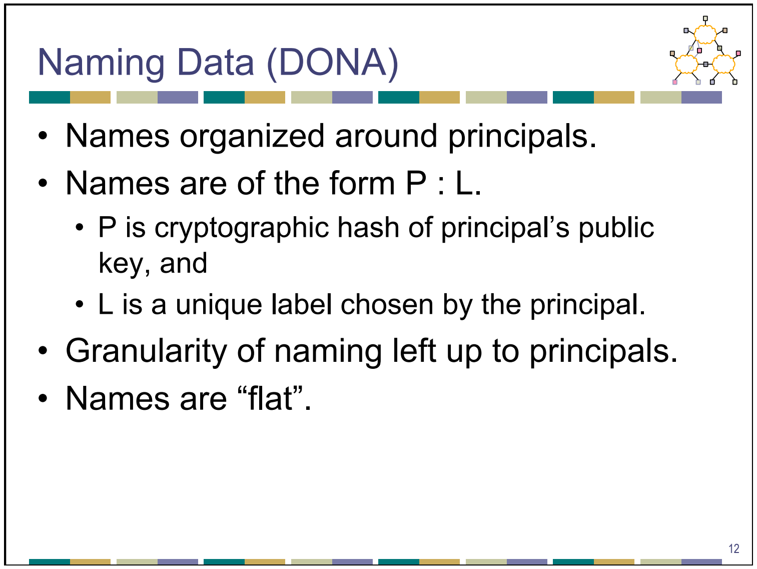


Naming Data (DOT)

- All objects are named based only on their data
- Objects are divided into chunks based only on their data

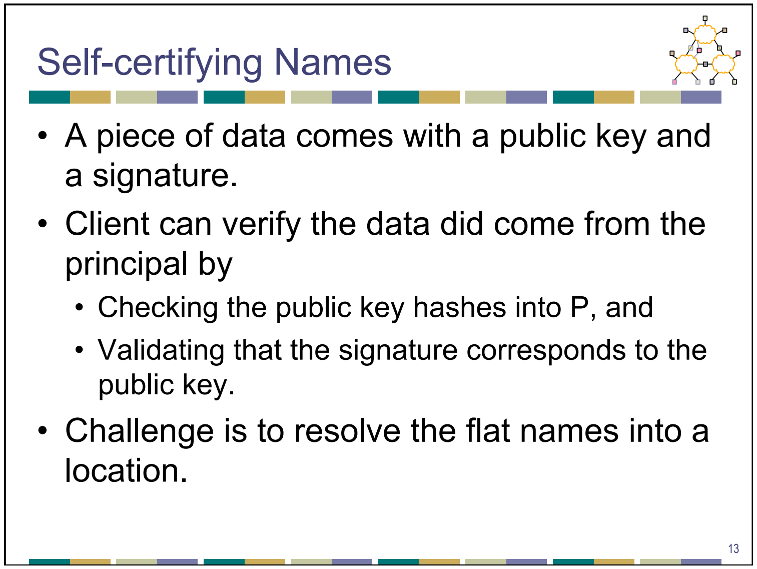
- Object “A” is named the same
  - Regardless of who sends it
  - Regardless of what application deals with it

- Similar parts of different objects likely to be named the same
  - e.g., PPT slides v1, PPT slides v1 + extra slides
  - First chunks of these objects are same



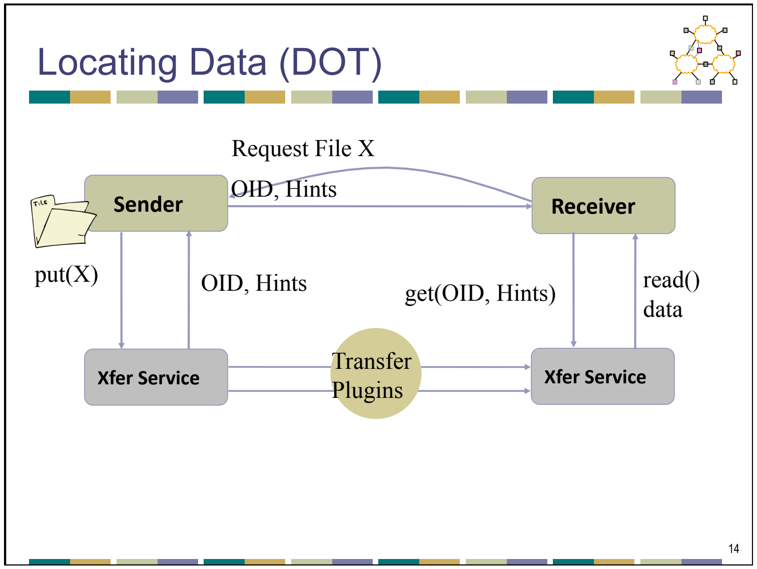
Naming Data (DONA)

- Names organized around principals.
- Names are of the form P : L.
  - P is cryptographic hash of principal’s public key, and
  - L is a unique label chosen by the principal.
- Granularity of naming left up to principals.
- Names are “flat”.

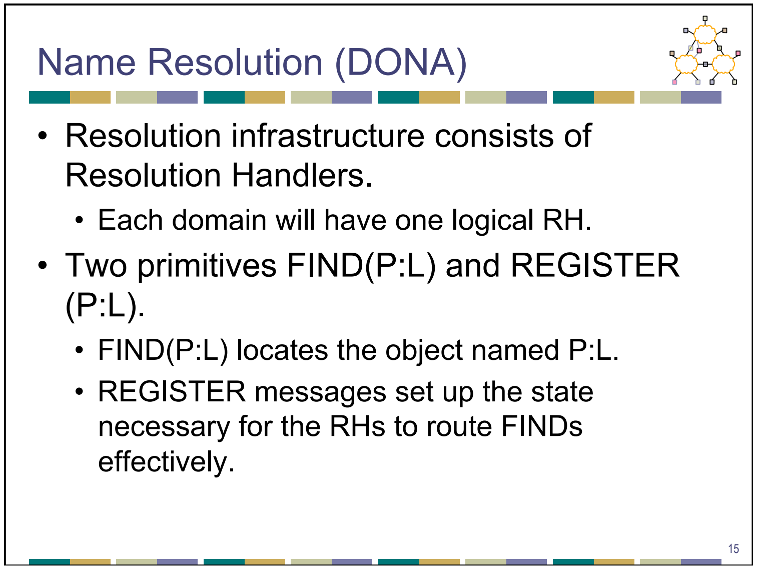


Self-certifying Names

- A piece of data comes with a public key and a signature.
- Client can verify the data did come from the principal by
  - Checking the public key hashes into P, and
  - Validating that the signature corresponds to the public key.
- Challenge is to resolve the flat names into a location.

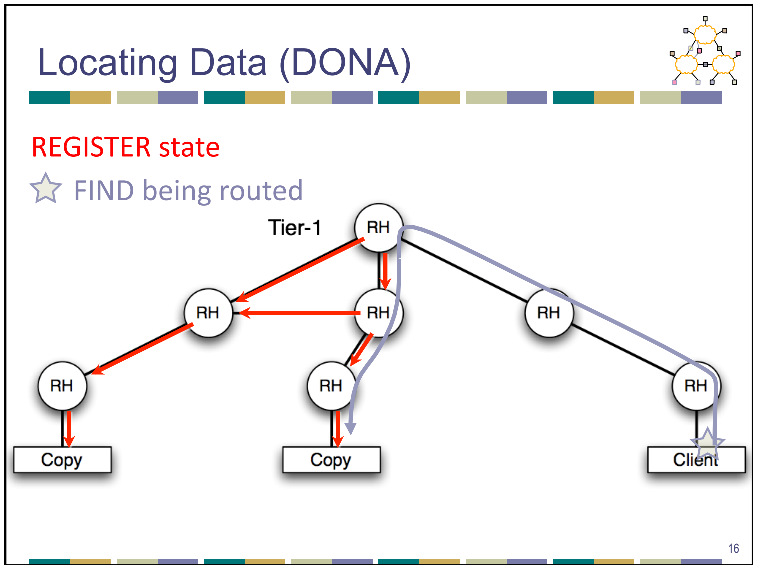


Locating Data (DOT)



Name Resolution (DONA)

- Resolution infrastructure consists of Resolution Handlers.
  - Each domain will have one logical RH.
- Two primitives FIND(P:L) and REGISTER (P:L).
  - FIND(P:L) locates the object named P:L.
  - REGISTER messages set up the state necessary for the RHs to route FINDs effectively.



Locating Data (DONA)

REGISTER state

☆ FIND being routed

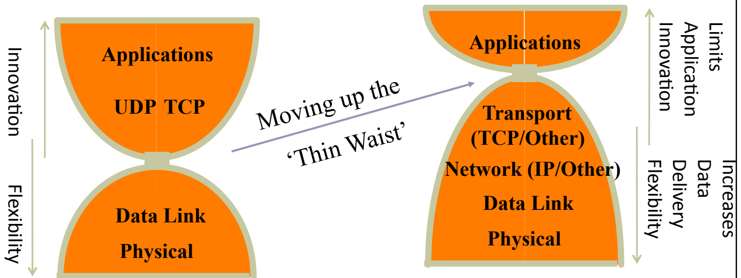
Establishing REGISTER state

- Any machine authorized to serve a datum or service with name P:L sends a REGISTER(P:L) to its first-hop RH
- RHs maintain a registration table that maps a name to both next-hop RH and distance (in some metric)
- REGISTERs are forwarded according to interdomain policies.
  - REGISTERs from customers to both peers and providers.
  - REGISTERs from peers optionally to providers/peers.

Forwarding FIND(P:L)

- When FIND(P:L) arrives to a RH:
  - If there's an entry in the registration table, the FIND is sent to the next-hop RH.
  - If there's no entry, the RH forwards the FIND towards to its provider.
- In case of multiple equal choices, the RH uses its local policy to choose among them.

Interoperability: New Tradeoffs



The Hourglass Model

The Hourglass Model

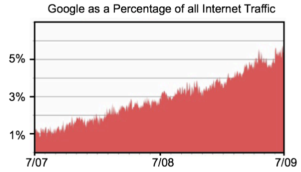
Interoperability: Datagrams vs. Data Blocks

	Datagrams	Data Blocks
What must be standardized?	IP Addresses Name→Address translation (DNS)	Data Labels Name → Label translation (Google?)
Application Support	Exposes much of underlying network's capability	Practice has shown that this is what applications need
Lower Layer Support	Supports arbitrary links Requires end-to-end connectivity	Supports arbitrary links Supports arbitrary transport Support storage (both in-network and for transport)

Outline

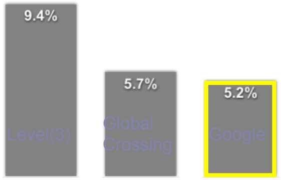
- DOT/DONA
- CCN
- DTNs

Google…

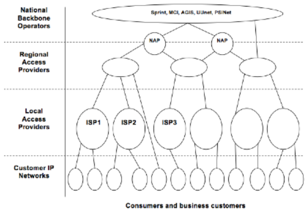


Biggest content source

Third largest ISP

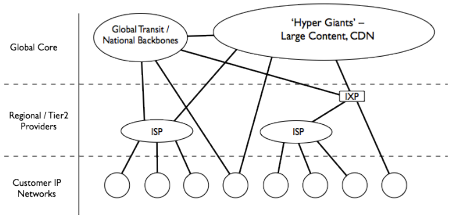


source: ‘ATLAS’ Internet Observatory 2009 Annual Report’, C. Labovitz et.al.


National Backbone Operators
Sprint, MCI, AGIS, UUnet, PSINet
NAP
NAP
Regional Access Providers
Local Access Providers
ISP1
ISP2
ISP3
Customer IP Networks
Consumers and business customers

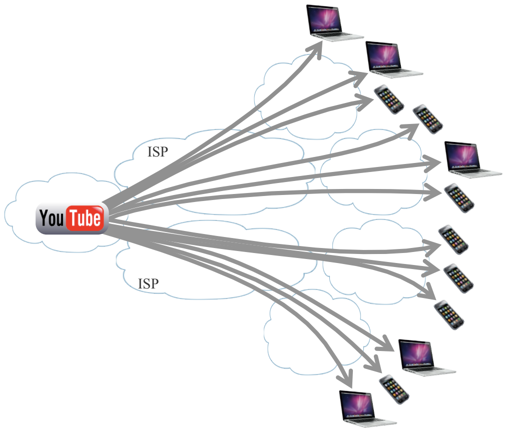
1995 - 2007:
Textbook Internet

2009:
Rise of the
Hyper Giants

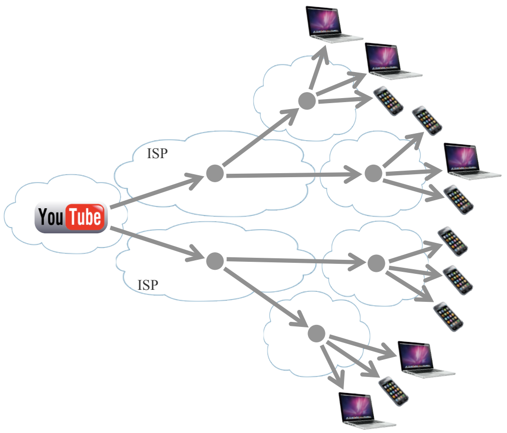

Global Core
Global Transit / National Backbones
'Hyper Giants' – Large Content, CDN
IXP
Regional / Tier2 Providers
ISP
ISP
Customer IP Networks

source: ‘ATLAS’ Internet Observatory 2009 Annual Report’, C. Labovitz et.al.

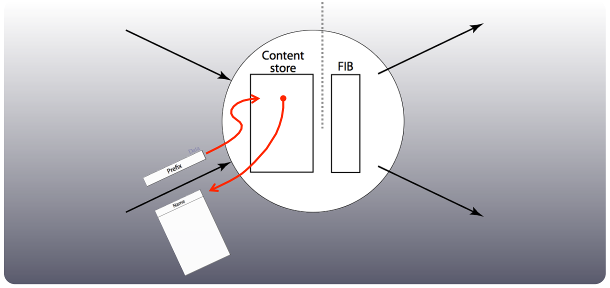
What does the network look like…



What should the network look like…



CCN Model



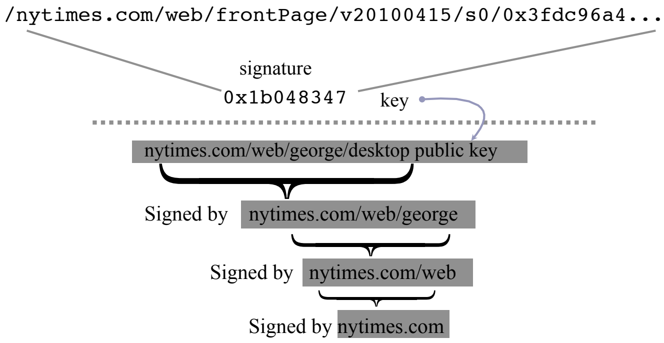
- Packets say ‘what’ not ‘who’ (no src or dst)
- communication is to local peer(s)
- upstream performance is measurable
- memory makes loops impossible

Context Awareness?

- Like IP, CCN imposes no semantics on names.
- ‘Meaning’ comes from application, institution and global conventions:

/parc.com/people/van/presentations/CCN
/parc.com/people/van/calendar/freeTimeForMeeting
/thisRoom/projector
/thisMeeting/documents
/nearBy/available/parking
/thisHouse/demandReduction/2KW

CCN Names/Security



`/nytimes.com/web/frontPage/v20100415/s0/0x3fdc96a4...`

signature
`0x1b048347`
key

nytimes.com/web/george/desktop public key

Signed by nytimes.com/web/george

Signed by nytimes.com/web

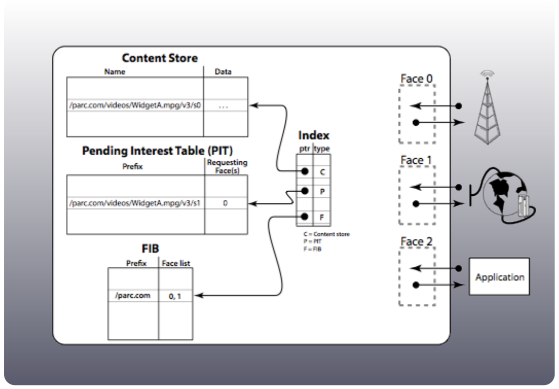
Signed by nytimes.com

- Per-packet signatures using public key
  - Packet also contain link to public key

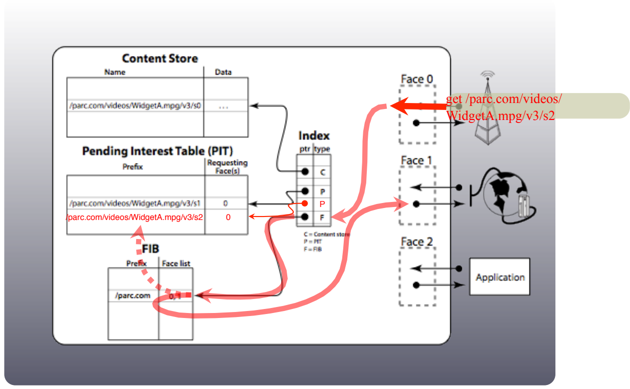
Names Route Interests

- FIB lookups are longest match (like IP prefix lookups) which helps guarantee log (n) state scaling for globally accessible data.
- Although CCN names are longer than IP identifiers, their explicit structure allows lookups as efficient as IP's.
- Since nothing can loop, state can be approximate (e.g., bloom filters).

CCN node model



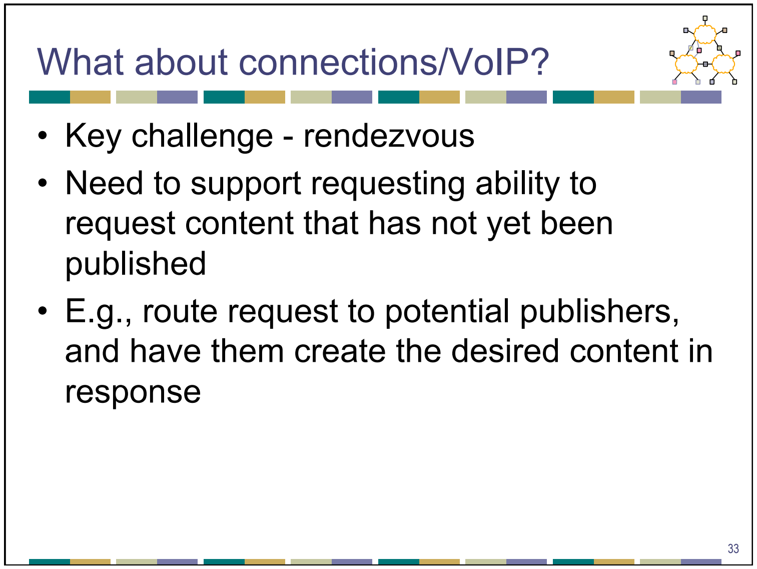
CCN node model



get /parc.com/videos/WidgetA.mpg/v3/s2

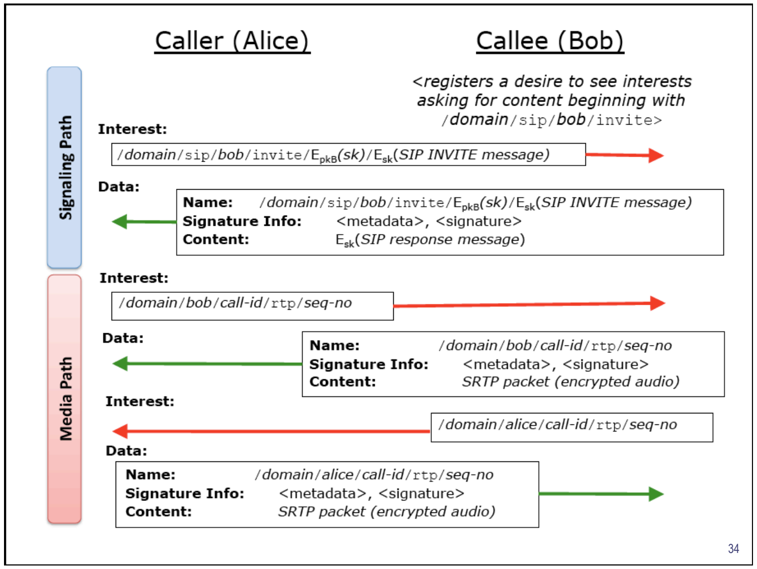
Flow/Congestion Control

- One Interest pkt → one data packet
- All xfers are done hop-by-hop – so no need for congestion control
- Sequence numbers are part of the name space



What about connections/VoIP?

- Key challenge - rendezvous
- Need to support requesting ability to request content that has not yet been published
- E.g., route request to potential publishers, and have them create the desired content in response



Caller (Alice)

Callee (Bob)

<registers a desire to see interests asking for content beginning with /*domain*/sip/*bob*/invite>

Interest:

/*domain*/sip/*bob*/invite/E_{pkB}(*sk*)/E_{sk}(*SIP INVITE message*)

Data:

Name: /*domain*/sip/*bob*/invite/E_{pkB}(*sk*)/E_{sk}(*SIP INVITE message*)
Signature Info: <metadata>, <signature>
Content: E_{sk}(*SIP response message*)

Interest:

/*domain*/*bob*/*call-id*/rtp/*seq-no*

Data:

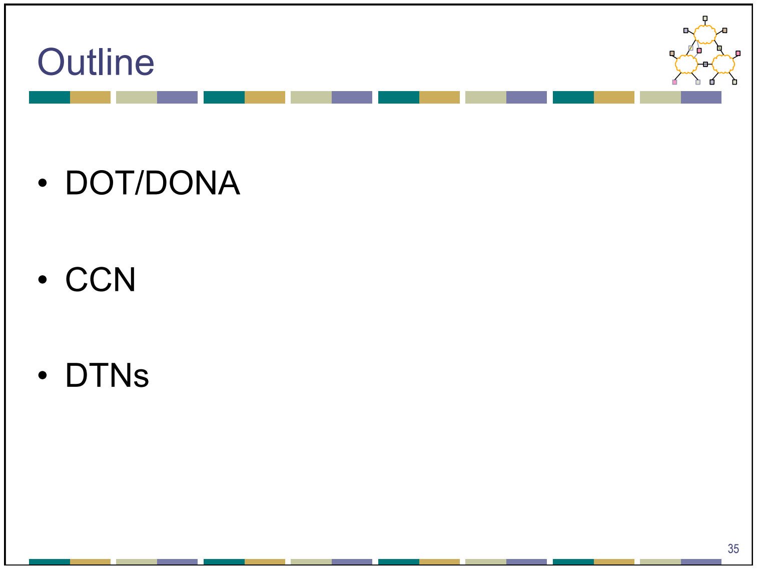
Name: /*domain*/*bob*/*call-id*/rtp/*seq-no*
Signature Info: <metadata>, <signature>
Content: *SRTP packet (encrypted audio)*

Interest:

/*domain*/*alice*/*call-id*/rtp/*seq-no*

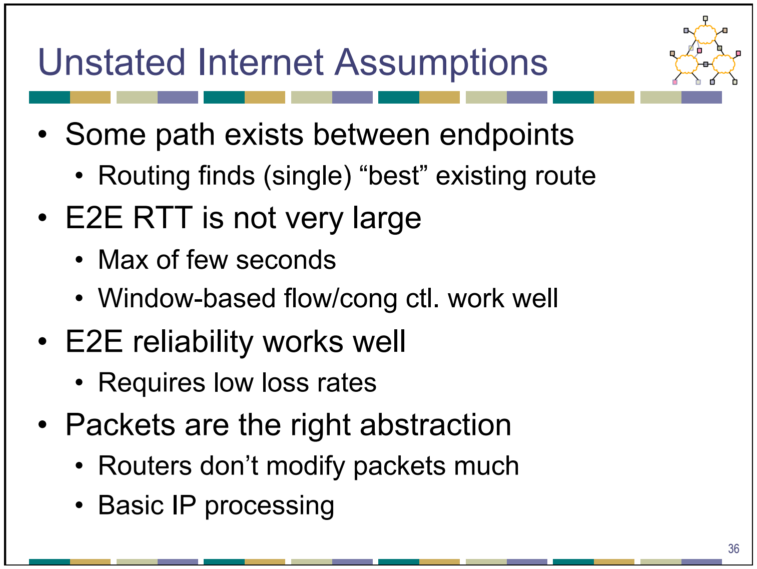
Data:

Name: /*domain*/*alice*/*call-id*/rtp/*seq-no*
Signature Info: <metadata>, <signature>
Content: *SRTP packet (encrypted audio)*



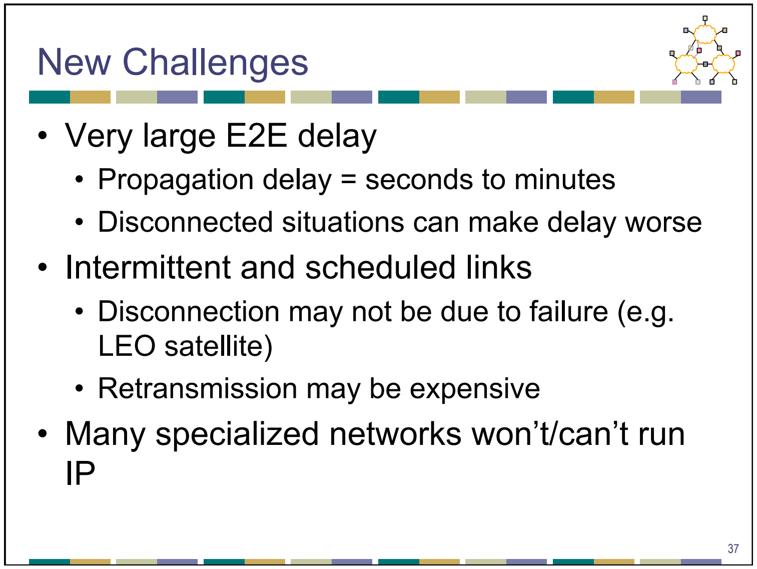
Outline

- DOT/DONA
- CCN
- DTNs



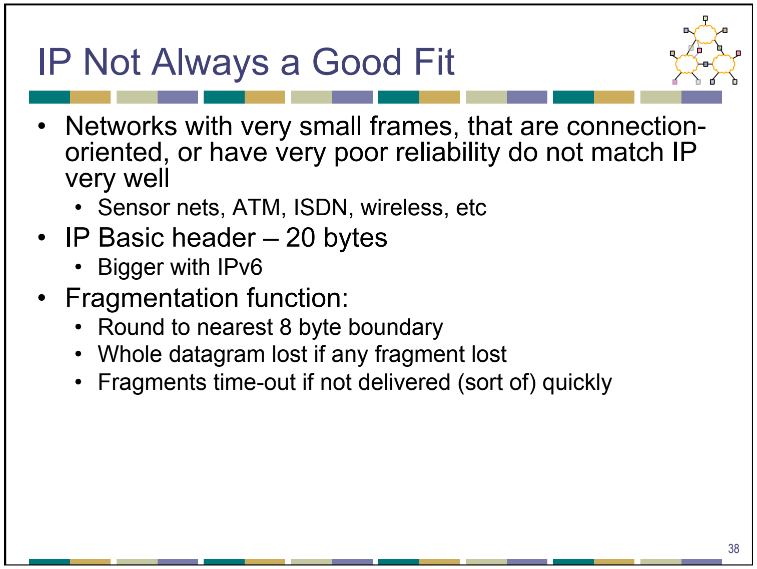
Unstated Internet Assumptions

- Some path exists between endpoints
  - Routing finds (single) "best" existing route
- E2E RTT is not very large
  - Max of few seconds
  - Window-based flow/cong ctl. work well
- E2E reliability works well
  - Requires low loss rates
- Packets are the right abstraction
  - Routers don't modify packets much
  - Basic IP processing



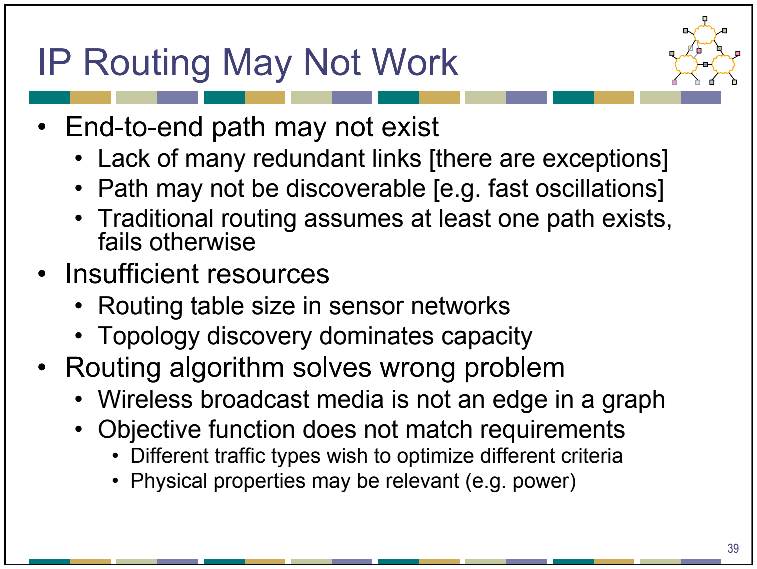
New Challenges

- Very large E2E delay
  - Propagation delay = seconds to minutes
  - Disconnected situations can make delay worse
- Intermittent and scheduled links
  - Disconnection may not be due to failure (e.g. LEO satellite)
  - Retransmission may be expensive
- Many specialized networks won’t/can’t run IP



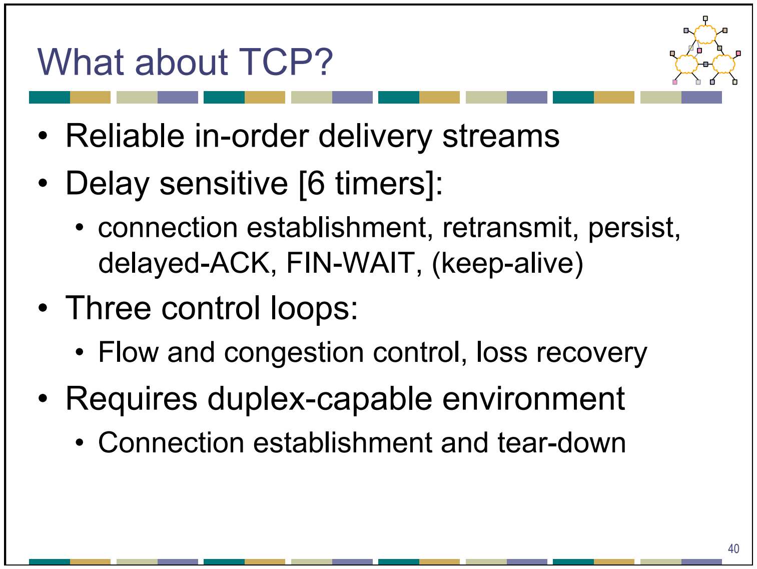
IP Not Always a Good Fit

- Networks with very small frames, that are connection-oriented, or have very poor reliability do not match IP very well
  - Sensor nets, ATM, ISDN, wireless, etc
- IP Basic header – 20 bytes
  - Bigger with IPv6
- Fragmentation function:
  - Round to nearest 8 byte boundary
  - Whole datagram lost if any fragment lost
  - Fragments time-out if not delivered (sort of) quickly



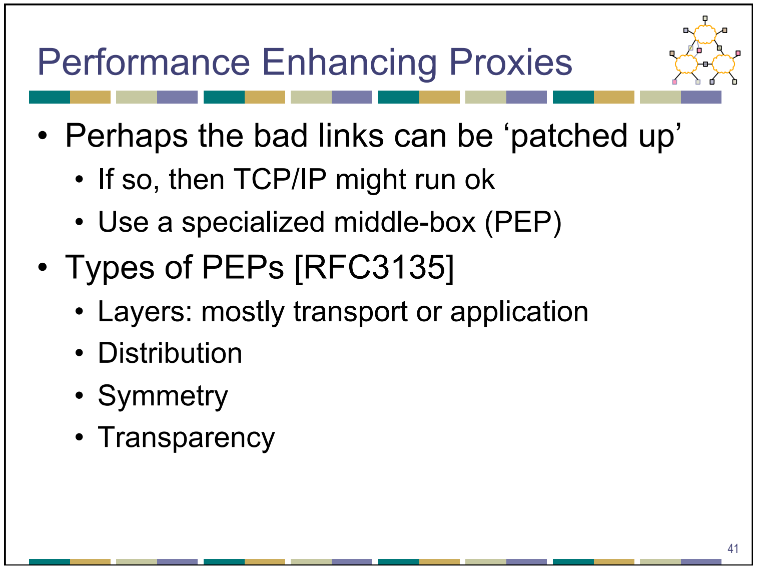
IP Routing May Not Work

- End-to-end path may not exist
  - Lack of many redundant links [there are exceptions]
  - Path may not be discoverable [e.g. fast oscillations]
  - Traditional routing assumes at least one path exists, fails otherwise
- Insufficient resources
  - Routing table size in sensor networks
  - Topology discovery dominates capacity
- Routing algorithm solves wrong problem
  - Wireless broadcast media is not an edge in a graph
  - Objective function does not match requirements
    - Different traffic types wish to optimize different criteria
    - Physical properties may be relevant (e.g. power)



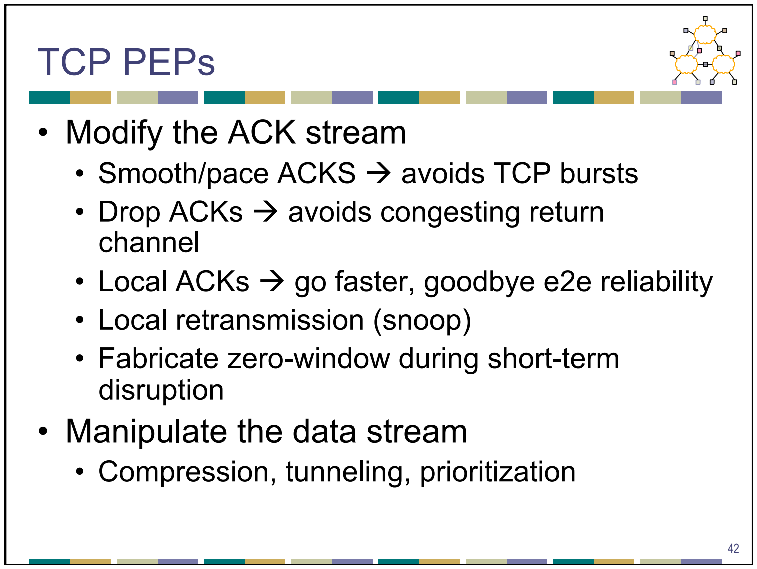
What about TCP?

- Reliable in-order delivery streams
- Delay sensitive [6 timers]:
  - connection establishment, retransmit, persist, delayed-ACK, FIN-WAIT, (keep-alive)
- Three control loops:
  - Flow and congestion control, loss recovery
- Requires duplex-capable environment
  - Connection establishment and tear-down



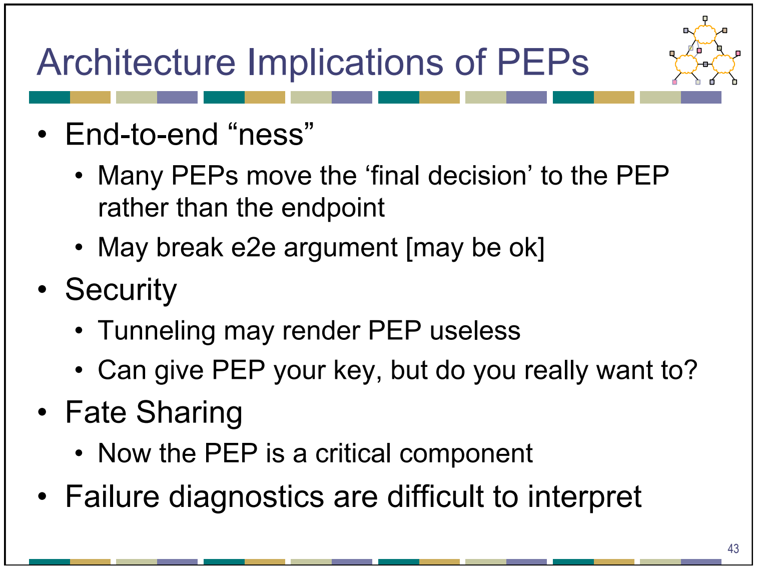
Performance Enhancing Proxies

- Perhaps the bad links can be ‘patched up’
  - If so, then TCP/IP might run ok
  - Use a specialized middle-box (PEP)
- Types of PEPs [RFC3135]
  - Layers: mostly transport or application
  - Distribution
  - Symmetry
  - Transparency



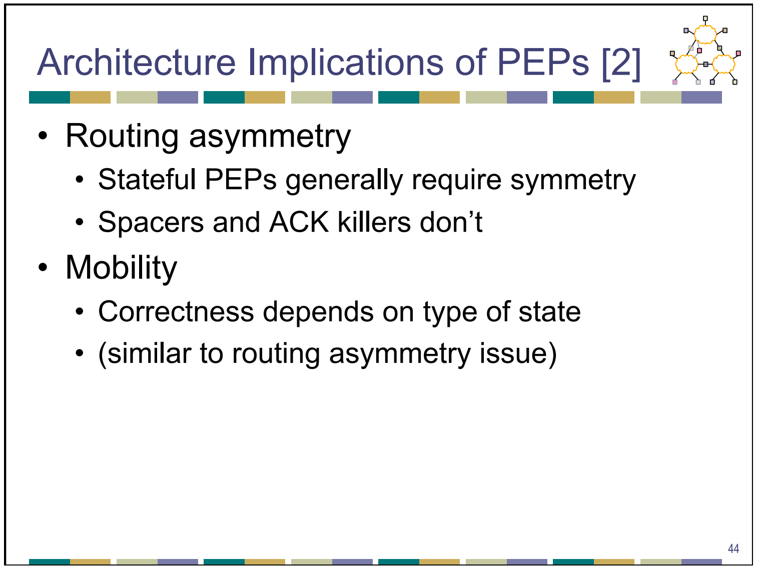
TCP PEPs

- Modify the ACK stream
  - Smooth/pace ACKS → avoids TCP bursts
  - Drop ACKs → avoids congesting return channel
  - Local ACKs → go faster, goodbye e2e reliability
  - Local retransmission (snoop)
  - Fabricate zero-window during short-term disruption
- Manipulate the data stream
  - Compression, tunneling, prioritization



Architecture Implications of PEPs

- End-to-end “ness”
  - Many PEPs move the ‘final decision’ to the PEP rather than the endpoint
  - May break e2e argument [may be ok]
- Security
  - Tunneling may render PEP useless
  - Can give PEP your key, but do you really want to?
- Fate Sharing
  - Now the PEP is a critical component
- Failure diagnostics are difficult to interpret



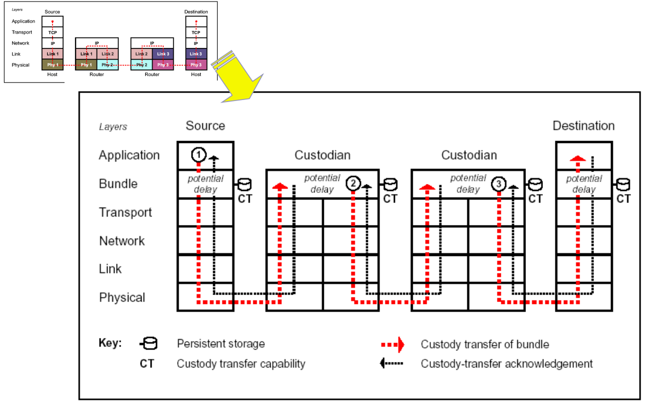
Architecture Implications of PEPs [2]

- Routing asymmetry
  - Stateful PEPs generally require symmetry
  - Spacers and ACK killers don’t
- Mobility
  - Correctness depends on type of state
  - (similar to routing asymmetry issue)

Delay-Tolerant Networking Architecture

- Goals
  - Support interoperability across ‘radically heterogeneous’ networks
  - Tolerate delay and disruption
    - Acceptable performance in high loss/delay/error/ disconnected environments
    - Decent performance for low loss/delay/errors
- Components
  - Flexible naming scheme
  - Message abstraction and API
  - Extensible Store-and-Forward Overlay Routing
  - Per-(overlay)-hop reliability and authentication

Disruption Tolerant Networks



Disruption Tolerant Networks

Naming Data (DTN)

- Endpoint IDs are processed as names
  - refer to one or more DTN nodes
  - expressed as Internet URI, matched as strings
- URIs
  - Internet standard naming scheme [RFC3986]
  - Format: <scheme> : <SSP>
- SSP can be arbitrary, based on (various) *schemes*
- More flexible than DOT/DONA design but less secure/scalable

Naming

- Support ‘radical heterogeneity’ using URI’s:
  - {scheme ID (allocated), scheme-specific-part}
  - associative or location-based names/addresses optional
  - Variable-length, can accommodate “any” net’s names/addresses
- Endpoint IDs:
  - multicast, anycast, unicast
- Late binding of EID permits naming flexibility:
  - EID “looked up” only when necessary during delivery
  - contrast with Internet lookup-before-use DNS/IP

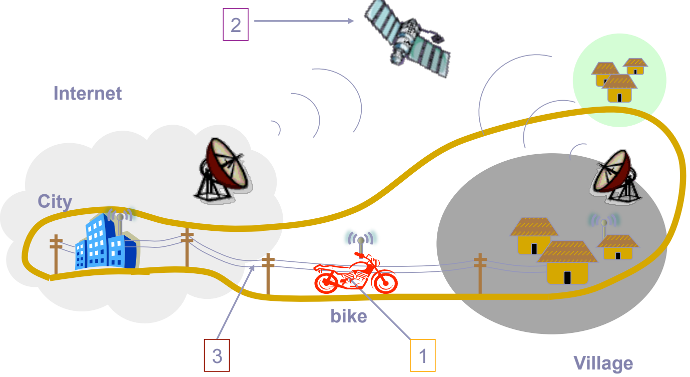
Message Abstraction

- Network protocol data unit: <u>bundles</u>
  - “postal-like” message delivery
  - coarse-grained CoS [4 classes]
  - origination and useful life time [assumes sync’d clocks]
  - source, destination, and respond-to EIDs
  - *Options*: return receipt, “traceroute”-like function, alternative reply-to field, custody transfer
  - fragmentation capability
  - overlay atop TCP/IP or other (link) layers [layer ‘agnostic’]
- Applications send/receive <u>messages</u>
  - “Application data units” (**<u>ADUs</u>**) of possibly-large size
  - Adaptation to underlying protocols via ‘convergence layer’
  - API includes persistent registrations

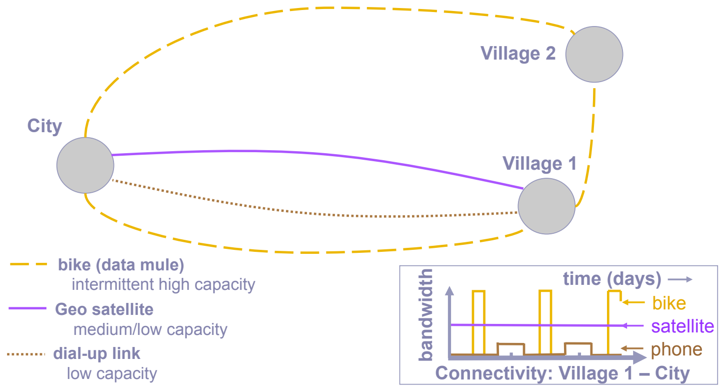
DTN Routing

- DTN Routers form an overlay network
  - only selected/configured nodes participate
  - nodes have persistent storage
- DTN routing topology is a **<u>time-varying</u>** multigraph
  - Links come and go, sometimes predictably
  - Use any/all links that can possibly help (multi)
  - Scheduled, Predicted, or Unscheduled Links
    - May be direction specific [e.g. ISP dialup]
    - May learn from history to predict schedule
- Messages fragmented based on dynamics
  - Proactive fragmentation: optimize contact volume
  - Reactive fragmentation: resume where you failed

Example Routing Problem



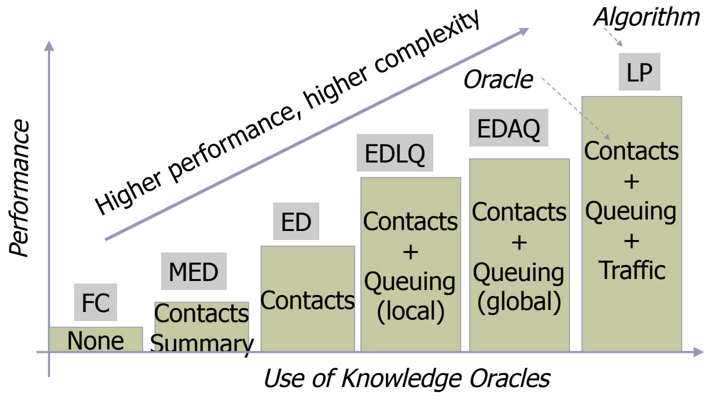
Example Graph Abstraction



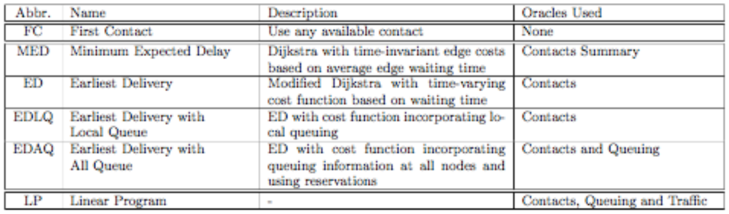
The DTN Routing Problem

- *Inputs*: topology (multi)graph, vertex buffer limits, contact set, message demand matrix (w/priorities)
- An ***edge*** is a possible opportunity to communicate:
  - One-way: (S, D, c(t), d(t))
  - (S, D): source/destination ordered pair of contact
  - c(t): capacity (rate); d(t): delay
  - A ***Contact*** is when c(t) > 0 for some period $[i_k, i_{k+1}]$
- Vertices have buffer limits; edges in graph if ever in any contact, multigraph for multiple physical connections
- *Problem*: optimize some metric of delivery on this structure
  - Sub-questions: what metric to optimize?, efficiency?

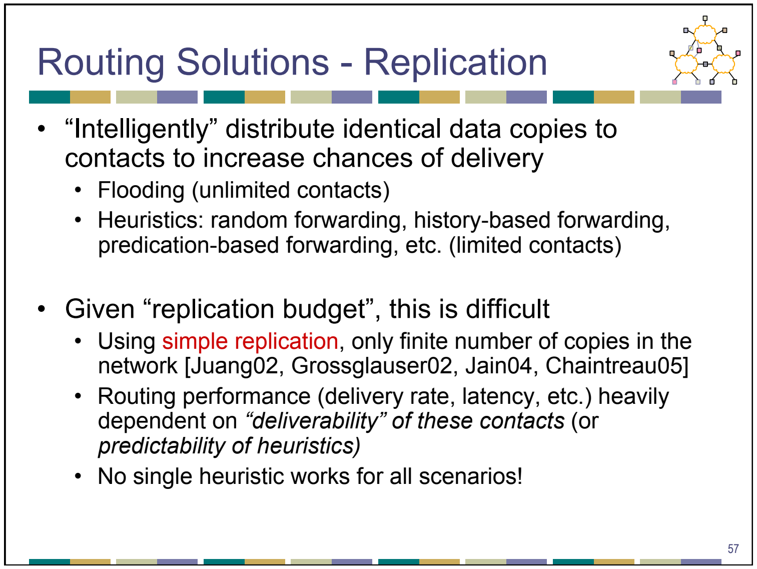
Knowledge-Performance Tradeoff


Algorithm
Higher performance, higher complexity
Oracle
Performance
LP
EDAQ
EDLQ
ED
MED
FC
None
Contacts Summary
Contacts
Contacts + Queuing (local)
Contacts + Queuing (global)
Contacts + Queuing + Traffic
Use of Knowledge Oracles

Knowledge-Performance Tradeoff

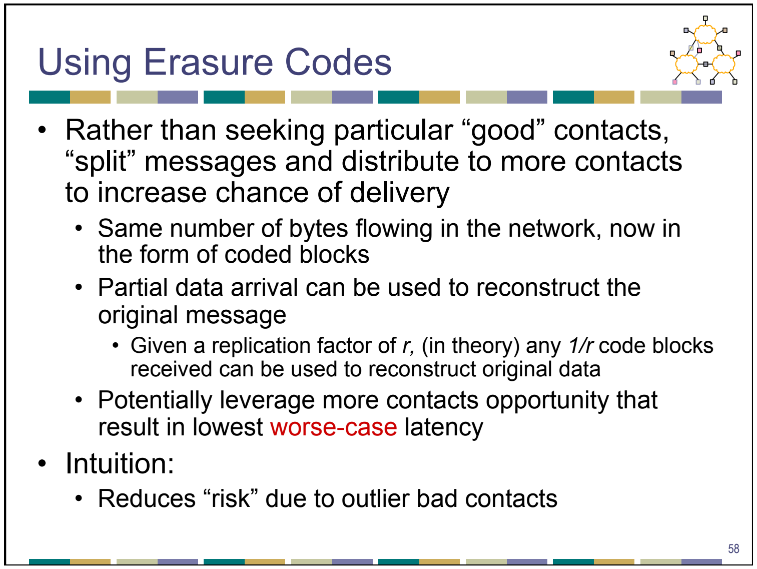


Abbr.	Name	Description	Oracles Used
FC	First Contact	Use any available contact	None
MED	Minimum Expected Delay	Dijkstra with time-invariant edge costs based on average edge waiting time	Contacts Summary
ED	Earliest Delivery	Modified Dijkstra with time-varying cost function based on waiting time	Contacts
EDLQ	Earliest Delivery with Local Queue	ED with cost function incorporating local queuing	Contacts
EDAQ	Earliest Delivery with All Queue	ED with cost function incorporating queuing information at all nodes and using reservations	Contacts and Queuing
LP	Linear Program	-	Contacts, Queuing and Traffic



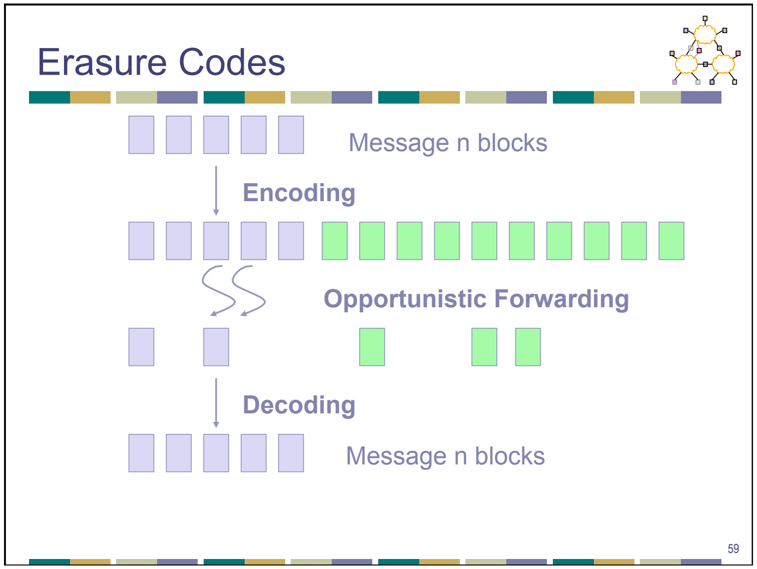
Routing Solutions - Replication

- “Intelligently” distribute identical data copies to contacts to increase chances of delivery
  - Flooding (unlimited contacts)
  - Heuristics: random forwarding, history-based forwarding, predication-based forwarding, etc. (limited contacts)
- Given “replication budget”, this is difficult
  - Using simple replication, only finite number of copies in the network [Juang02, Grossglauser02, Jain04, Chaintreau05]
  - Routing performance (delivery rate, latency, etc.) heavily dependent on *“deliverability” of these contacts* (or *predictability of heuristics)*
  - No single heuristic works for all scenarios!



Using Erasure Codes

- Rather than seeking particular “good” contacts, “split” messages and distribute to more contacts to increase chance of delivery
  - Same number of bytes flowing in the network, now in the form of coded blocks
  - Partial data arrival can be used to reconstruct the original message
    - Given a replication factor of *r*, (in theory) any *1/r* code blocks received can be used to reconstruct original data
  - Potentially leverage more contacts opportunity that result in lowest worse-case latency
- Intuition:
  - Reduces “risk” due to outlier bad contacts



Erasure Codes

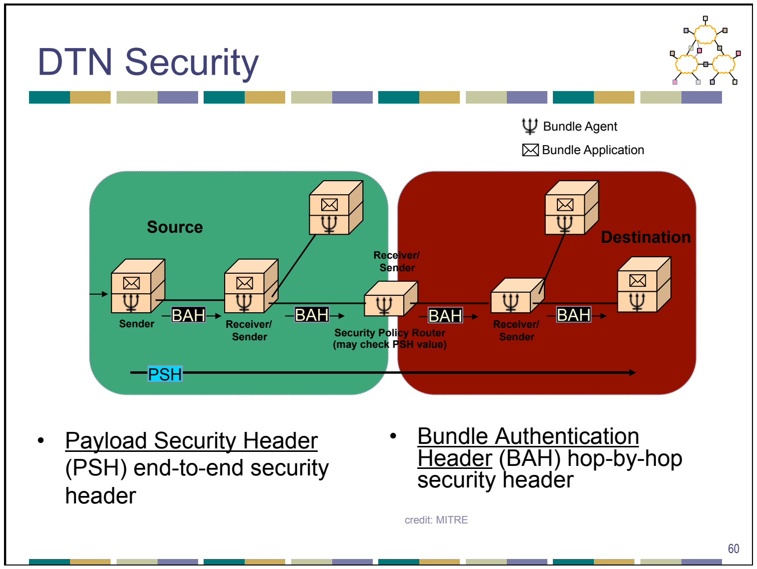
Message n blocks

Encoding

Opportunistic Forwarding

Decoding

Message n blocks



DTN Security

- Payload Security Header (PSH) end-to-end security header
- Bundle Authentication Header (BAH) hop-by-hop security header

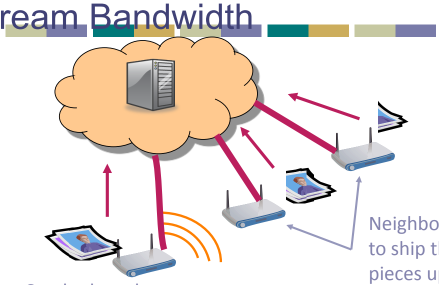
credit: MITRE

So, is this just e-mail?

	naming/	routing	flow	multi-	security	reliable	priority
	late binding		contrl	app		delivery	
e-mail	Y	N (static)	N(Y)	N(Y)	opt	Y	N(Y)
DTN	Y	Y (exten)	Y	Y	opt	opt	Y

- Many similarities to (abstract) e-mail service
- Primary difference involves routing, reliability and security
- E-mail depends on an underlying layer's routing:
  - Cannot generally move messages 'closer' to their destinations in a partitioned network
  - In the Internet (SMTP) case, not disconnection-tolerant or efficient for long RTTs due to "chattiness"
- E-mail security authenticates only user-to-user

Performance: Opportunistically Aggregate Upstream Bandwidth



Neighbors decide whether to ship the pieces upstream

Sender broadcasts to available neighbors

- Challenges:
  - Multi-hop: decide whether to send upstream or forward one extra hop
  - Requires both data-oriented design and opportunistic forwarding

"But ...

- "this doesn't handle conversations or realtime.
  - Yes it does - see ReArch VoCCN paper.
- "this is just Google.
  - This is IP-for-content. We don't search for data, we route to it.
- "this will never scale.
  - Hierarchically structured names give same log (n) scaling as IP but CCN tables can be much smaller since multi-source model allows inexact state (e.g., Bloom filter).