



Next Generation Internet

IPv6 and Beyond

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Agenda

Motivation

- ➔ The Internet – Paradigm & Reality
- ➔ The Limits of IPv4
- ➔ Internet Service Problems
- ➔ IPv6 Highlights

Basic IPv6 Architecture

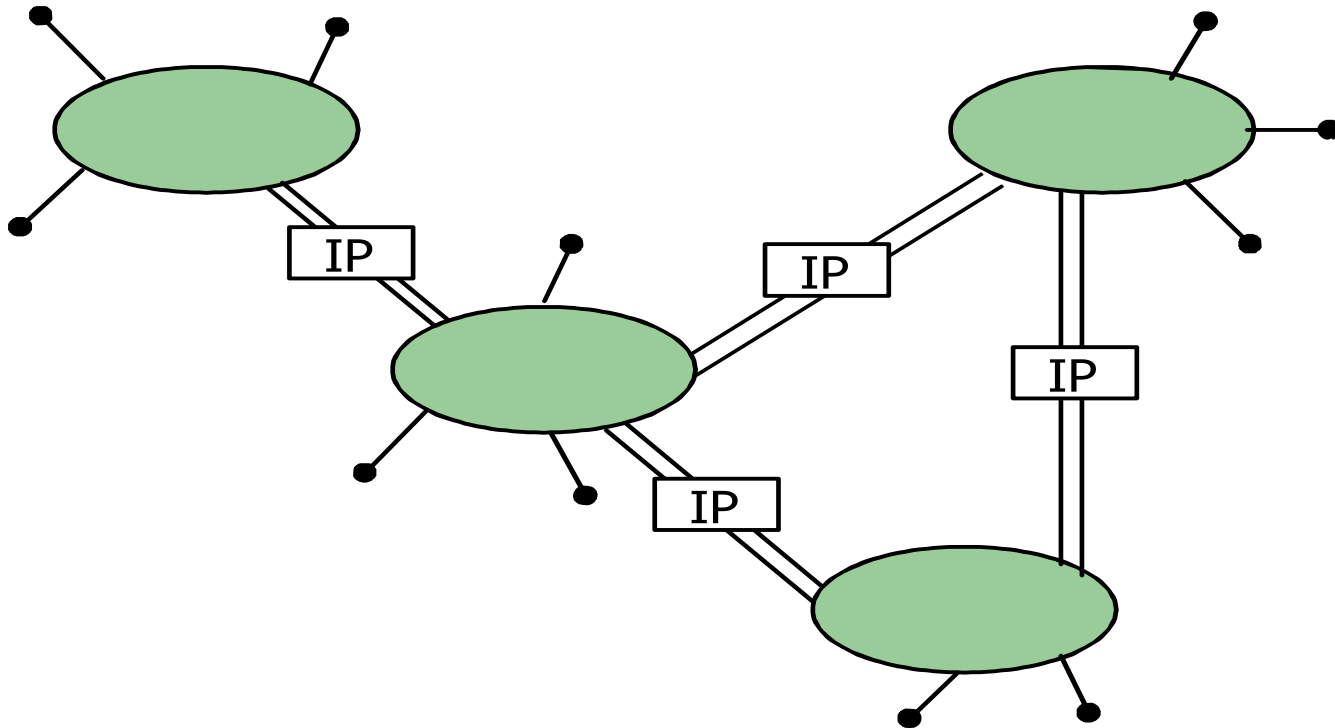
IPv6 Migration: Transition and Coexistence

Internet of Things: 6LoWPAN

Future Trends: Beyond IPv6



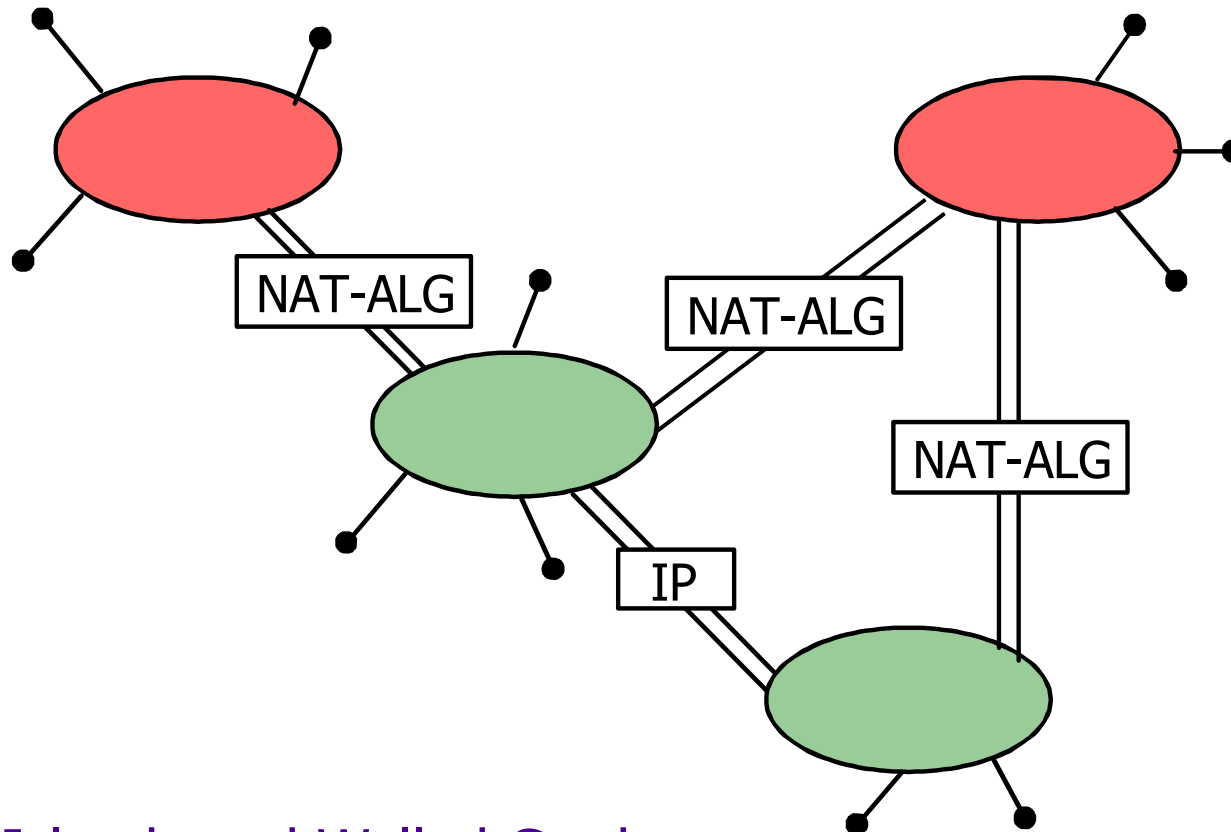
The Internet: Original Paradigm



One **End-to-End** Internet-Layer

- Global addressing
- Simple, application independent, transparent
- Stateless, application independent gateways

The Internet Today



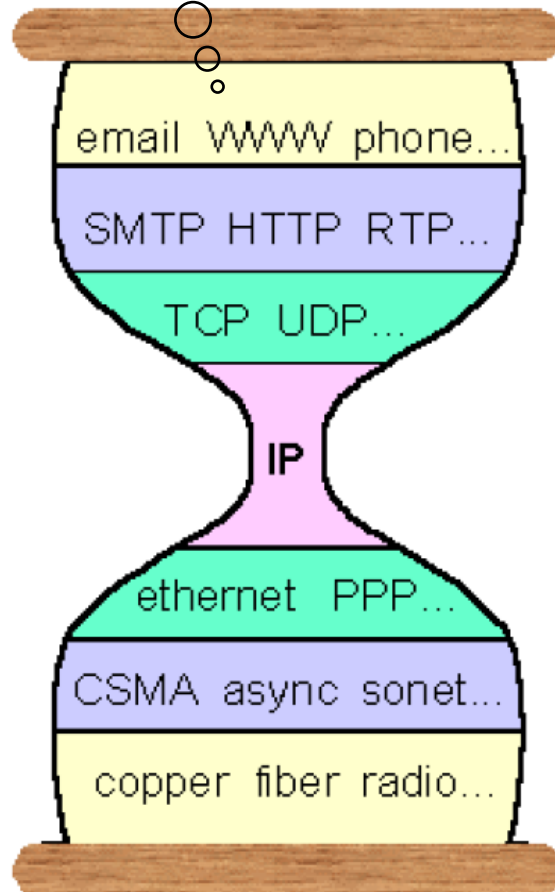
Private Islands and Walled Gardens

- No global addressing, **NAT Application-Layer Gateways**
- Statefull gateways for selected applications

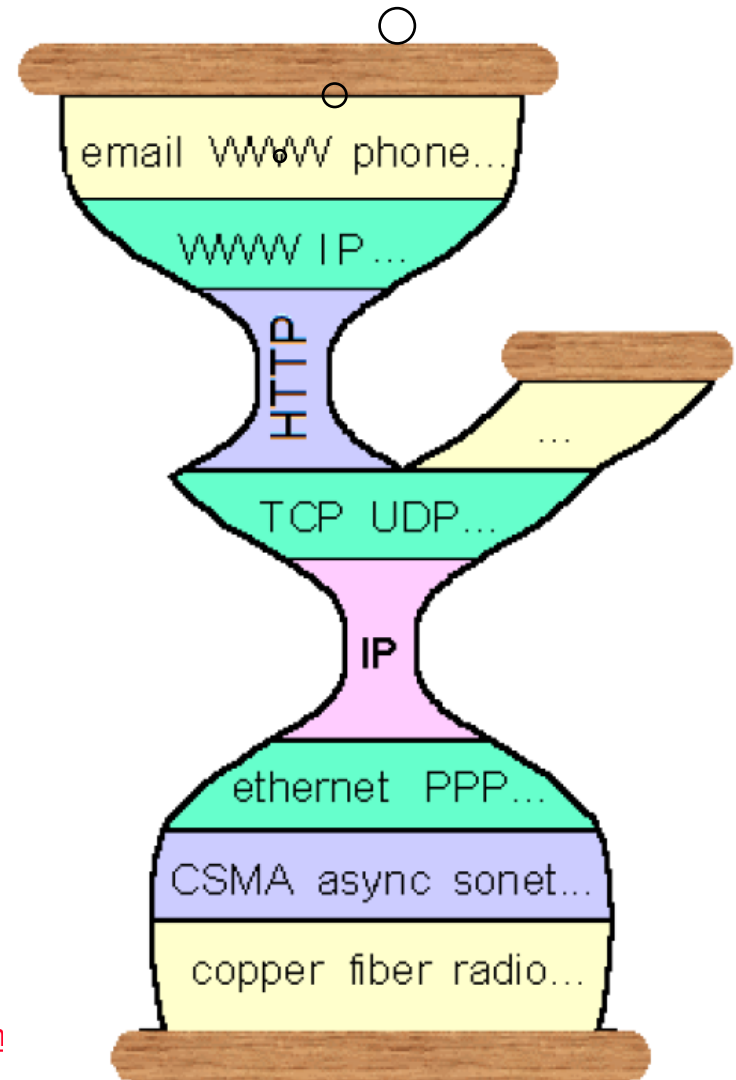


Distortion of the IP Model (Deering/Rosenberg)

Deering
1990



Rosenberg
2008

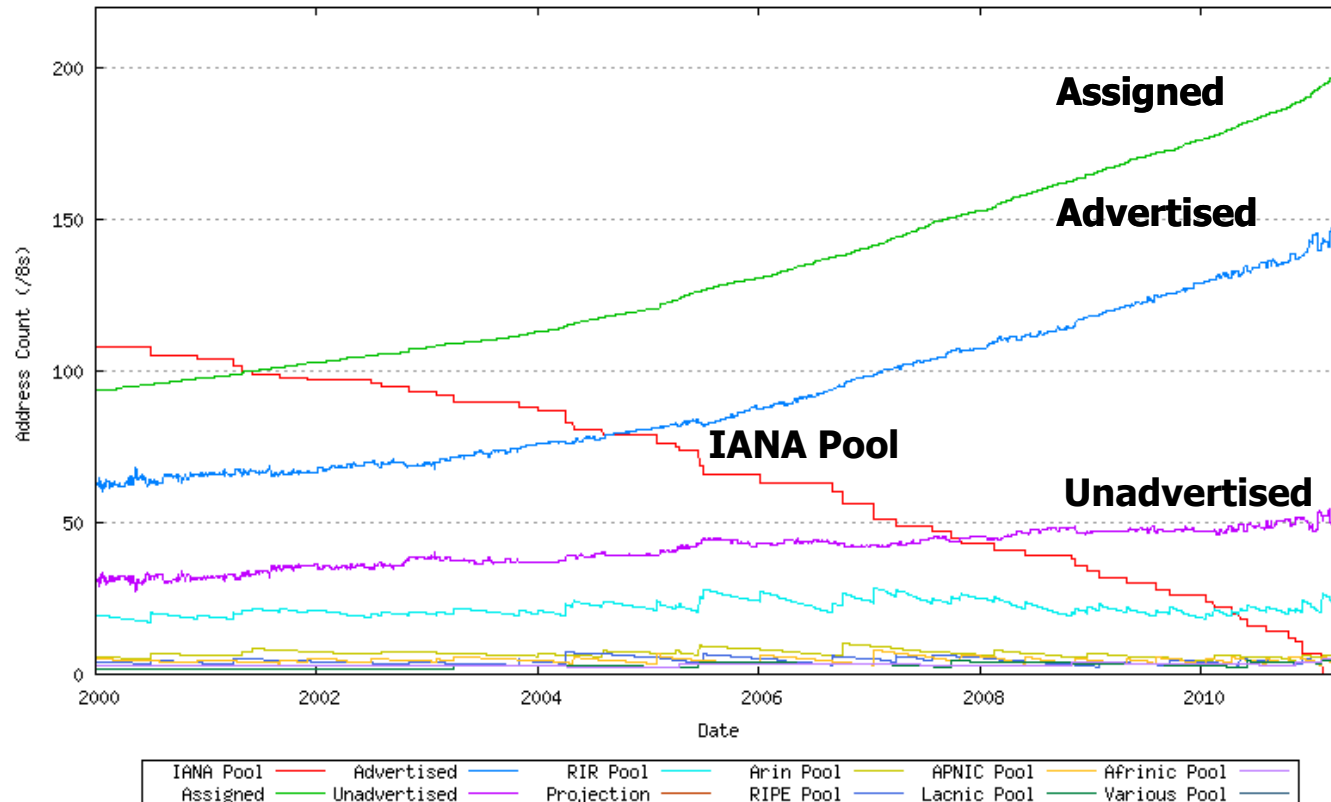


The Limits of IPv4

- o Basic design almost 40 years old
 - Packet format ... outdated
 - Hardware development of networks overran IP algorithms
- o Address space exhausted
 - ‚Regular‘ Internet growth runs out of addresses
 - New kinds of Internet devices (mobile telephones, intelligent devices,...) need new quantities of addresses
 - Caused by address bottle-neck: NAT-ALGs
- o Support of new services tedious to implement



IPv4 Address Exhaustion



- o IANA Unallocated Address Pool Exhaustion: 03-Feb-2011
 - o Projected RIR Unallocated Address Pool Exhaustion: Apr-11 – Jul-14
- Source: Geoff Huston, <http://www.potaroo.net/tools/ipv4/> as of Apr. 2011

IP Service Problems

- o **Address configuration:** Static, not stateless
- o **Backbone Routing:** Table explosion due to unstructured addresses
- o **Security:** IP over IP tunnelling
- o **Multicasting:** Routing too complex
- o **Anycasting:** Application specific solutions
- o **QoS:** No flow support
- o **Mobility:** Identifier/locator problem - inefficient triangular tunnelling
- o **Multihoming:** Provider abstraction missing



Why IPng: IPv6 + + + ?

- o Tackle the Internet scaling problem: Addressing & Routing
- o Return to openness for new services & future development
- o Evolve the architecture of the Internet
- o Meet new requirements of a 'business-critical' network
- o Avoid tedious patchwork to keep the Internet going



IPv6 Innovations

o Addressing and routing

- Elimination of address bottle-neck: 128 Bit addresses
- Address hierarchy can (was intended to) simplify backbone routing
- Several addresses per interface

o Simple administration

- Autoconfiguration of interfaces without DHCPv6
- Floating net masks, renumbering via prefix change

o Security: IPSec

- Security header extension for authentication, integrity and encryption



IPv6 Innovations (2)

o Protocol architecture

- Slim, fixed header for fast processing
- Optional extension headers
- Format framework for header classes
- No header checksum
- No fragmentation in routers

o Improved multicast, anycast, QoS and mobile services

o Support of Jumbograms (> 64 KB)

o Transition and coexistence concept IPv4 ↔ IPv6



IPv6 History

- o IETF WG IPng began to work in the early 90er
- o Winter 1992: 7 proposals for development of IP
 - CNAT, IP Encaps, Nimrod, Simple CLNP, PIP, SIP, TP/IX
- o Autumn 1993: several mergers lead to
 - 'Simple Internet Protocol Plus' (SIPP) and 'Common Architecture for the Internet' CATNIP
- o July 1994: IPng Area Director recommend roadmap (RFC 1752) on basis of SIPP (Steve Deering)
- o Dec. 1995: S. Deering, R. Hinden, „Internet Protocol, Version 6 (IPv6) Specification“ (RFC 1883, now RFC 2460)
- o July 1999: End user addresses available (RIPE-NCC, APNIC, ARIN)
- o May 2007: ARIN advises Internet Community on Migration to IPv6

IPv6 Standardisation

- o Key components in standard track:

Specification (RFC2460) Neighbour Discovery (RFC2461)

ICMPv6 (RFC2463)

IPv6 Addresses (RFC1884 ++)

RIP (RFC2080)

BGP (RFC2545)

IGMPv6 (RFC2710)

OSPF (RFC2740)

Router Alert (RFC2711)

Jumbograms (RFC2675)

Auto configuration (RFC2462)

- o IPv6 over: PPP (RFC2023)

Ethernet (RFC2464)

FDDI (RFC2467)

Token Ring (RFC2470)

NBMA(RFC2491)

ATM (RFC2492)

Frame Relay (RFC2590)

ARCnet (RFC2549)

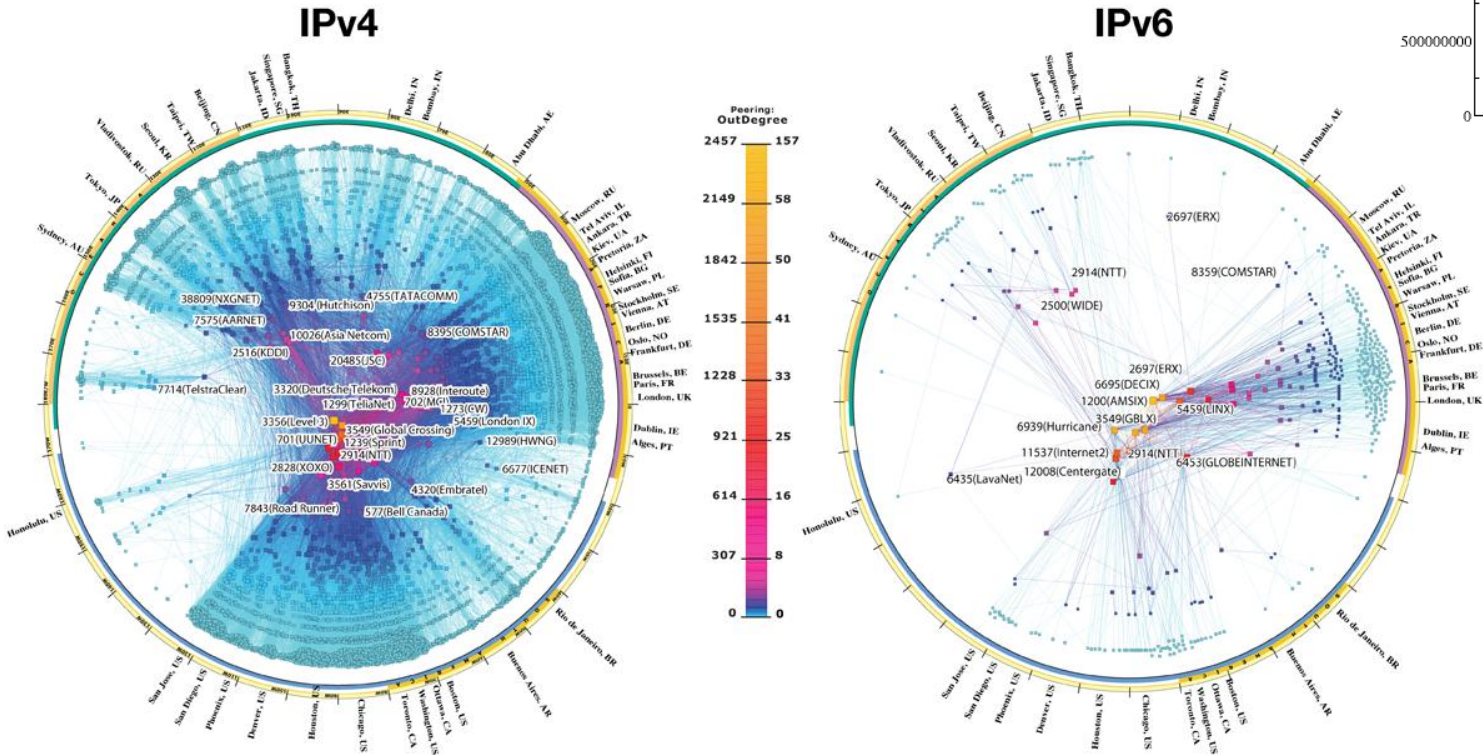
- o Since then 100++ further standards: Flow labelling, MIPv6, 3GPP, Routing advertisement,

- o Implemented basically in every Internetworking system platform

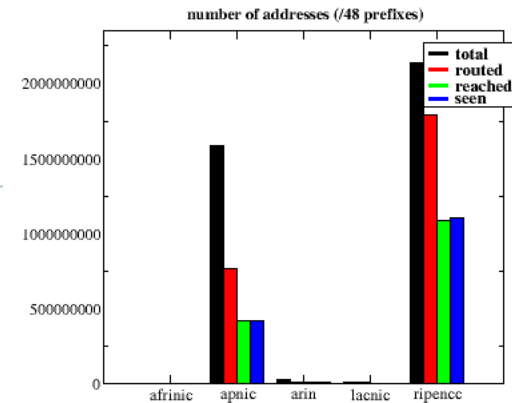


IPv4 & IPv6 INTERNET TOPOLOGY MAP JANUARY 2009

AS-level INTERNET GRAPH



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o Source: CAIDA

(http://www.caida.org/research/topology/as_core_network/ipv6.xml)

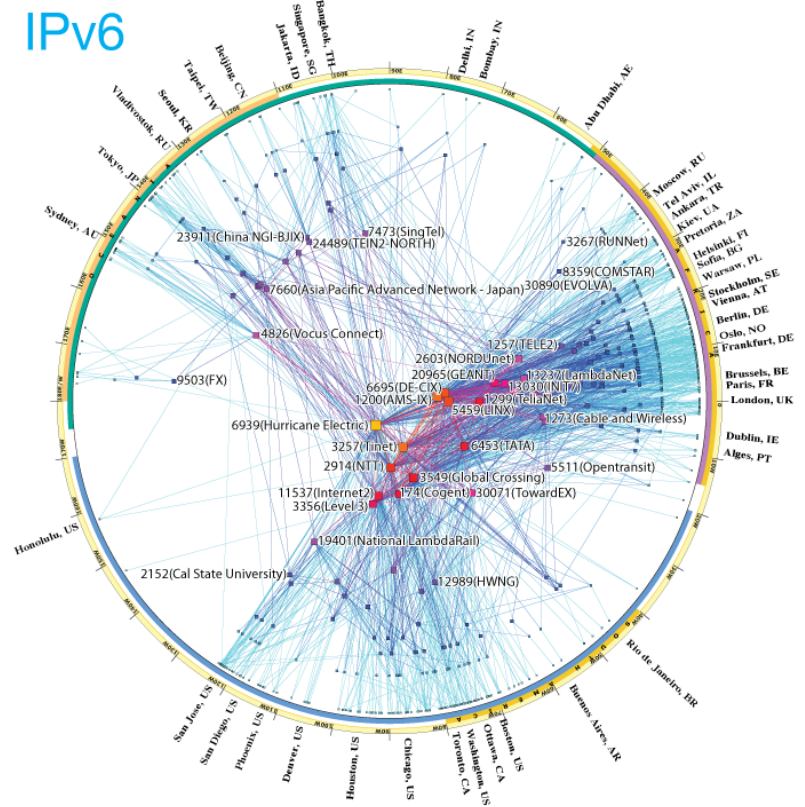
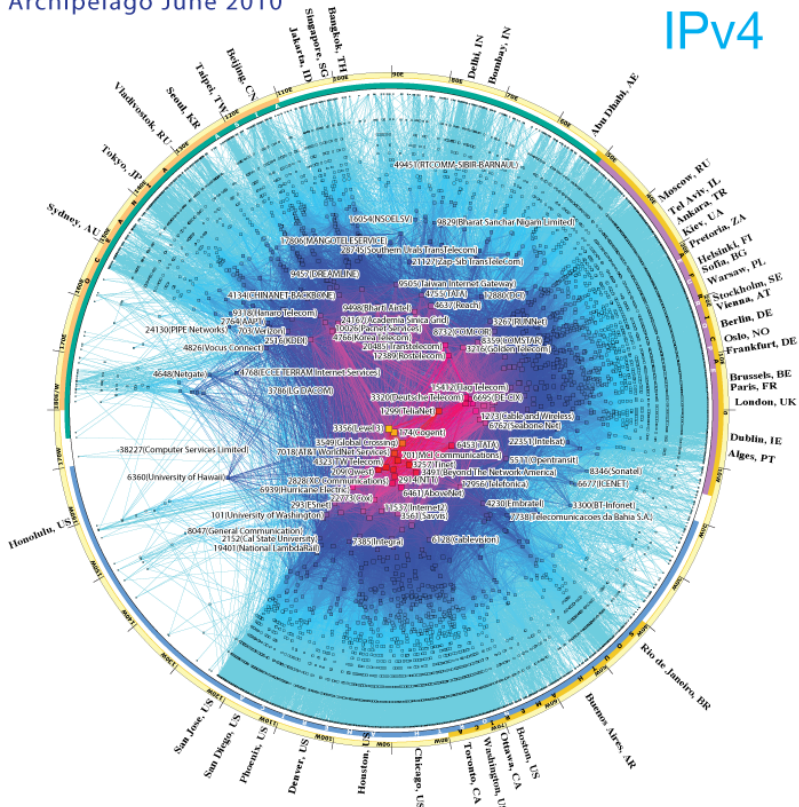


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IPv6 Deployment Progress June '10

CAIDA's IPv4 & IPv6 AS Core AS-level INTERNET GRAPH

Archipelago June 2010



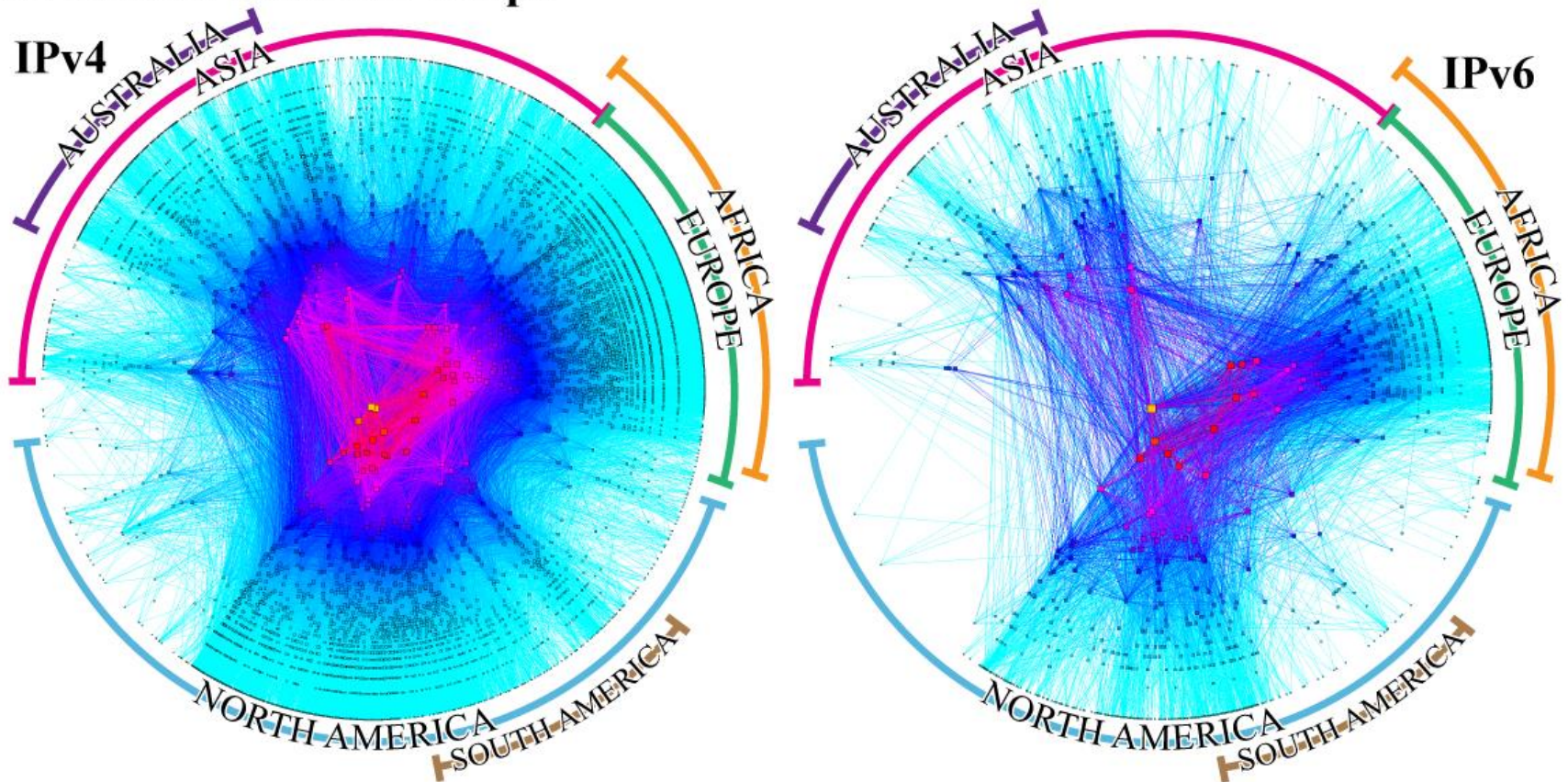
o Source: CAIDA

(http://www.caida.org/research/topology/as_core_network/ipv6.xml)

IPv6 Deployment Progress Jan '13

CAIDA's IPv4 & IPv6 AS Core
AS-level INTERNET Graph

Archipelago
Jan 2013

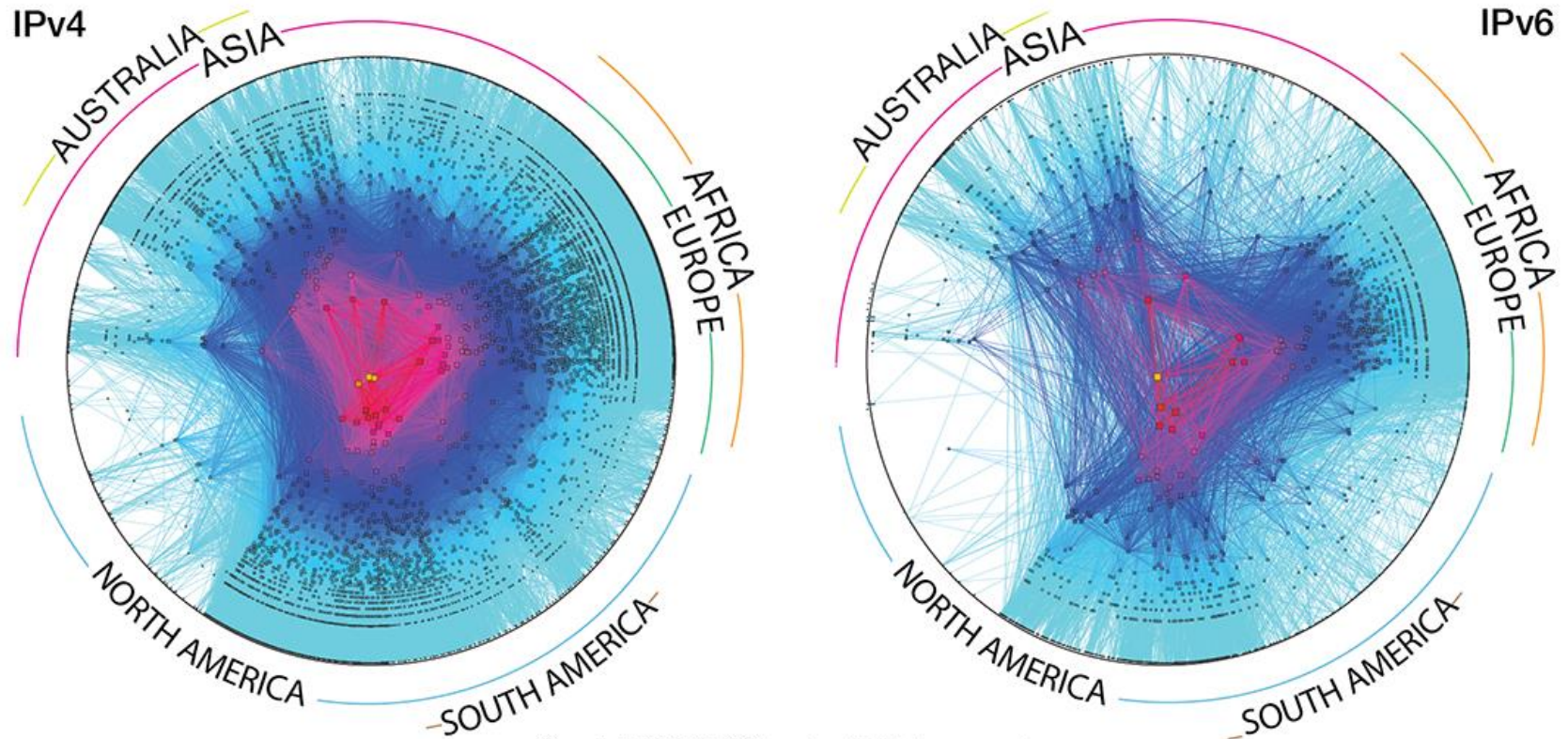


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IPv6 Deployment Progress Jan '14

CAIDA's IPv4 & IPv6 AS Core AS-level INTERNET Graph

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Agenda



Motivation



Basic IPv6 Architecture

- ➔ Addressing
- ➔ Packet Format
- ➔ ICMP, Neighbour Discovery, Autoconfiguration
- ➔ Routing, Anycasting, QoS, Multihoming



IPv6 Migration: Transition and Coexistence



Internet of Things: 6LoWPAN



Future Trends: Beyond IPv6



Addressing

- o IPv6 addresses are 128-bit long and variably built
- o Address architecture: RFC 1884, now 4291 (Feb '06, Hinden & Deering)
- o Automatic address configuration
- o **Global address hierarchy** from top level allocation to the interface-ID designated
- o **Aggregation-based allocation** to simplify the global routing (target objective)
- o **Format prefix (FP)** (3 Bit initially) used for identification of address type



Notation of IPv6 Addresses

- o **Standard form:** 8 x 16 bit hexadecimal
Example: 1080:0:FF:0:8:800:200C:417A
- o **Short form:** sequences of nulls replaced by ::
Example: FF01:0:0:0:0:0:0:43 → FF01::43
- o **IPv4 compatible addresses:**
Example: 0:0:0:0:0:FFFF:13.1.68.3 → ::FFFF:13.1.68.3
- o **CIDR notation for prefixes:**
Example: 1080:645:FF::/48

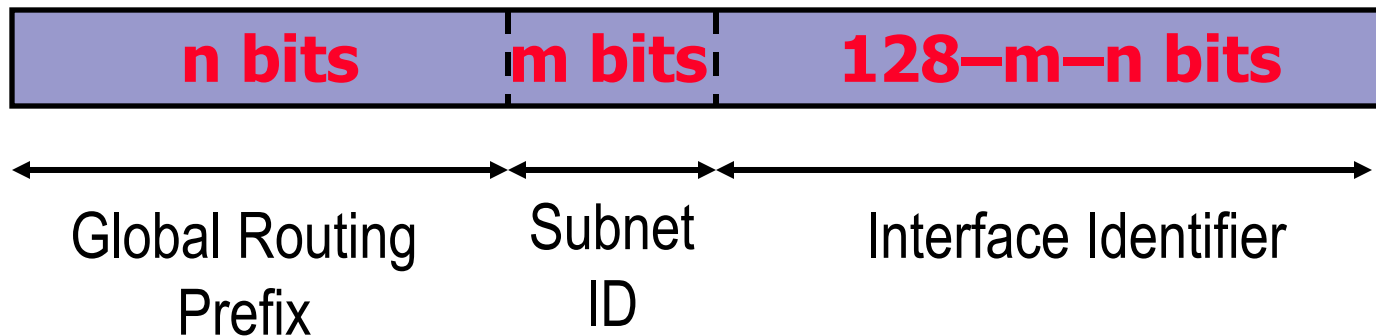


Address Types

<u>Type</u>	<u>Binary Prefix</u>	
o Unicast (one-to-one)		
- global	all not specified elsewhere	
- site-local (deprecated)	1111 1110 11	(FEC0::/10)
- unique local (ULA)	1111 110	(FC00::/7)
- link-local	1111 1110 10	(FE80::/10)
- IPv4-mapped	000...0:FFFF	(::FFFF:xxx.xxx.xxx.xxx)
- loopback	0000...1	(::1/128)
- unspecified	0000...0	(::/128)
o Multicast (one-to-many)	1111 1111	(FF00::/8)
o Anycast (one-to-nearest)	of Unicast Prefixes	
o No broadcast addresses (only multicast)!		



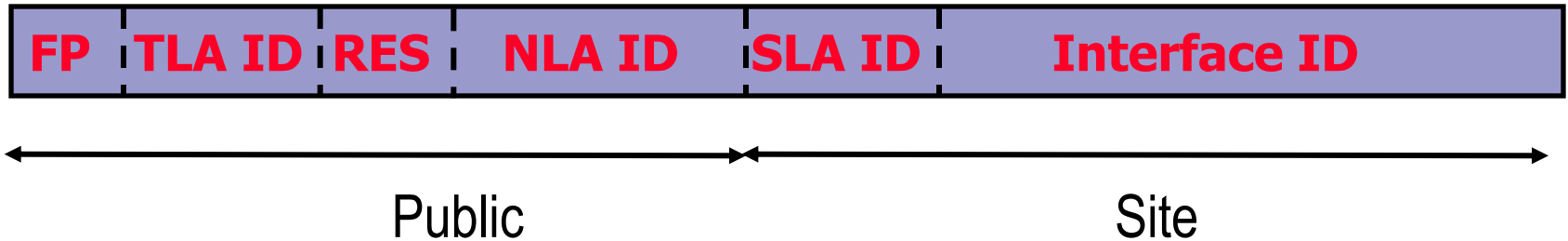
Global Unicast Addresses - RFC 4291



- o All fields have variable length and are not 'self-explanatory' (as of CIDR)
- o All global unicast addresses, which do not begin with 000 (binary), carry a **64 bit interface ID**, this means $m + n = 64$
- o Mechanisms of automatic prefix exchange provided



Historic – RFC2374: Aggregatable Global Unicast Format



- o Previous approach: Standardized prefix hierarchy as **Top/Next/Side Level Aggregator**
- o Current approach:
 - IAB/IESG Recommendations on IPv6 Address Allocations to Sites, RFC 3177
 - Left to RIR policies cf. <http://www.ripe.net/ripe/docs/ipv6policy.html>



Local Unicast Addresses

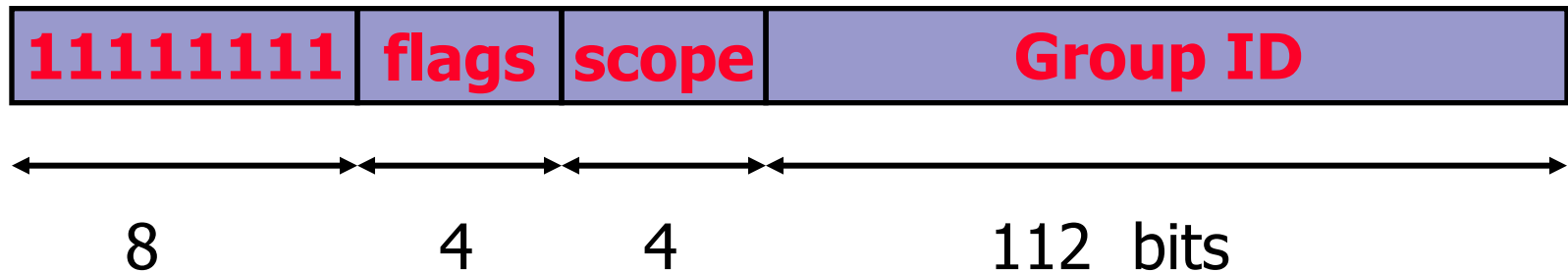
- o Link-local addresses for use during auto-configuration and in nets without routers:



- o Unique local addresses (RFC 4193), independent of TLA/NLA:
 - Globally unique for local communication, only (avoiding conflicts)
 - Not intended for global routing (but e.g., for dedicated site interconnects)



Multicast Addresses



- o **Flag field:** lower bit indicates permanent (=0) respectively transient (=1) group, rest is reserved (==0)
- o **Scope field:**
 - 1 - node local
 - 2 - link-local
 - 5 - site-local
 - 8 - organisation local
 - B - community-local
 - E - global (other values reserved)



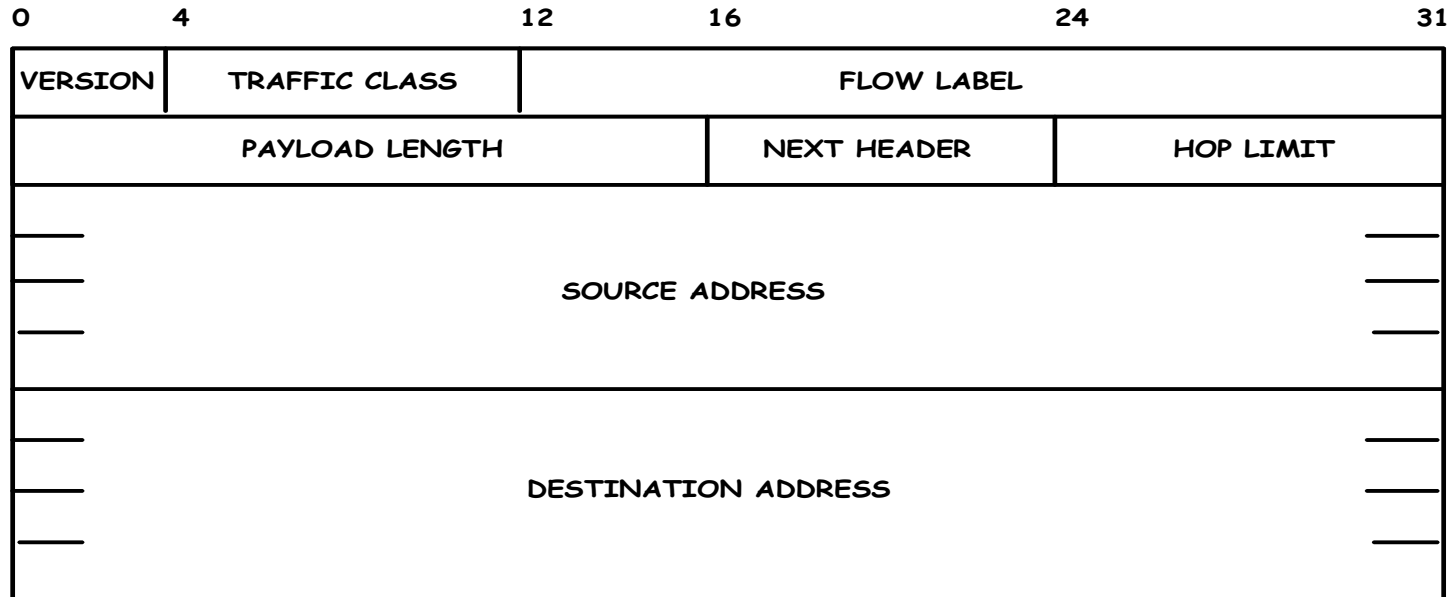
Example: FHTW IPv6 Net

- 2001:: /16 - Pre-set prefix
- 2001:**0600**:: /24 - Regional registry Europa (RIPE)
- 2001:06**38**:: /32 - DFN prefix
- 2001:0638:**0801**:: /48 - FHTW net address
- 2001:0638:0801:**0001**:: /64 - First FHTW subnet
- 2001:0638:0801:0001:**0000:0000:0000:0001** /128
 - First IPv6 computer address at FHTW in 2001 😊

Addressing of Sub-TLAs (Ripe) according to RFC 2450



IPv6 Packet Format: Basic Header



VERSION	4 Bit	Internet Protocol Version Number = 6
TRAFFIC CLASS	8 Bit	Type of Services (QoS DiffServ field)
FLOW LABEL	20 Bit	Flow Identification at Routers (QoS)
PAYLOAD LENGHT	16 Bit	Octetts of Payload without IPv6-Header
NEXT HEADER	8 Bit	Type of Encapsulated Protocol
HOP LIMIT	8 Bit	TTL-Counter, Decrementd per Router
SOURCE ADDRESS	128 Bit	Adress of Sender (128 Bits)
DESTINATION ADRESS	128 Bit	Adress of Receiver (128 Bits)

Compare: IPv4 Header

IP-Protocolkopf

1 4 8 16 19 24 32

Version	Länge	Servicetypen	Paketlänge			
Identifikation			D F	M F	Fragmenabstand	
Lebenszeit	Transport		Kopfprüfsumme			
Senderadresse						
Empfängeradresse						
Optionen					Füllzeichen	

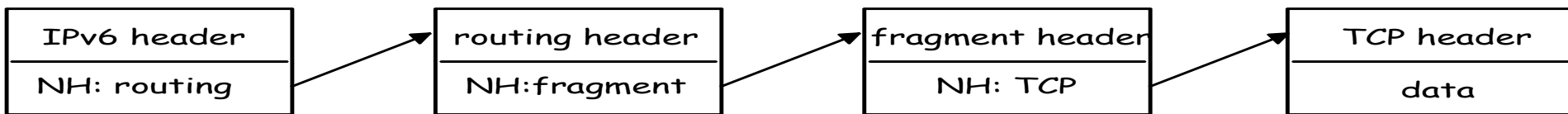
Header Changes of IPv4

- o Addressing grows from 32 to 128 Bit
- o Fragmenting will be deleted from basis header
- o IP Options will be deleted from basis header → fixed length
- o Header Checksum drop out
- o Header length field drop out
- o Flow Label newly included
- o Time to Live → Hop Limit
- o Protocol → Next Header
- o Service types → Traffic Class
- o Length field describes data without header
- o Alignment increases from 32 to 64 Bit



IPv6 Packet Format: Option Headers

- Extended option mechanisms: Each header references a possible successive header or data, e.g.:



- Option headers have no length limit (IPv4: 40 Octets), Padding to 8 Octets
- Option headers will be processed only at destination host, not by routers. Exception: **Hop-by-Hop** Option Header

Basic Option Headers

- o Routing

Advanced routing information (source routing)

- o Fragmentation

Fragmentation / defragmentation information

- o Authentication

Security information: authentication and integrity

- o Encapsulation

„Tunnelling“, i.g. for confidential data

- o Hop-by-Hop Option

Dedicated options to be processed by every router

- o Destination Option

Information for the destination host (header extension)



Order of Headers

The processing order of the headers will be arranged by the sender according to the following recommendation (RFC 2460):

1. IPv6
2. Hop-by-Hop Option
3. Destination Option (1)
4. Routing / Encapsulation
5. Fragmentation
6. Authentication
7. Destination Option (2)
8. Upper Layer



Internet Control Message Protocol (ICMPv6)

- o RFC 2463 (Conta, Deering), now RFC 4443 + 4884
- o Extension header protocol class (following base IP header)
- o Defines two (expandable) message classes:

Informational Messages Error Messages

- Echo Request (128)
- Echo Reply (129)
- Destination Unreachable (1)
- Packet Too Big (2)
- Time Exceeded (3)
- Parameter Problem (4) 

IPv6 Neighbour Discovery

- o RFC 2461, now RFC 4861
- o Protocol over ICMPv6
 - Combination of IPv4 Protocols (ARP, ICMP,...)
- o Autonomous interaction between hosts and routers
 - Defines 5 ICMPv6 packet types:
 - Router Solicitation / Router Advertisement
 - Neighbour Solicitation / Neighbour Advertisement
 - Redirect



IPv6 Neighbour Discovery (2)

- o Defines communication mechanisms for nodes on the same link:
 - Router discovery
 - Prefix discovery
 - Parameter discovery, i.e.: link MTU, hop limit,...
 - Address auto-configuration
 - Address resolution (same function as ARP)
 - Next-hop determination
 - Neighbour unreachable detection (useful for default routers)
 - Duplicate address detection
 - Redirect
 - Network load balancing

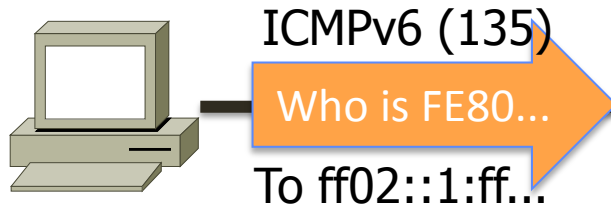


Neighbour Discovery Handshake

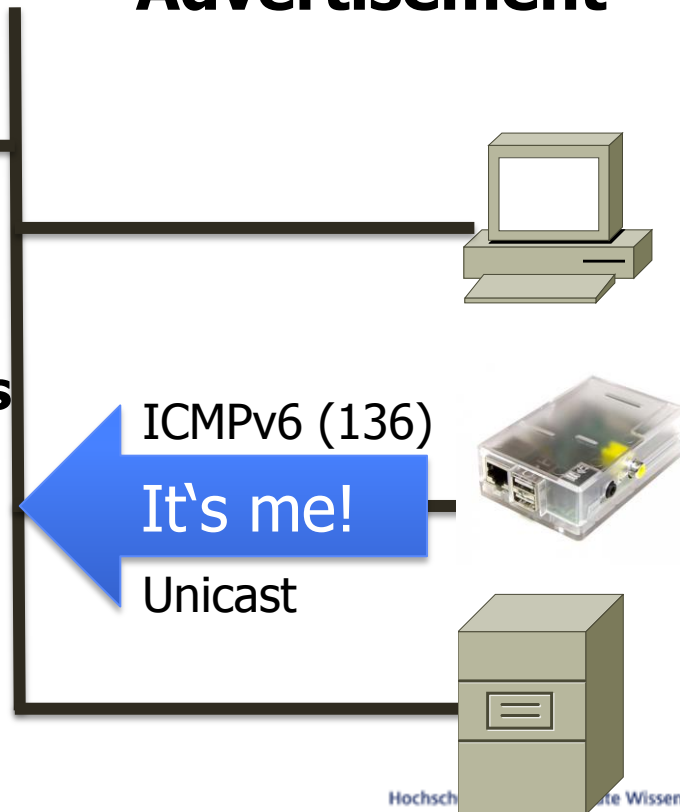
- Address of my neighbour?

Search **FE80::ba27:ebFF:FE3b:7def**64

Solicitation



Advertisement



**NDP uses
Solicited-node Multicast Address
Prefix: ff02::1:ff00:0000/104**

Remaining 24 Bits are from
Interface ID

Our Example: **ff02::1:ff3b:7def**

Stateless Auto-Configuration

1. Interface assigns a link-local address on activation (default: EUI-64 built from a hardware address).
2. Interface sends *router solicitation*, to omit waiting for router advertisements.
3. Router sends *router advertisement* (prefix, default gateway, ...).
4. The interface creates its global address from prefix and link-local address.
5. For verification of uniqueness, an ICMP *neighbour solicitation* will be issued on own address (Duplicate Address Detection).



Secure Neighbour Discovery - SEND

- o RFC 3971 (Arkko et al.)
- o Employs Cryptographically Generated Addresses (CGAs – RFC 3972) to authenticate NDP (“prevent ARP spoofing”)
- o SEND ND messages can self-consistently authenticate its IP sender address (without PKI)
- o Router/prefix advertisements require certificates (X.509v3) from a PKI to assure routing responsibility

Details in
MIPv6 Section



Auto-Reconfiguration

- o New address-prefixes can be distributed and retreated:
 - Coexistence periods between old and new prefixes
 - Hosts learn prefix-lifecycle and priorities via router advertisements
 - Old TCP-connections survive within coexistence periods, new TCP-connections survive prefix change
- o Prefix-distribution via **router renumbering protocol**
- o DNS-Structure (AAAA) does not follow this flexibility.



IPv6 DNS

Two approaches:

- o AAAA ("Quad A") Res. Rec. – RFC 1886, 3596

- A record type of 128 bit length
- Reverse lookup domain IP6.ARPA

- o A6 RR – RFC 2874

- Idea to support renumbering by prefix delegation
- A6 record contains a domain name pointer:

Prefix len.	Address suffix	Prefix name
-------------	----------------	-------------

- o IETF decided for AAAA – RFC 3363

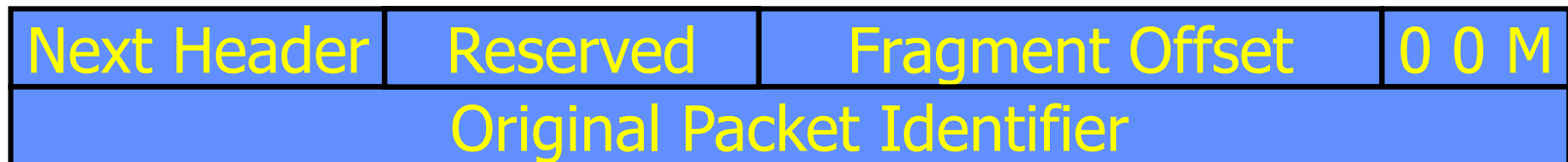


MTU Handling

- The minimal **Link-MTU** for IPv6 is **1280 Bytes** (versus 68 Bytes for IPv4).
- **Path-MTU discovery:**
 - Repeatedly send packets with known path-MTU size until no more ICMP 'Packet-too-big' is received
 - necessary only for packets > 1280 Bytes
- Minimal IP implementation can live without path-MTU discovery and without fragmentation (Packets ≤ 1280 Bytes).
- Upper Layer (TCP): **MSS** $\leq$ MTU – 60.
- A Hop-by-Hop Option supports the execution of **Jumbograms** with sizes up to 2^{32} Octets Payload.

Fragmentation

- IPv6 avoids the expensive fragmentation process on routers. The sender has to fragment, if necessary.
- Sender should execute path-MTU discovery.
- Routers answer with ICMP „Packet too big“.
- IPv6 Fragmentation Header can be used to support upper layers without dynamically executing MTU-Discovery.



Generic Packet Tunnelling of IPv6

- RFC 2473 (Conta, Deering)
- Mainly used for explicit routing path control
- Defines (statefull) end points:
 - Tunnel Entry-Point
 - Tunnel Exit-Point (at Unicast, Anycast or Multicast address)
- State variables contain MTU, Traffic Class, Flow Label
- Fragmentation may be necessary at tunnel entry point



IPv6 Routing

- o Uses CIDR „longest prefix match“/ largest mask to go for.
- o Hierarchical addressing is key issue for a scalable routing
 - VLSM route aggregation
 - Relies on provider-bound prefixes
- o Dynamical routing protocols from IPv4 updated:
 - Unicast: OSPF, RIP-II, BGP4+,...
 - Multicast: MLD, MOSPF, PIM, BIDIR-PIM ...
- o Can send packets through predefined regions by
 - routing headers (source routing) – type 0 deprecated (RFC 5095)
 - Anycast



5. Example: BGP RIB Entry

```
TIME: 2008-7-1 02:36:49
TYPE: MSG_TABLE_DUMP/AFI_IP6
VIEW: 0 SEQUENCE: 2702
PREFIX: 2001:0638::/32
ORIGINATED: Mon Jun 30 10:29:18 2008
FROM: 2001:0418:0000:1000:0000:0000:0000:f000 AS2914
AS_PATH: 2914 3549 680
MULTI_EXIT_DISC: 1
COMMUNITIES: 2914:420 2914:2000 2914:3000
```

Inter-AS Link Metric
Priorising redundant
Interprovider Peerings

Routing Policy Group
Groups type of propagation



Anycast

- o Service to 'one out of many' , RFCs 4291, 4786
- o Addressing from unicast
 - Prefix must cover all group members (least common)
 - Reg. Global Unicast, but some reserved:
 - Subnet (RFC 2526): subnet router, MIPv6 home agent
 - RFC 3068: 6to4 relays anycast address
 - RFC 4610: anycast rendezvous point in PIM
- o Anycast Routing
 - Within IGP: Host routes (dynamic/static)
 - Globally: According to covering prefix, global Anycast ASNs

Anycast (2)

o There are transport issues with Anycast:

- Subsequent packets may not always reach the same peer
 - Source address may never be anycast, so a unicast address must be used in a response
- TCP and IPSec cause conflicts, UDP deployable

o Today's deployment:

- Use for routers only
- Local / regional configuration
- DNS root servers
- 6-to-4 transition: Tunnel relay prefix 192.88.99.0/24
- Multicast: PIM rendezvous point anycast addressing + AMT

IPv6 & QoS

Priority: Traffic Class Field (8 Bit) break down in two classes:

- o Flow controlled traffic (0 - 7) – IPv4 compatible

- 0 Not specified

- 1 ‚Feeder‘ (i.g. netnews)

- 2 Unnoticed (i.g. email)

- 3 (Reserved)

- 4 Bulk (i.g. ftp, http)

- 5 (Reserved)

- 6 Interactive (i.g. telnet, X11)

- 7 Internet control (i.g. rip)

- o Traffic without flow control (Realtime, Constant Bitrate, ...)

- Priority from 8 to 15 (ascending)

- o Remaining prioritisation according to DiffServ code points



Flow Labels

20-bit Flow Labels can be used by senders to mark associated packets.

- o RFC 3697
- o Goal: accelerated, uniform handling of packet streams through routers
- o Flow label assignment: Random per Flow
- o Header information consistent per flow (router caching)
- o Defines router states: 120 s lifecycle



Multihoming

- o Goal: Redundant ISP connectivity for customers
 - o Problem space: Addressing & Routing
 - Using provider independent (PI) addresses prevents route aggregation
 - Using provider-bound addresses leaves administration to the end system domain
 - o Originally: No PIs in IPv6, but concept is broken
- ⇒ Threat of routing table explosion returned to IPv6

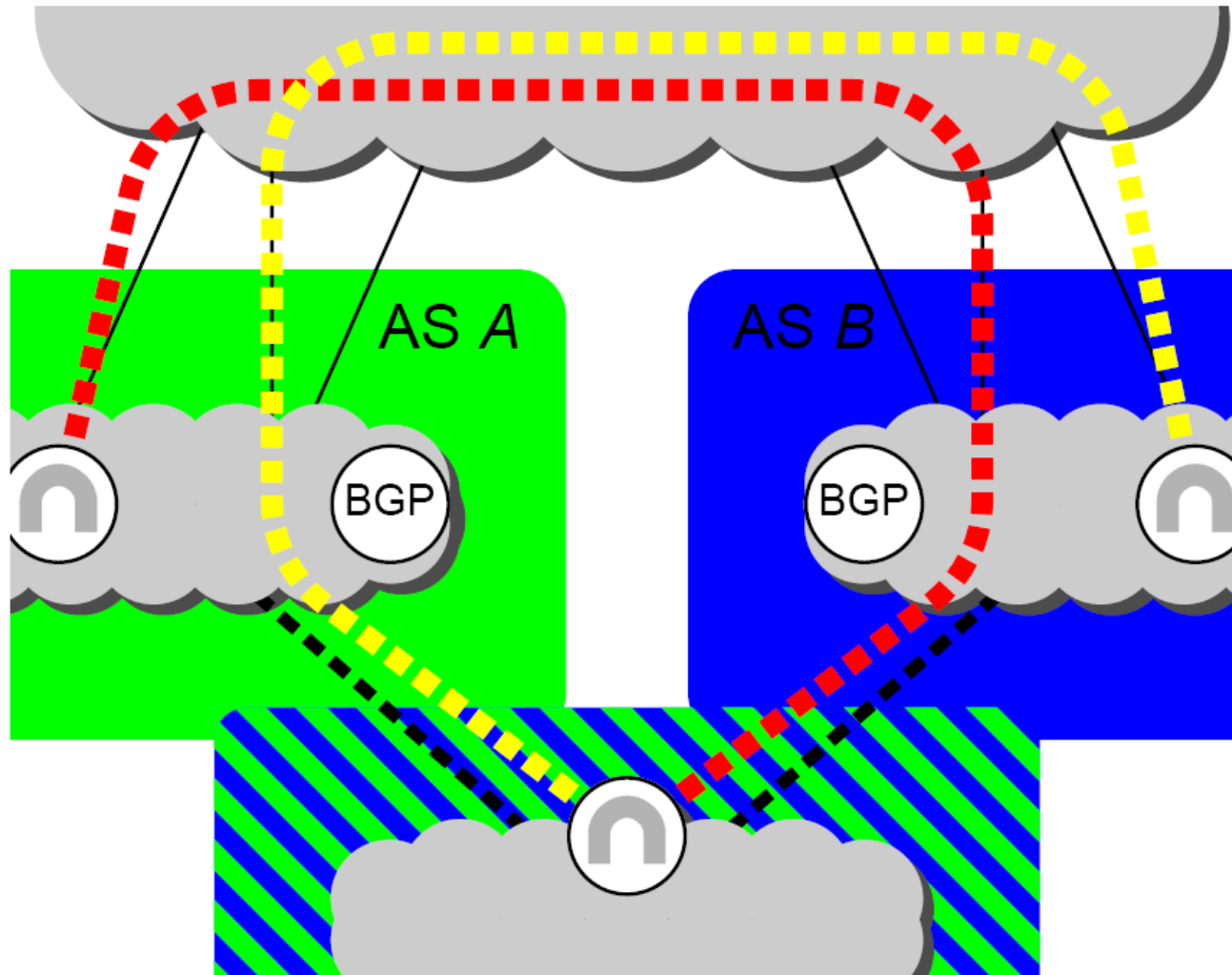


Multihoming without PI

- o Two prefixes in end system domains
- o Solution at node level:
 - Multiple DNS entries
 - End systems must choose preferred/correct address
 - SHIM6 protocol: RFC 5533
- o Solution at network level
 - Need failover implementation in network
 - Typically: Own AS, BGP announcements
- o Continuous disturbing issue within the IETF



Multihoming: Cooperative Redundant Connectivity



Agenda

- 🕒 Motivation
- 🕒 Basic IPv6 Architecture
- 🕒 IPv6 Migration: Transition and Coexistence
 - ➡ Programming: IPv6 API
 - ➡ Dual Stack
 - ➡ Tunnelling
- 🕒 Internet of Things: 6LoWPAN
- 🕒 Future Trends: Beyond IPv6



IPv4 → IPv6 Porting

- Source and binary code compatibility for existent application: 'all goes on', provided IPv4 is around
- Indirection for address data structure, new for IPv6:
`addrinfo` is linked list of interface address structs
- Name-to-address translation:
New functions to support IPv6 and IPv4
- Address conversion functions:
New functions to support IPv6 and IPv4
- DNS resolver:
Returns IPv6 or IPv4 address, or both
- Almost all standard (open source) applications ported

IPv4 → IPv6 Porting: API Changes

	IPv4	IPv6	
Data structures	AF_INET	AF_INET6	
	in_addr sockaddr_in	in6_addr sockaddr_in6	
Address conversion functions	inet_aton() inet_addr()	inet_pton()	IPv4 and IPv6 functions
	inet_ntoa()	inet_ntop()	
Name-to-address functions	gethostbyname() gethostbyaddr()	getnameinfo() * getaddrinfo() *	

* POSIX protocol independant functions

IPv4 → IPv6 Migration

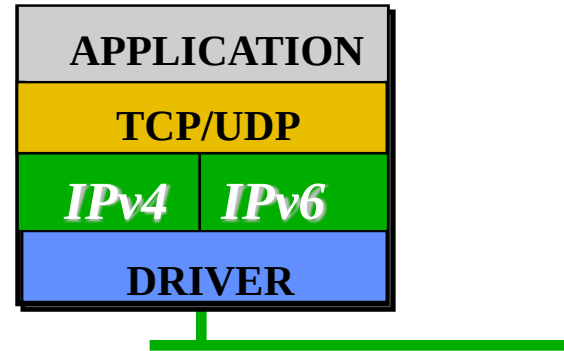
Many migration techniques have been designed and implemented according to the following approach:

- **Dual-Stack** techniques, which allow the coexistence of IPv4 and IPv6 at the same device and subnet
- **Tunnel**, which connects IPv6 regions over IPv4 regions
- **Protocol translator**, which let IPv6 devices with IPv4 devices speak

During migration, the combined use of all these methods is likely.



Dual Stack

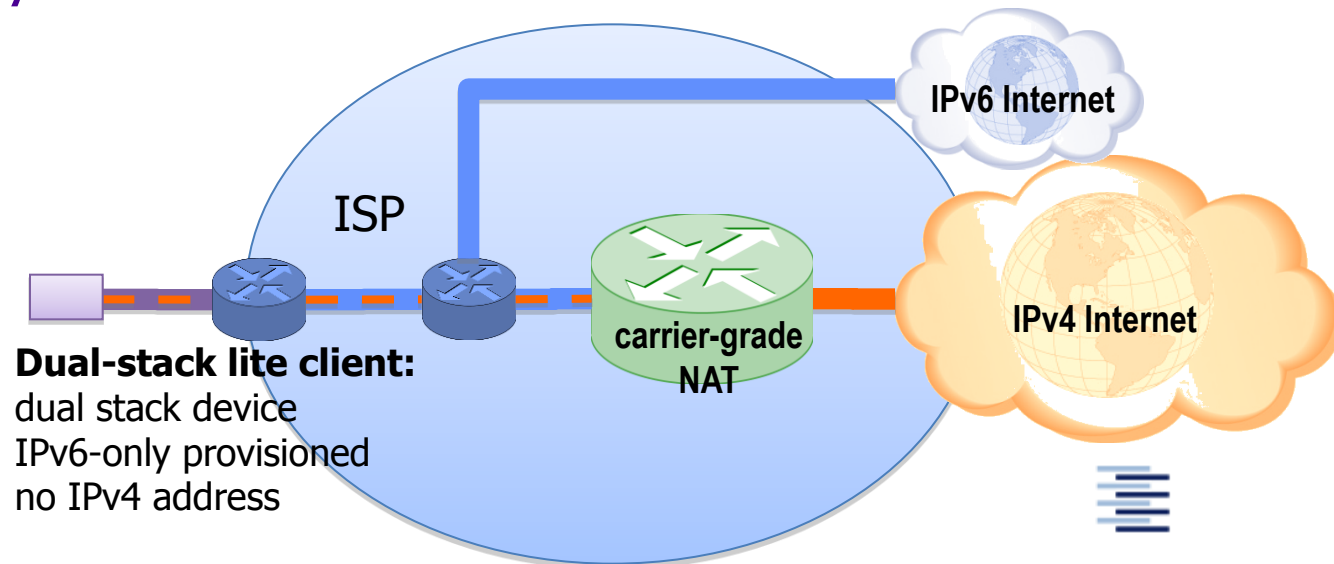


- o On activation of IPv6, the IPv4 can continuously be used (multi protocol approach)
- o Devices can keep their addresses (IPv4 in IPv6)
- o Application / libraries choose the IP version:
 - in dependence of DNS answer with IPv6 preference
 - in dependence of received packets
- o The Dual stack operation can continue without limits, allowing the step by step porting of applications
 - But requires an increasing use of IPv4-NATting (recursive)
- o Problems result from inconsistencies of Network / DNS configurations

Dual Stack Lite

- RFC 6333 -

- o IPv6-only at customer – but dual stack at system
- o IPv4 over IPv6 tunnel to Carrier-grade IPv4-IPv4 NAT
- o IPv4 access via globally unique IPv4 address shared among many customers



Transition by Tunnels

- o Embedding of IPv6 packets in IPv4 packets

- o Diverse methods to build a tunnel:

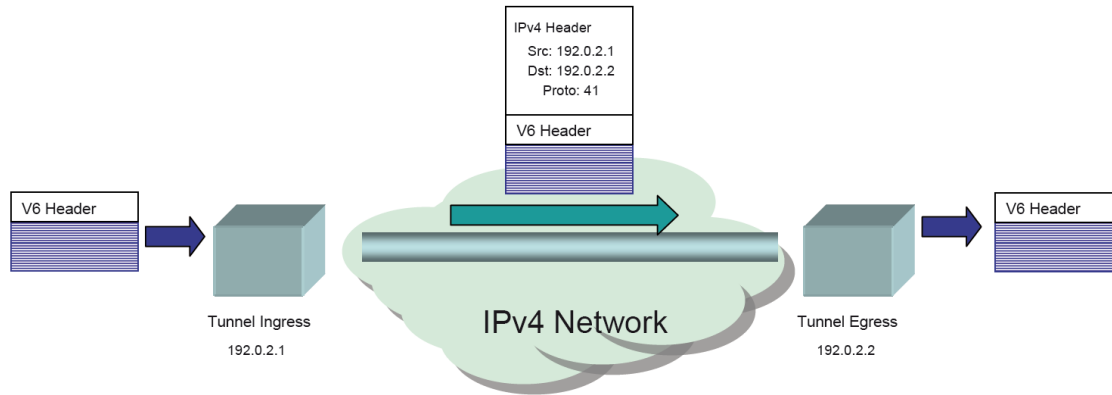
- Manuel
- Tunnel Broker (web based application to build a tunnel)
- 6-over-4 (intradomain)
- 6-to-4 (interdomain, IPv4 address as IPv6 site prefix)

- o View:

- IPv6 use IPv4 as a virtual link layer
- IPv6 VPN over IPv4

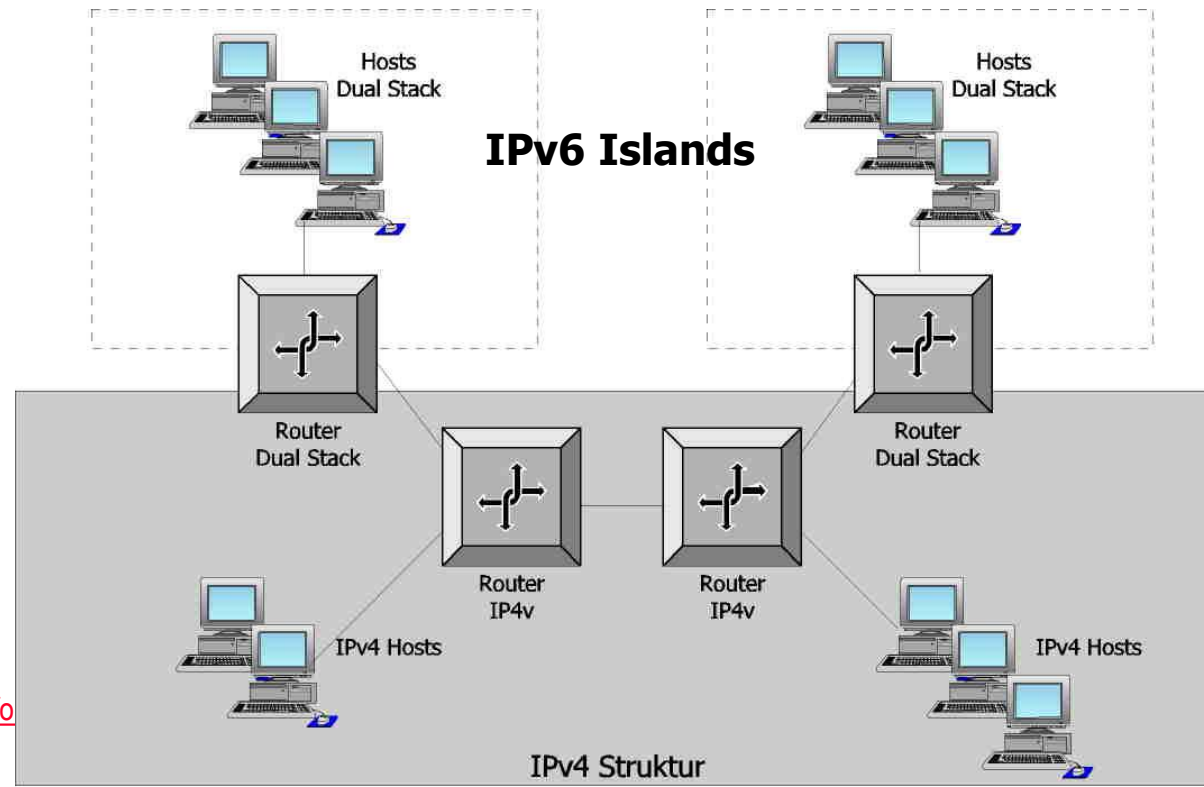


6-over-4 Tunnels

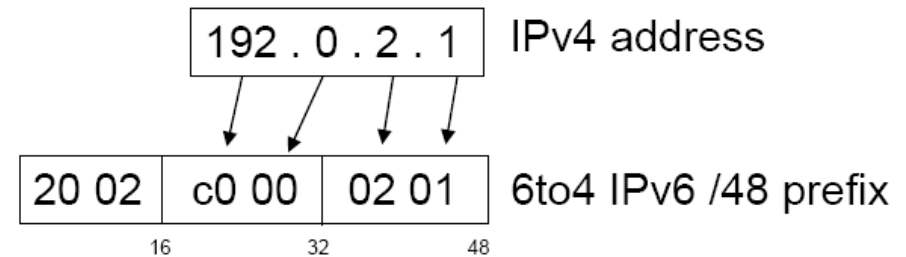


Isolated IPv6 islands in an IPv4 world

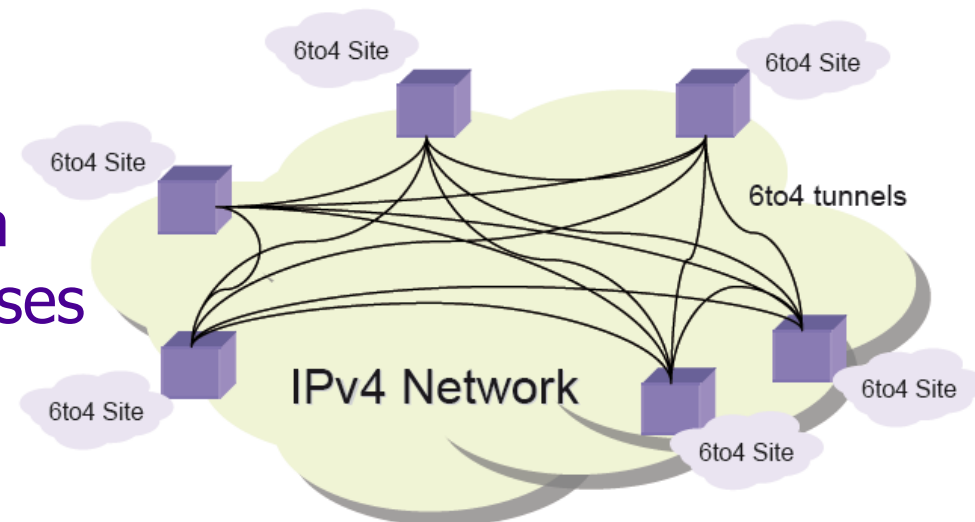
IPv6 ↔ IPv4 inter-connects: Embedding
IPv6 ↔ IPv6 inter-connects: Following tunnel configurations



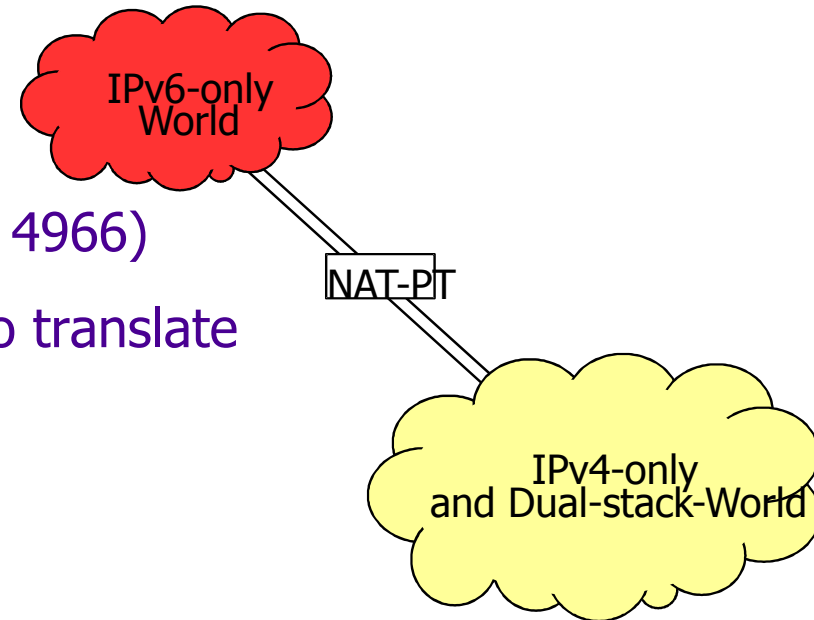
6-to-4



- o Defines automated point-to-multipoint tunnels, RFC 3056 ff.
- o Assigns an IPv6 network to each IPv4 address (taken as prefix)
- o Allows IPv6 islands to automatically interconnect, using IPv4 as a non-broadcast multi-access network
- o Automatic tunnel access via well-known Anycast addresses
- o TEREDO: Extension to NAT traversal



Protocol Translation



- o RFCs 3142, 2766 (deprecated by RFC 4966)
- o NAT-PT: stateless extension of NAT to translate header formats and addresses
 - IPv6 nodes behind translator attain full IPv6 functionality
 - Stateless protocol translation by SIIT (RFC 2765)
- o NAPT-PT: Statefull address + port translation (RFC 2766)
- o Scenario:
 - New ‚domains‘ from Internet devices (telephones, cars, ...)
 - When a pure IPv6 configuration should/must be used



Agenda

- 🕒 Motivation
- 🕒 Basic IPv6 Architecture
- 🕒 IPv6 Migration: Transition and Coexistence
- 🕒 Internet of Things: 6LoWPAN
 - ➡ IP in the Internet of Things
 - ➡ Architectural Challenges
 - ➡ 6LoWPAN Contributions
- 🕒 Future Trends: Beyond IPv6



IP in the Internet of Things

- o 100+ Billion microcontrollers exist worldwide (in contrast to several hundred million Internet devices)
 - Rapid growths and demands for *scalable* connectivity
 - Integrate into the global Internet with E2E data flows
 - Interoperable, long-lived, reliable standards required: **IP++**
- o Link-layers are different
 - All wireless (traditionally wired unavailable or too expensive)
 - Dedicated technologies: 802.15.4, Power-Line, Z-Wave (home automation), Sub-GHz Industrial, Scientific and Medical radios
- o Constraint Communication: Low Power Lossy Networks (LLN)
 - Measures of Bytes ... instead of Megabytes
- o Constraint Devices: Microcontrollers
 - Measures of kHz and kByte



What is 6LoWPAN

- o IPv6 over Low-Power ($\supset$ Personal) wireless Area Networks
- o A transparent way to integrate embedded devices into the global Internet
 - Global addressing
 - E2E transport between embedded and core devices
- o IPv6 adaptation to LLNs
 - Stateless header compression
 - Optimized neighbor discovery
 - Standard Socket API



6LoWPAN Applications

- o Facility, Building and Home Automation
- o SmartCities & SmartGrids
- o Personal Sports & Entertainment
- o Healthcare and Wellbeing
- o Asset Management
- o Advanced Metering Infrastructures
- o Environmental Monitoring
- o Security and Safety
- o Industrial Automation



Link Layer Excursion

- o Low power, typically battery operated
- o Relatively low cost
- o Inherently unreliable due to wireless medium
- o Small packet size: ~100 Bytes
- o Low bandwidth: ~100 kbit/s
- o Topologies include star and mesh
- o Networks are ad hoc & devices have limited accessibility
- o Characteristics of 802.15.4:
 - 16-bit short or IEEE 64-bit extended MAC addresses
 - Entire 802.15.4 frame size is 127 bytes, 25 bytes frame overhead
 - Bandwidth ranges from 20 to 250 kbit/s
 - 802.15.4 subnets may utilize multiple radio hops



Challenges of LoWPAN

Impact Analysis	Addressing	Routing	Security	Network management
Low power (1-2 years lifetime on batteries)	Storage limitations, low overhead	Periodic sleep aware routing, low overhead	Simplicity (CPU usage), low overhead	Periodic sleep aware management, low overhead
Low cost (<\$10/unit)	Stateless address generation	Small or no routing tables	Ease of Use, simple bootstrapping	Space constraints
Low bandwidth (<300kbps)	Compressed addresses	Low routing overhead	Low packet overhead	Low network overhead
High density (<2-4? units/sq ft)	Large address space – IPv6	Scalable and routable to *a node*	Robust	Easy to use and scalable
IP network interaction	Address routable from IP world	Seamless IP routing	Work end to end from IP network	Compatible with SNMP, etc 

Protocol Stack

TCP/IP Protocol Stack

HTTP		RTP	
TCP	UDP	ICMP	
IP			
Ethernet MAC			
Ethernet PHY			

Application

Transport

Network

Data Link

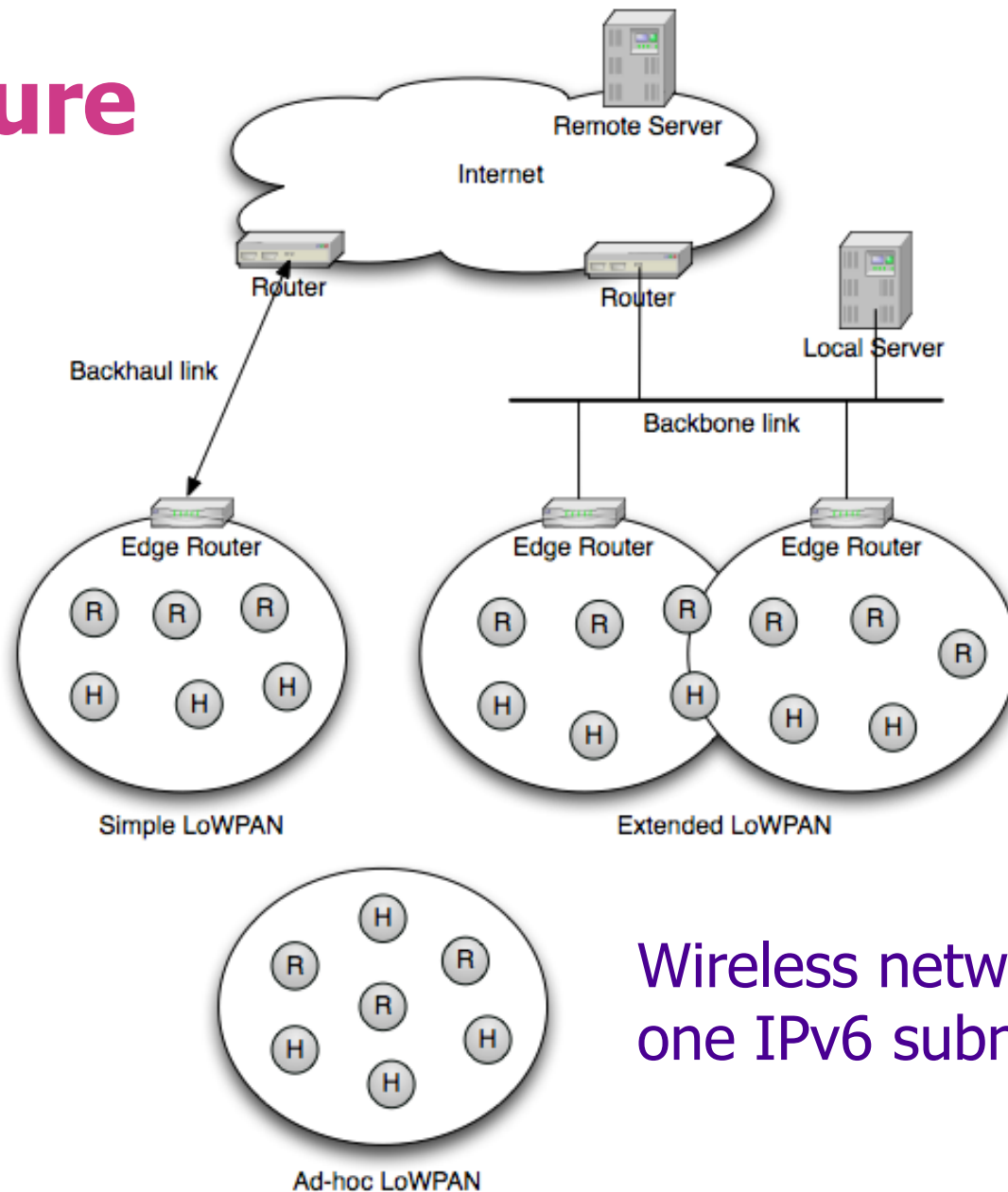
Physical

6LoWPAN Protocol Stack

Application	
UDP	ICMP
IPv6 with LoWPAN	
IEEE 802.15.4 MAC	
IEEE 802.15.4 PHY	



Architecture



Wireless network is
one IPv6 subnet



Architecture

- o LoWPANs are stub networks
- o Simple LoWPAN
 - Single Edge Router
- o Extended LoWPAN
 - Multiple Edge Routers with common backbone link
- o Ad-hoc LoWPAN
 - No route outside the LoWPAN
- o Internet integration issues
 - Maximum transmission unit
 - Application protocols
 - IPv4 interconnectivity
 - Firewalls and NATs
 - Security

IPv6	
Ethernet MAC	LoWPAN Adaptation
	IEEE 802.15.4 MAC
Ethernet PHY	IEEE 802.15.4 PHY

IPv6-LoWPAN Router Stack



Key Problems

- o Efficient use of available bits in a packet
 - Frame: 127 bytes – 25 bytes L2 header
 - IPv6 header: 40 bytes, UDP header: 8 bytes ...
- o IPv6 MTU size ≥ 1280
 - IP packets need transparent fragmentation on frames
 - Lost fragments cause retransmission of entire packet
- o Wireless ad hoc networks can be multihop
 - No direct router link $\leftrightarrow$ Router Advertisement
 - Multicast is only local $\leftrightarrow$ Neighbor Discovery



Base Solution: RFC 4944

Makes 802.15.4 look like an IPv6 link:

- o Efficient encapsulation

- Stateless IP/UDP header compression of intra-packet redundancy
- Unicast + Multicast address mapping

- o Adaptation layer for fragmentation (1280 MTU on ~100 bytes packets)

- Fragmentation: Datagram tag + offset
- No dedicated fragment recovery

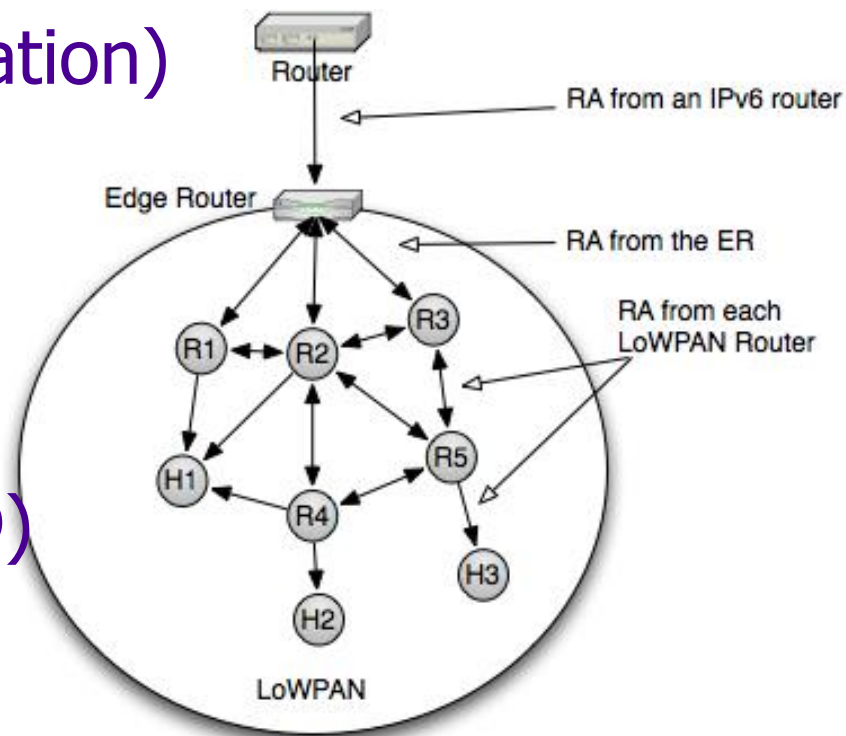
- o Mesh forwarding

- Link generated by „mesh-under“ (L2) routing
- Identify originator and final destination



Improved Neighbor Discovery RFC 6775

- o Includes „route-over“ (L3 routing)
- o Multihop forwarding of Router Advertisements (GW and prefix dissemination)
- o Address Registration and Confirmation at Router
- o Router keeps track of wireless nodes (incl. DAD)

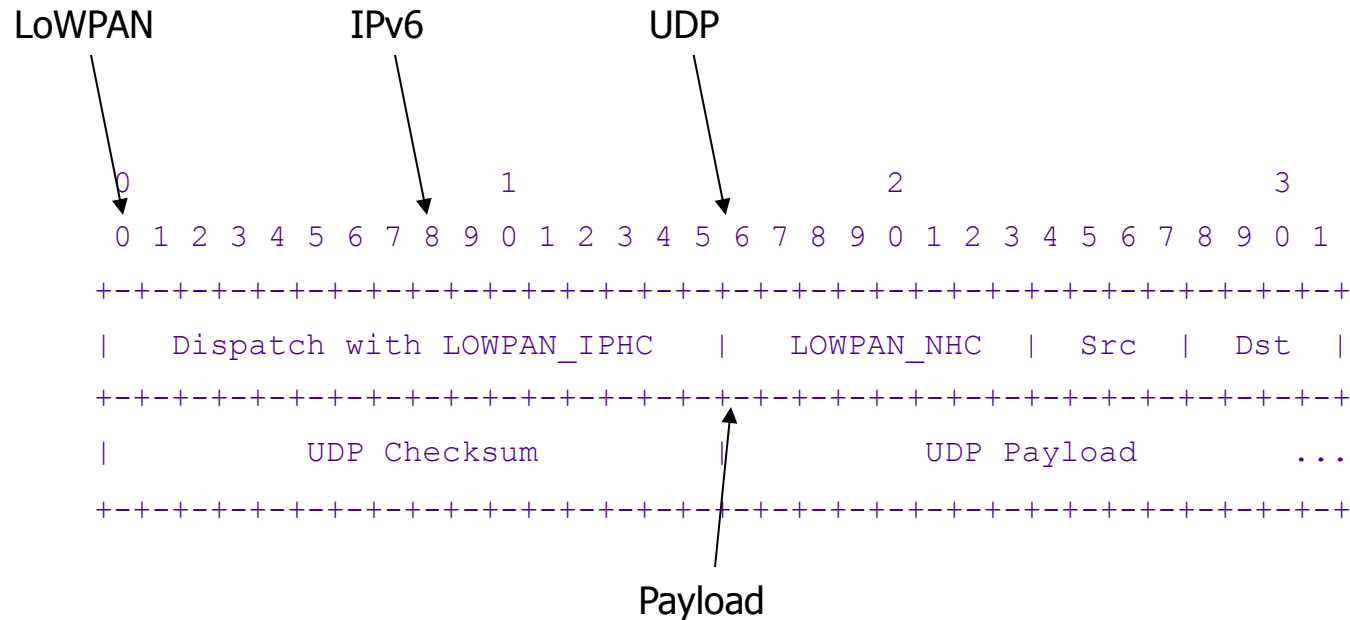


Improved Header Compression RFC 6282

- o Router Advertisements distribute a well-known area context
 - Common prefix – LoWPAN is a flat network
 - 6LoWPAN-HC – header compression methods
- o No addresses – Interface Identifiers derived from MAC addresses
 - Optional unicast and multicast address fields (compressed)
- o Remaining IPv6 header fields compressed or elided
 - Length derived from frame, ToS and Flow Label elided
- o Stateless UDP header compression including short ports and selected checksum removal
 - Length derived from frame length



LoWPAN UDP/IPv6 Headers

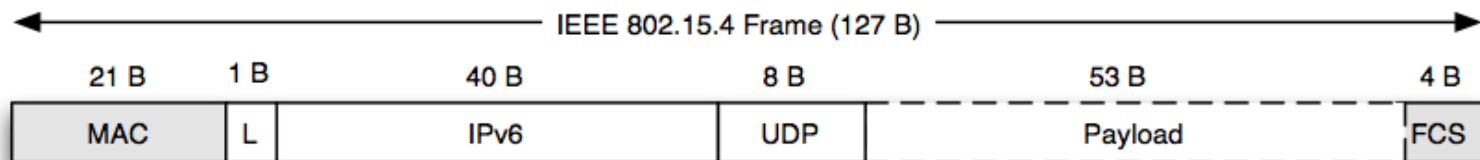


6 Bytes!

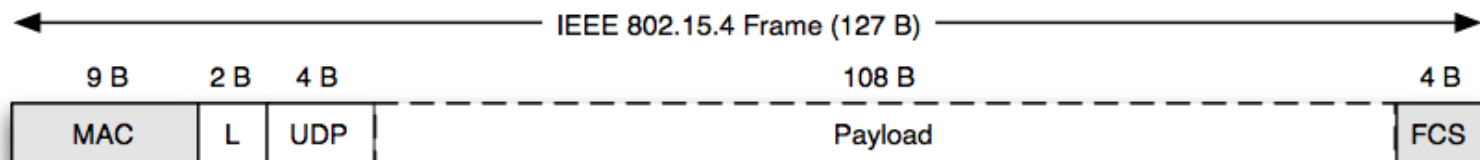


6LoWPAN Headers

- o Orthogonal header format for efficiency
- o Stateless header compression



Full UDP/IPv6 (64-bit addressing)



Minimal UDP/6LoWPAN (16-bit addressing)

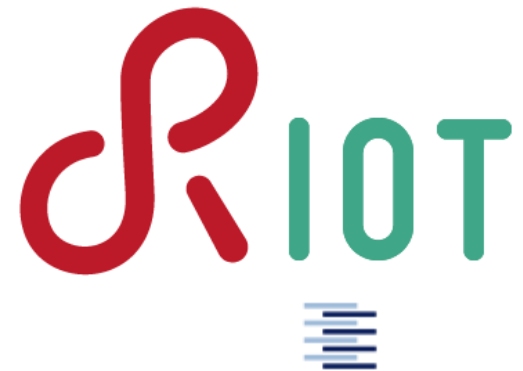


Further Aspects & Activities

- o 6LoWPAN on Blue Tooth Low Energy
- o Routing: RPL +?
- o Application Layer: COAP
 - Optimized variant of http
- o Widely implemented:



Contiki



Agenda

- 🕒 Motivation
- 🕒 Basic IPv6 Architecture
- 🕒 IPv6 Migration: Transition and Coexistence
- 🕒 Internet of Things: 6LoWPAN
- 🕒 Future Trends: Beyond IPv6
 - ➡ Lessons Learned
 - ➡ IRTF/IETF Work
 - ➡ Some Visionary Proposals



Lessons Learned

- o IPng deployment
 - Internet is inert “victim” of IPv4 success
 - Internet is “victim” of its uniqueness constraint
- o Development of innovations within the Internet
 - Clear trend: broadening of the range of applications
 - Unclear: “who steers the IP layer” – Pipe owners pushing packets versus user-driven, intelligent layer 3 services
- o Internet design – Quo Vadis?
- o Routing – *the* scaling issue
- o DNS – inflexible, updates too slow, *but scalable*



Issue: Economic Models for Internet Operation

o Several players:

- Infrastructure providers (pipes, routers, hosting)
- Top-level ISPs (international transit providers)
- Customer-oriented / regional ISPs
- Edge domain operators (companies, consumer-ISPs)

o Problem: Grouping according to regions, not services

- Little room for service innovation / dedication

o Approach: **Virtualization of infrastructure**

- Allows for slicing of cables (λ s), routers and servers
- Offers playground for specialized service provisioning



Issue: Naming & Addressing

- o IP addresses carry a dual meaning of Identifier (who) and locator (where)
 - Initially ID=name, Loc=address [Cohen, D., "On Names, Addresses and Routings", IEN 23, 1978]
 - TCP used addresses as identifiers (DNS was not ready)
- o Mobility re-raises the problem
 - MIPv6 creates an ID/Locator split on network layer
- o Host Identity Protocol (HIP, RFC 5201) introduces abstraction layer between network and transport



Issue: Route Scalability

- o Routing table size and dynamics in the core increases due to growing numbers and heterogeneity at edge domains
- o Two counter measures:
 - **Aggregation** – PA addressing as proposed by IPv6
 - **Separation** – decoupling of edges from core by a Map-Encapsulate mechanism
- o Ongoing debate
 - Map/Encap opens freedom of design at edge domains



IRTF / IETF Work

- o IAB Workshop on Routing and Addressing
s. [draft-iab-raws-report-00](#)
- o From 2007 on, the Routing Research Group
called for and discussed proposals
s. [http://trac.tools.ietf.org/group/irtf/
trac/wiki/RoutingResearchGroup](#)
- o RRG made a decision March '10 and published
recommendations in [RFC 6115](#) (Feb. '11)



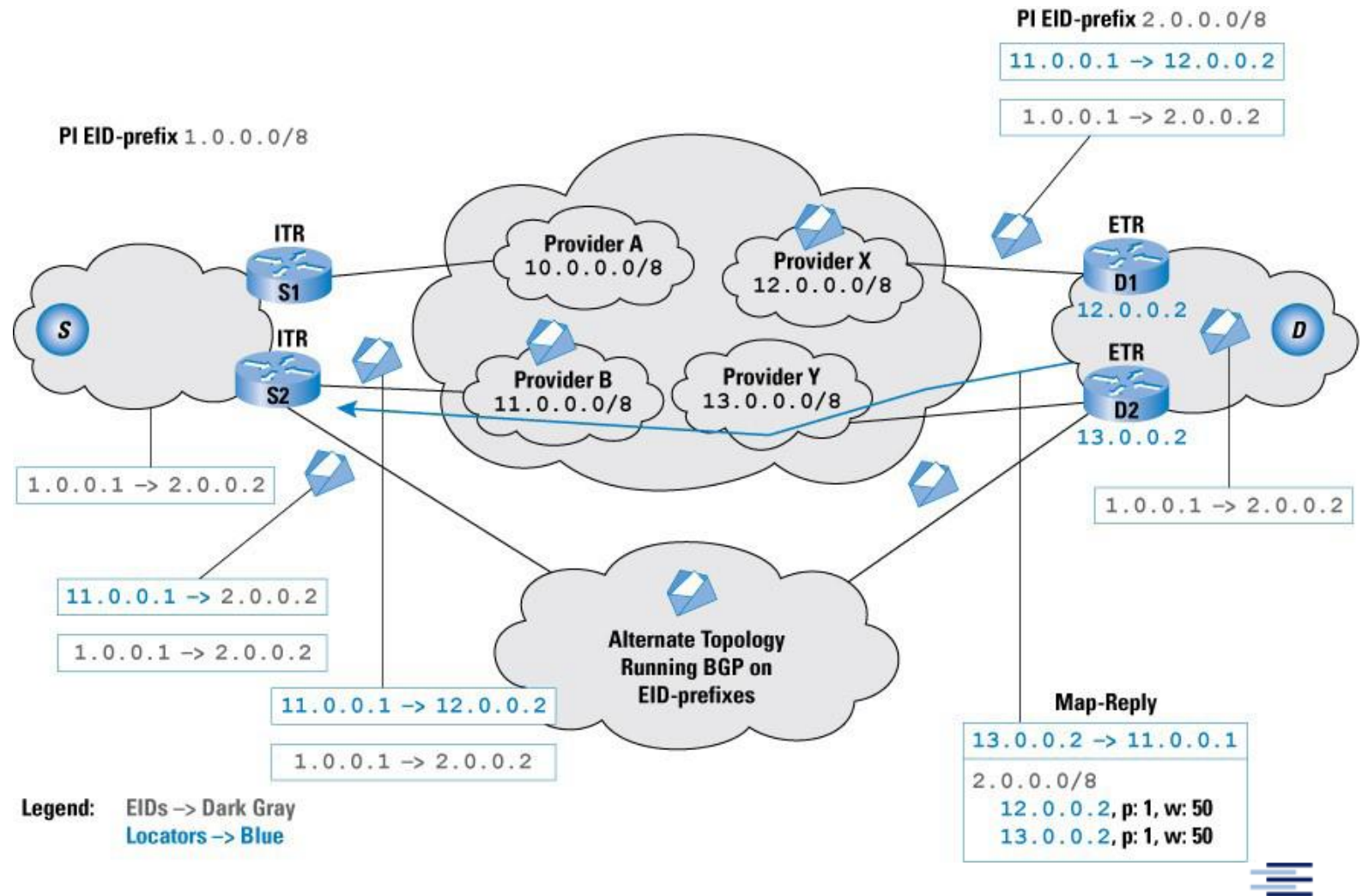
Locator ID Separation Protocol (LISP)

RFC 6830

- o Sites / nodes have addresses (as in DNS): provider independent IDs
- o Routers maintain a database of "Routing Locators (RLOCs)": provider-bound IP addresses of routers in a destination site
- o Packets are tunnelled from egress to ingress router using RLOCs
- o Problem: Router databases ... to be learned from ICMP advertisements in LISP
- o Result: Removes load from core routers



LISP Scenario



Name-based Socket

draft-ubillos-name-based-sockets

o Straight-forward approach

- DNS Name is Identifier
- IP Address is Locator
- Initial name exchange
(for backward compatibility)

o Requires change of Socket API

- New address family (AF_NAME)

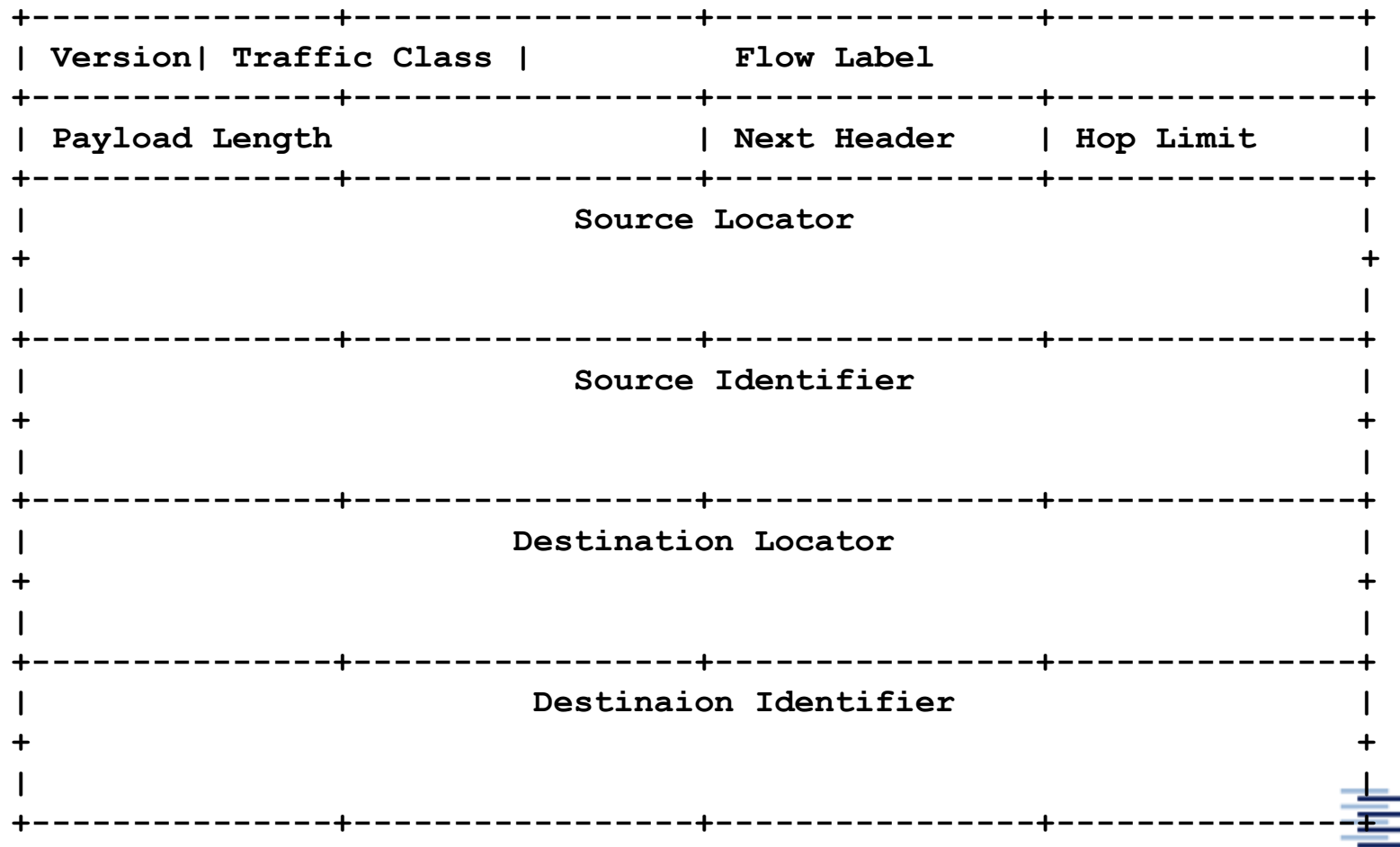


Identifier Locator Network Protocol (ILNP) RFCs 6740–6748

- o Idea (Clark/O'Dell ~1995) to split IPv6 addresses
 - Routing Locator – in IPv6: first 64 bits
 - Unique Identifier – in IPv6: second 64 bits
- o Locator and Identifier independently stored in a (modified) DNS
 - Additional records for resolution
 - Dynamic update function for locators at DNS
- o New, high-level API



ILNP: Re-interpretation of the IPv6 Header



Aggregation in Increasing Scopes

draft-zhang-zhang-evolution

- o Idea: Increase aggregation on global scale on the price of possible detours
 - Reduce global prefix resolution, e.g., route to 145.01/15 to reach an Aggregation Point
 - Provide detailed knowledge (full prefix resolution) at Aggregation Point and tunnel packets over the last hops



Recommendations of the RRG

- o Highly controversial debate lasting over more than 3-Years
- o Recommended for further development to the IETF
 1. Aggregation in Increasing Scopes
 2. ILNP
 3. Renumbering



Information-centric Networking

Idea: Access content by names from a network that

- o Operates in a Publish/Subscribe paradigm
- o Provides universal caching
- o Includes a content security model
- o Schemes: TRIAD, Dona, NDN, PSIRP, NetInf
- o Differences in Naming, Routing, Searching, Finding, and Security



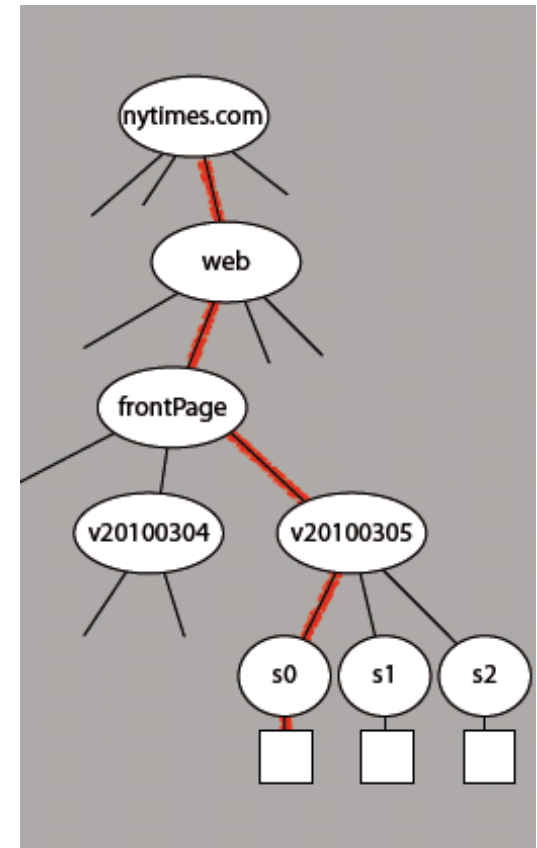
Named Data Networking

Van Jacobson et.al.

o Routes on Names

- Source publishes Content ,to a network` that caches and replicates
- Network distributes names in its routing protocol
- Subscriber requests content from network by name
- Request places `trail of breadcrumbs` in the network

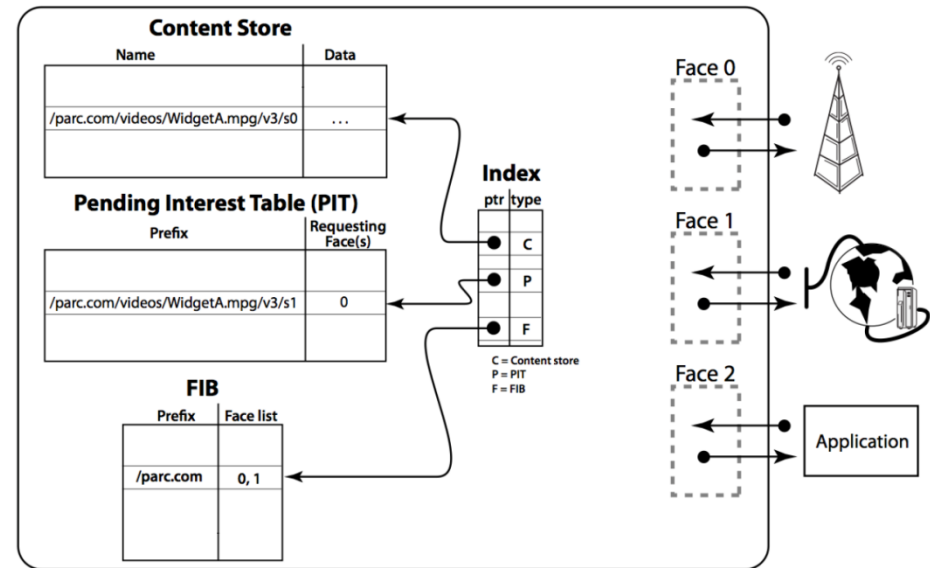
o Forwarding on reverse path



NDN Statefull Routing and Forwarding

Details on state management:

- o Each router holds
 - Forwarding states (FIB)
 - Pending Interest Table (PIT)
 - In-network storage
- o States describe data chunks
 - Updates at high frequency



The Problem of State

Two kinds of states:

1. Content publication (and caching)
→ routing
2. Content request trails (bread crumbs)
→ forwarding

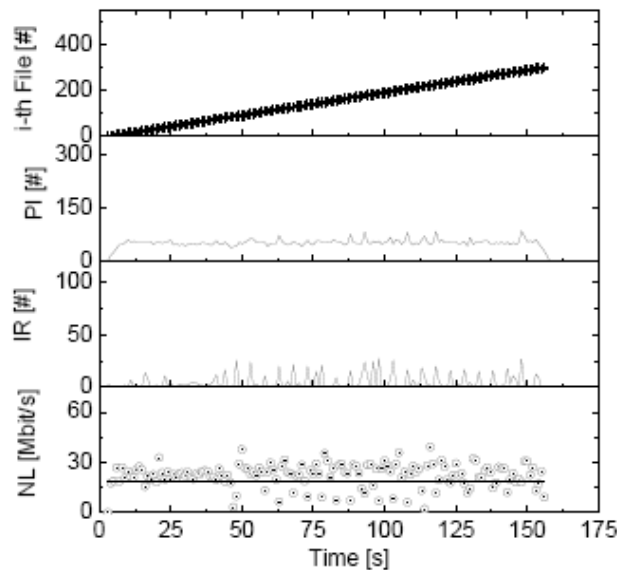
Both kinds are 'content-aware':

- o Control states are open to user activities
- o State management relies on data-driven events

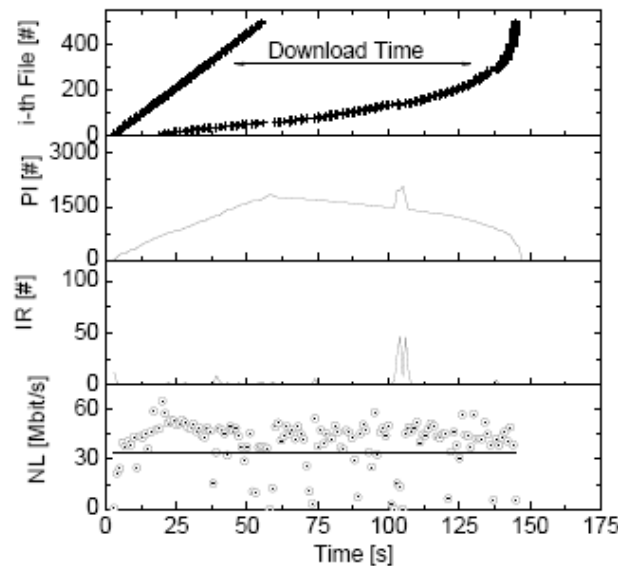


Data-driven States in Praxis

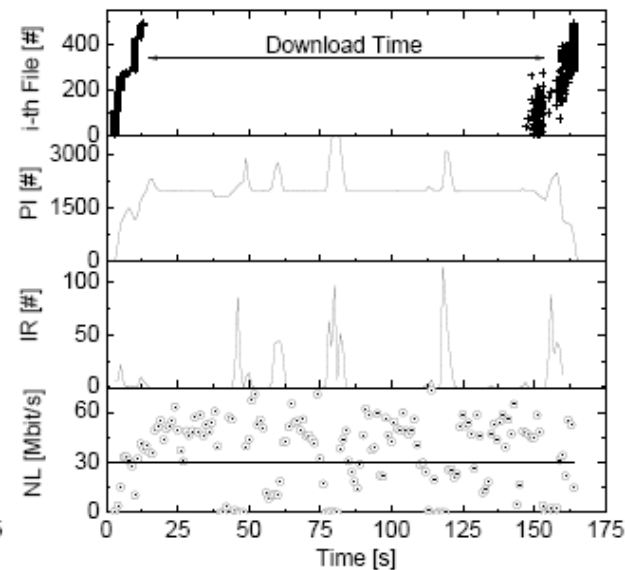
Example: Experimental Analysis for CCNx



(a) 2 files per second



(b) 10 files per second



(c) 100 files per second

Bulk of Interest: Performance Measurement of Content-Centric Routing,
In: *Proc. of ACM SIGCOMM Poster, 2012*



Reverse Path Forwarding States (PIT)

Consider the # of PI states at a router

$$\begin{aligned} S_i(t) &= S_i(t - T_i) + \int_{t-T_i}^t \alpha_i(\tau) - \omega_i(\tau) d\tau \\ &= S_i(t - T_i) + \int_{t-T_i}^t \alpha_i(\tau) - \alpha_i(\pi(\tau)) d\tau \\ &= \langle \alpha_i \rangle \cdot \min(\langle RTT \rangle, T_i) + \\ &\quad \mathcal{O}(\sigma(\alpha_i) \cdot \sigma(\min(RTT, T_i))) \\ &\approx \langle \alpha_i \rangle \cdot (\langle RTT \rangle + \kappa \sigma(RTT)) \\ &\approx U_i(t) / \langle l \rangle (\langle RTT \rangle + \kappa \sigma(RTT)) \end{aligned}$$



Implications

1. The RTT distribution covers Internet-wide traffic:
A **long-tailed Gamma** law (unlike TCP that deals with dedicated endpoints)
2. Rapidly varying RTTs are characteristic for ICN interfaces and even for prefixes (due to content delocalization)
3. Limits of PIT sizes, state timeout, and interest rates are hard to define well – and don't protect routers without degrading network performance
4. Routing resources (memory, CPU) are required orders of magnitude higher than previously predicted

Software-defined Networking

Problem:

Network components are mainly closed systems

- Vendor hardware only allows “configuration”
- Difficult to define and probe new behaviour

Idea of Openflow:

Open network fabrics to a programming interface

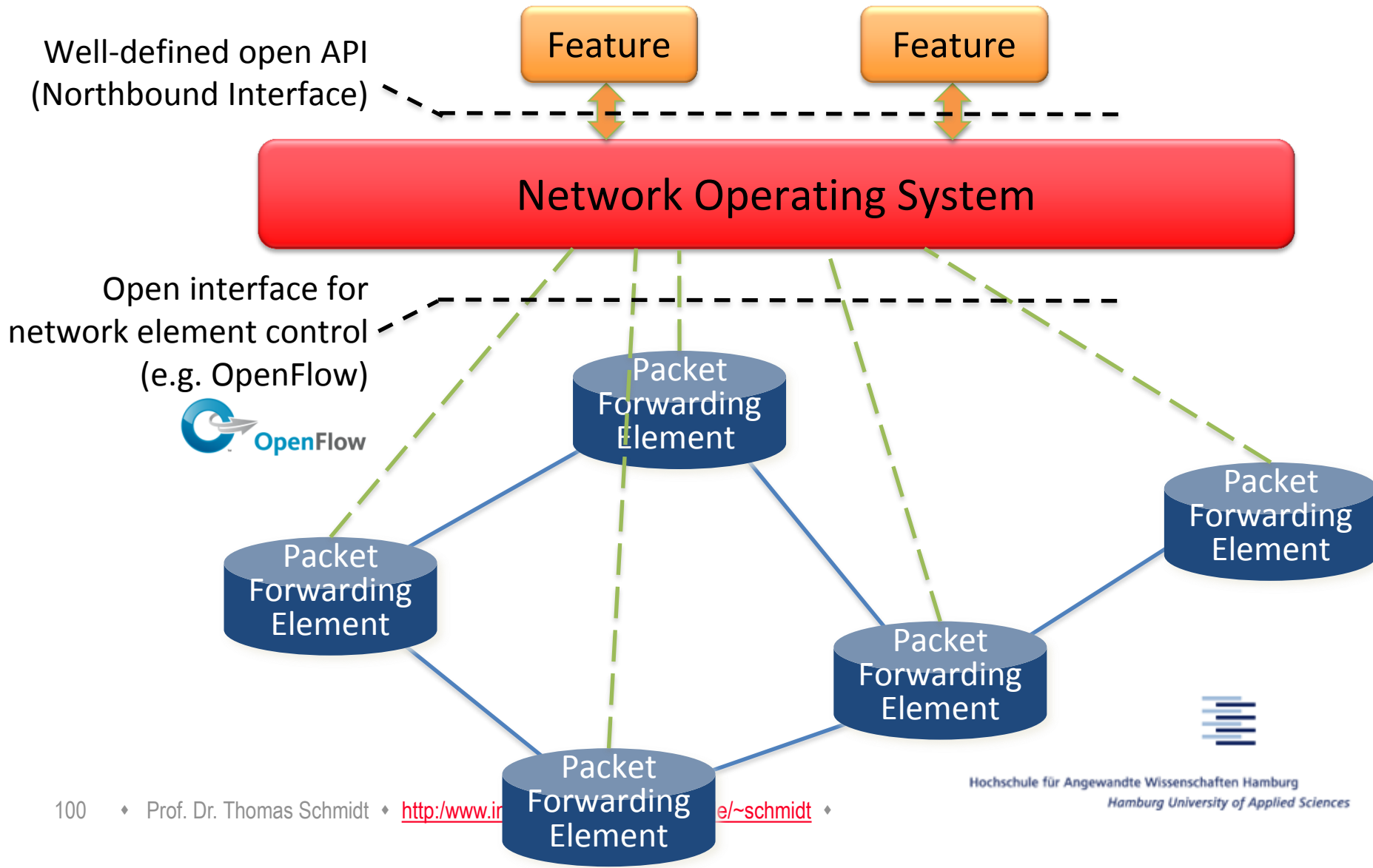
- Speed, scale, performance of vendor hardware
- Flexibility and control of software switches

Alternative formulation

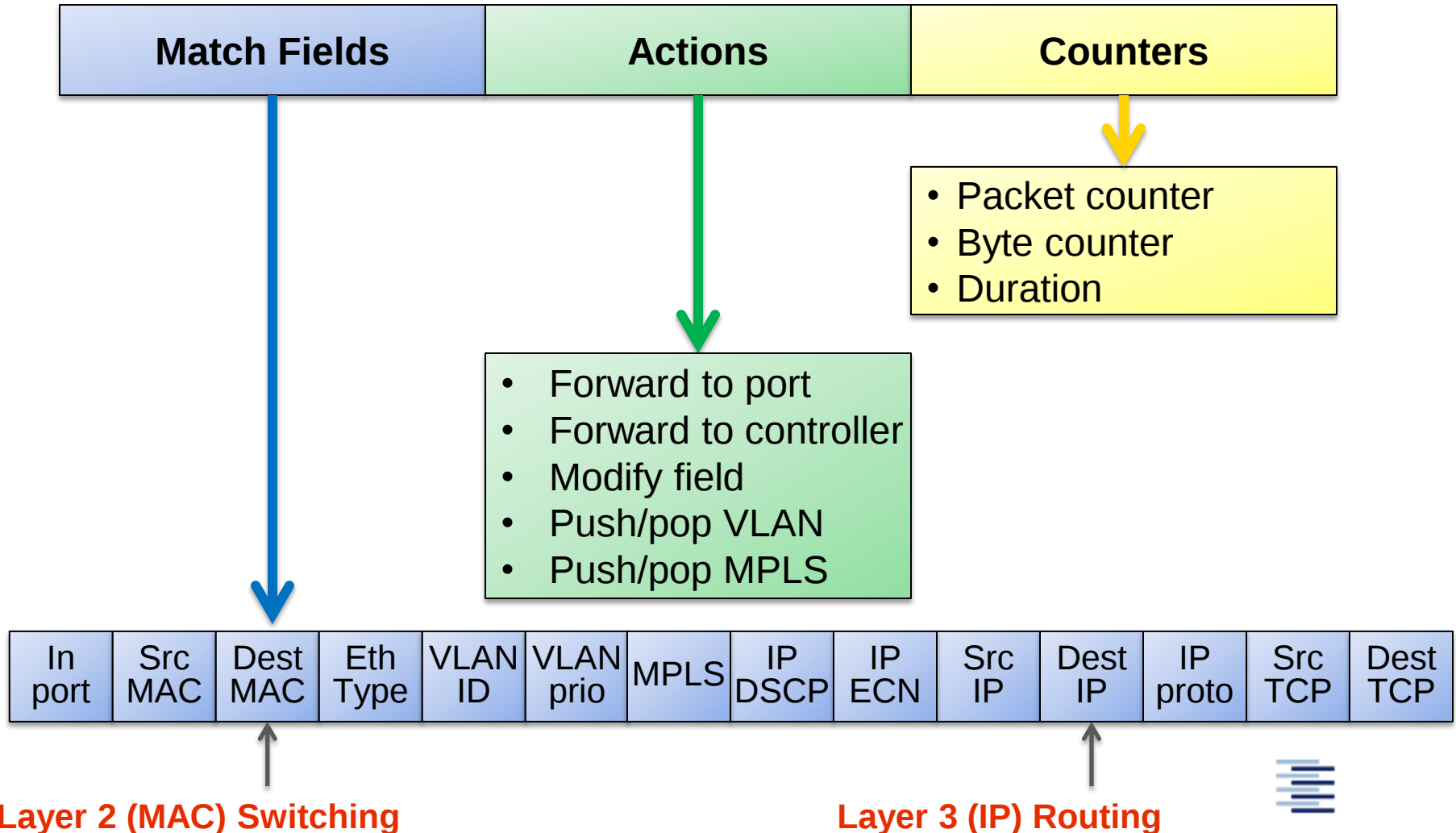
- Make switch fabrics (TCAMs) accessible to high-level intelligence
- Separate a (central) control plane



SDN/OpenFlow Architecture



Flow Table Entries



Characteristic SDN Operations

- o Packet processing according to policies
 - Header match rules implemented at switches
- o Rules distributed by central controller
 - Proactively: at network configuration time
 - Reactively: in response to first unmatched packet
 - Controller provides “global” knowledge
- o Obvious scaling deficits on Internet scale
 - Common deployment: Data-centers, Enterprise Networks



Clean Slate Internet Initiatives

- o Outside IETF/IRTF
- o Focus **scaling**: overall logarithmic ... as of DHTs (β)
- o Focus **virtualisation**:
Programmable virtual infrastructures for dedicated purposes
- o Focus **pluralisation/federation**:
Break with the paradigm of a universal network layer
- o Focus **programmability**:
 - Software-defined Networking
 - Software-defined Radios
- o Major US initiative: **GENI**
- o EU: Future Internet Research and Experimentation – **FIRE** initiative
- o Germany: German LAB (**G-LAB**)

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