IPv6 Adoption Worldwide: Momentum, Challenges and Next Steps

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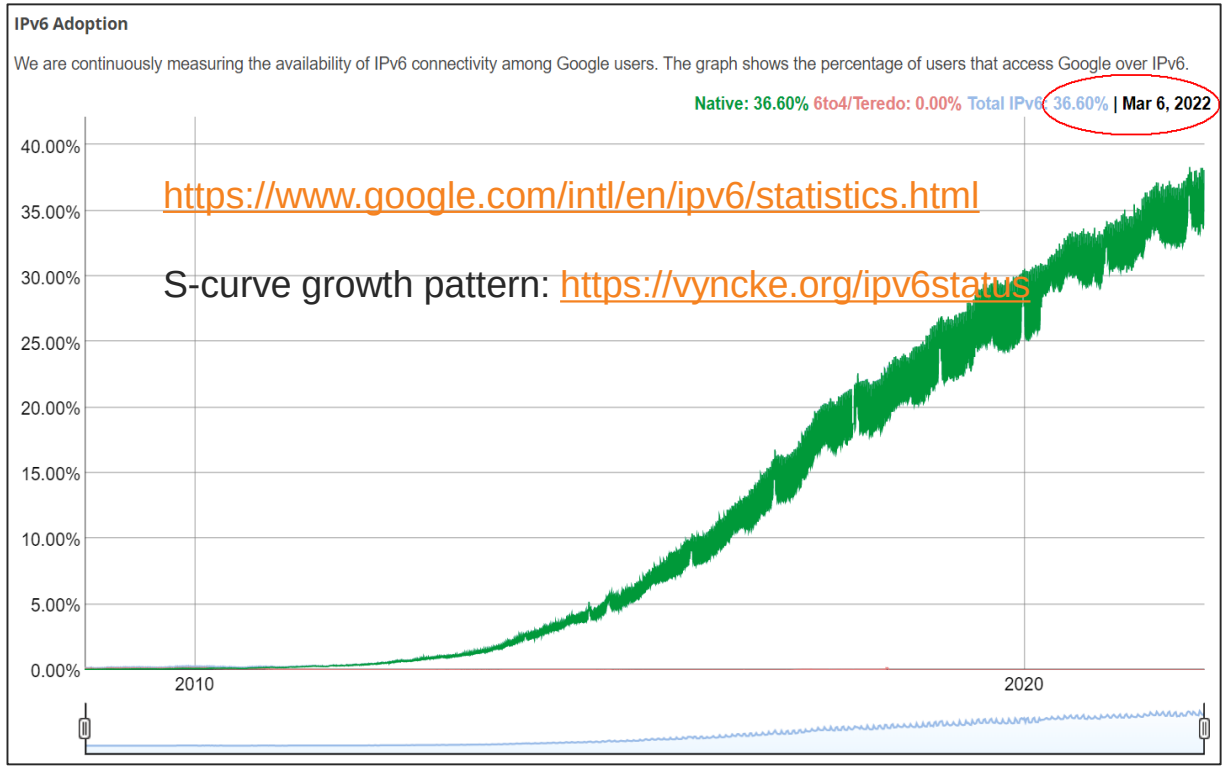
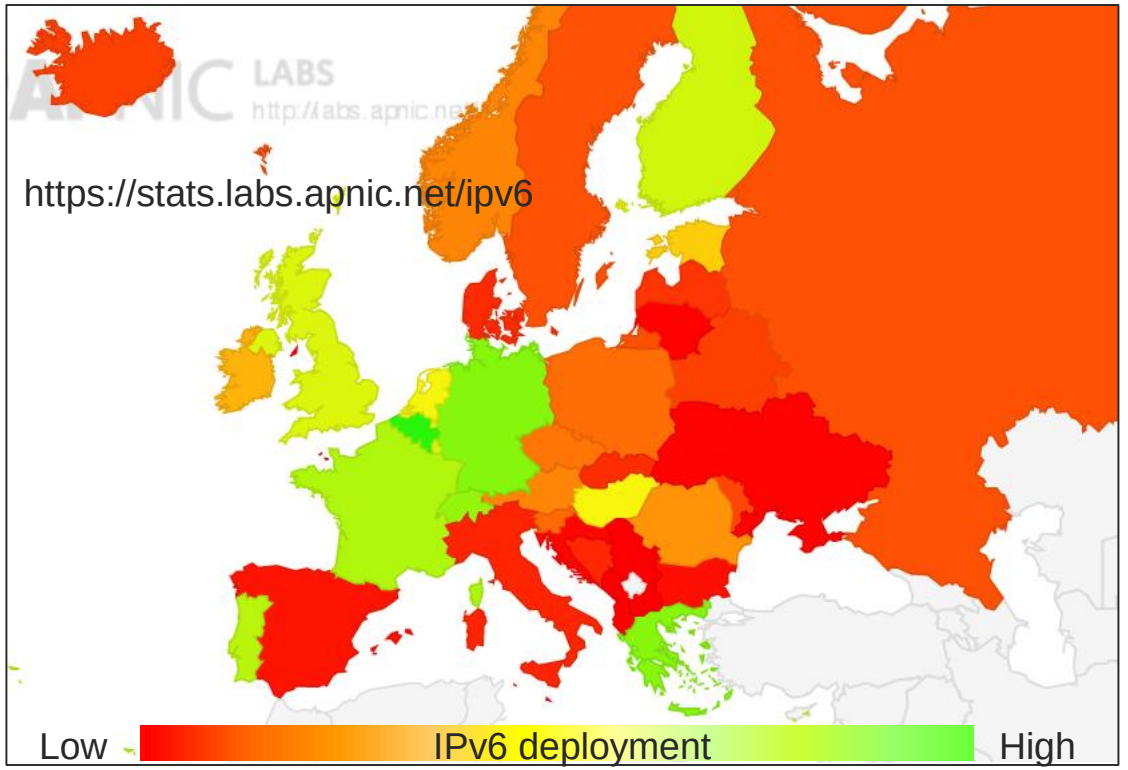
Agenda

- Momentum
- Challenges & possible solutions
- Next steps

IPv6 Adoption Steady although Uneven. What's the Momentum?

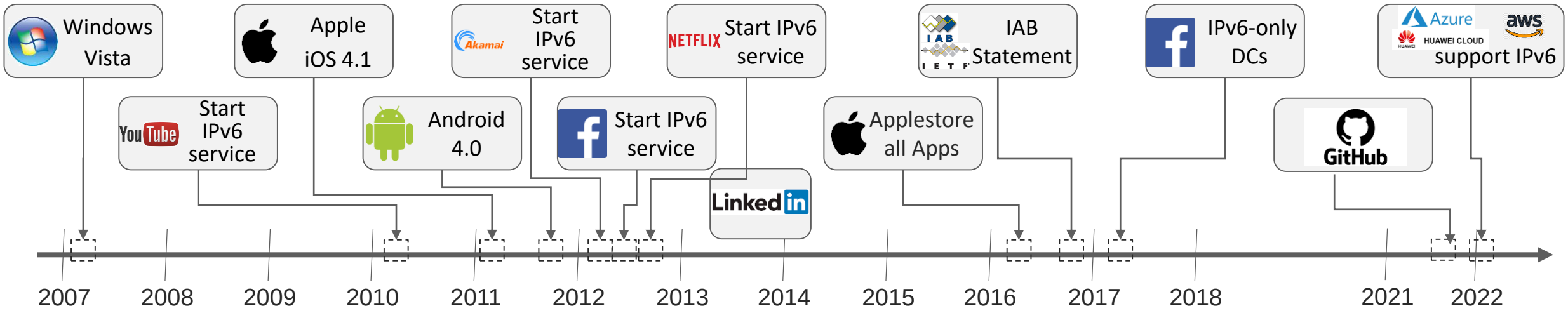




- GDP per capita, user growth, IPv4 shortage, competition help [Huston 2018]
- What else?

IPv6 “UEs – Networks – Applications" Value Chain Ready Now

IETF transition solutions ready by 2011; UEs & big applications ready by 2017; Public clouds getting ready in 2022 to move SMEs to IPv6

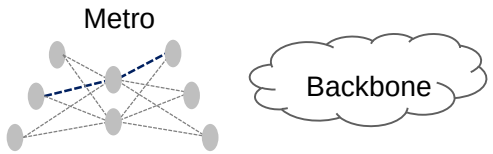


in IPv6 value chain, networks slightly behind UEs and big applications/clouds

2021

UEs: 80%+ support IPv6

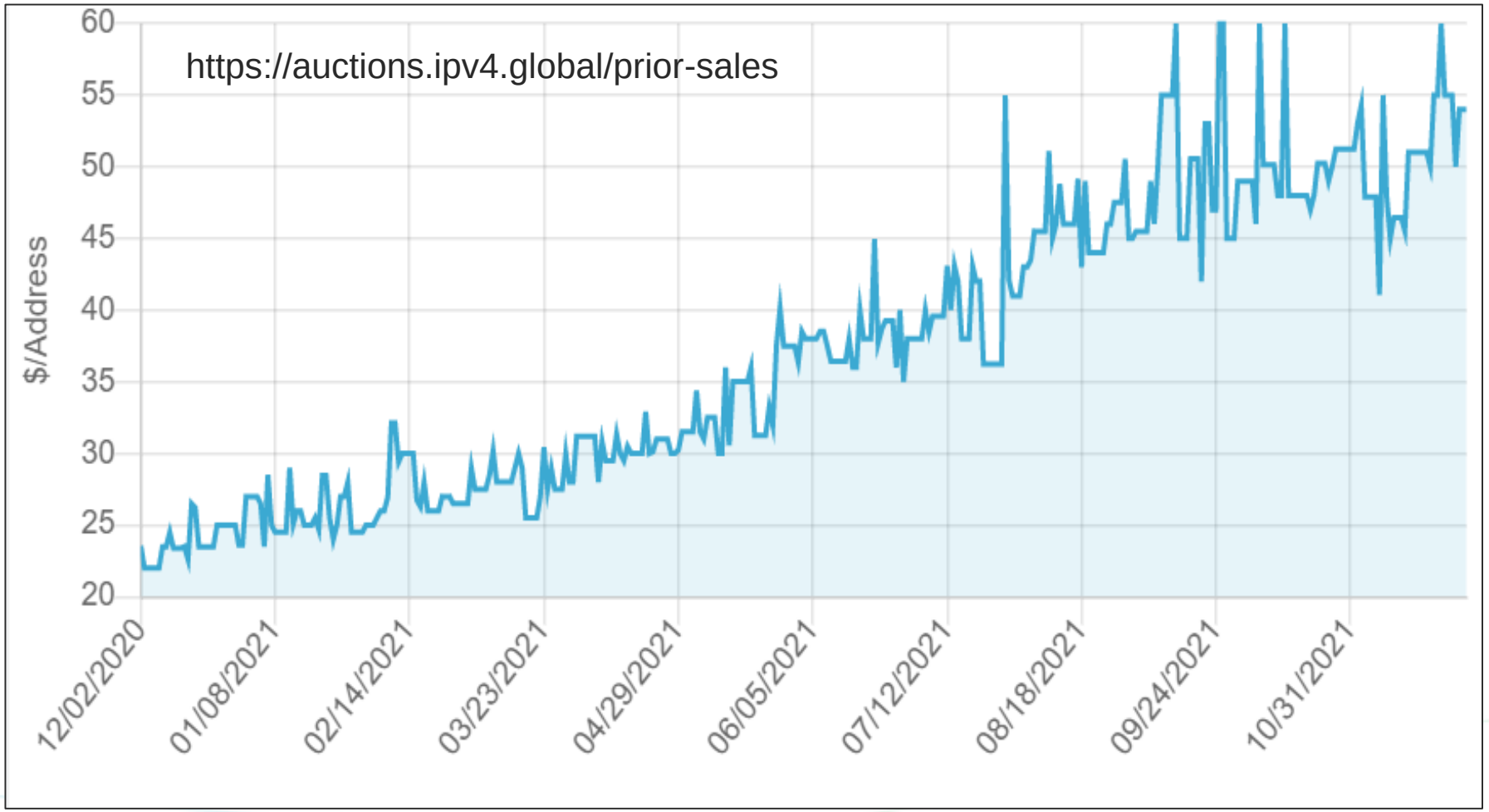
Networks: 42% support IPv6 [BGP]



Clouds: 50%+ support IPv6

IPv4 Address Price Doubled in 2021

- Price per IPv4 doubled in 2021 to $50+ (7x since April 2014)



Public Cloud's IPv6 Support, IoT, 5G, SRv6 Add New Momentum

- Public clouds like AWS, Azure's IPv6 support moves some SMEs (Small & Medium Enterprises) to IPv6 [AWS][Azure]
  - SMEs slow to adopt IPv6. Public cloud's IPv6 support hopefully change the situation

- 6LoWPAN IoT widely deployed in the smart grid world
  - G3-PLC: ~80M devices [G3PLC]
  - Wi-SUN: ~91M devices [WiSUN]

- 5G brings new network builds. Some operators take the opportunity to deploy IPv6
  - In 2018, France regulator ARCEP required 5G spectrum bidders be IPv6 ready by end of 2020

- IPv6 enhanced innovations like SRv6 add additional incentives
  - Some operators like SRv6 for better traffic engineering, network programming [Comcast] [SRv6 cases]

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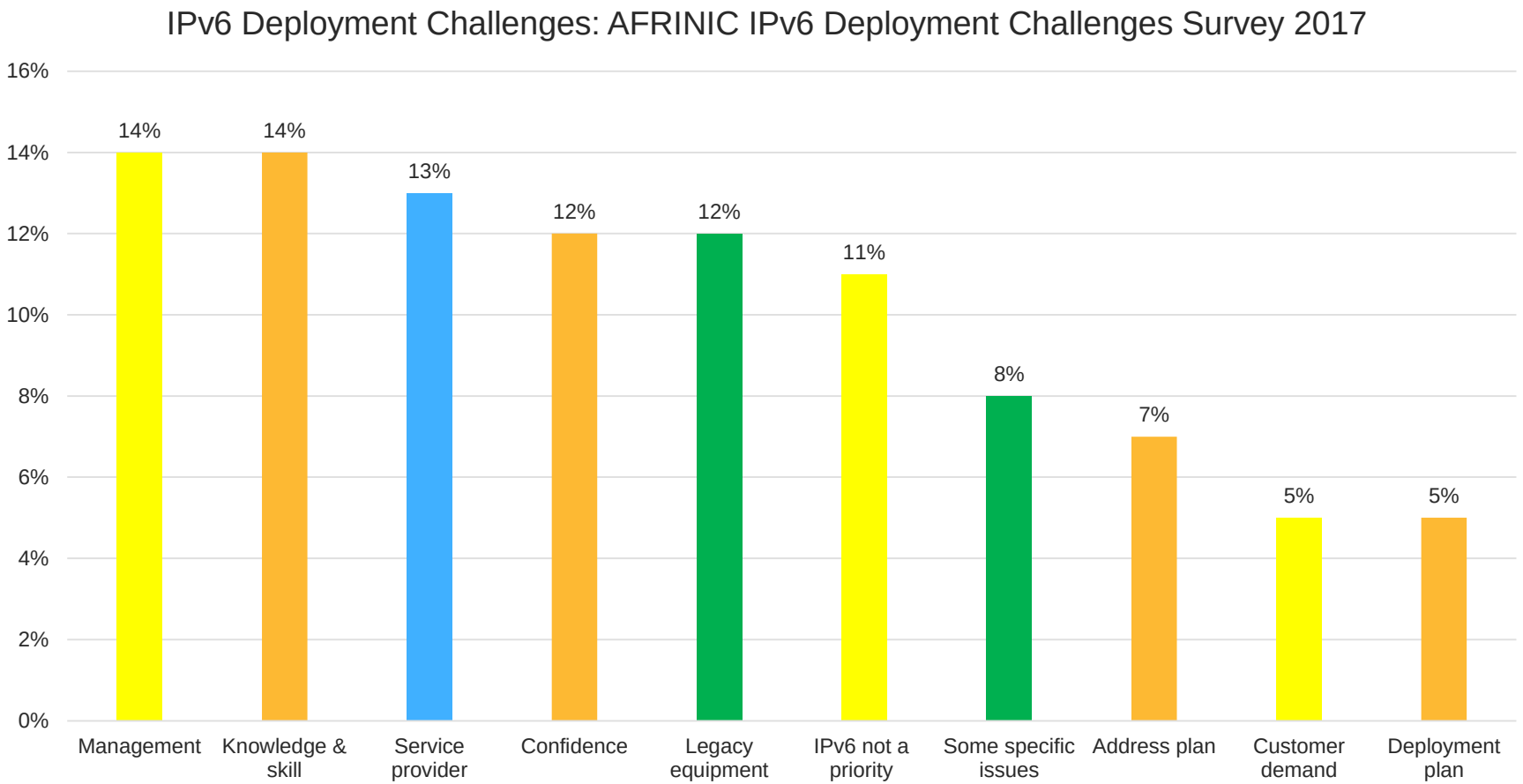
IPv6 Challenges: An AFRINIC Survey



Challenges can be classified into 4 categories:

- motivation
- knowledge
- ecosystem
- technology

Challenge Analysis & Possible Solutions – An Overview

IPv6 experience sharing from **leading operators and IPv6 Forums/Councils** can help

Challenge 1

- Thinking that IPv6 may be delayed with NAT or IPv4 purchase
- Lack the motivation or pressure to make the difficult transition.

Challenge 2

- Not aware of progress in IPv6 standards, products, and deployment. Thinking IPv6 still has many problems

Challenge 3

- Most user devices with mainstream OS support |Pv6, but some (e.g. old CPEs, smart TVs) don't
- Big cloud services support IPv6, but many SMEs don't
- Incompatible vendor roadmap

Challenge 4

- Legacy devices not support IPv6
- IPv6 NMS, OAM immature compared to IPv4
- Some IPv6 products not as field-proven as IPv4

Big ICT players, government policy can help

IETF can lead to solve some technical challenges

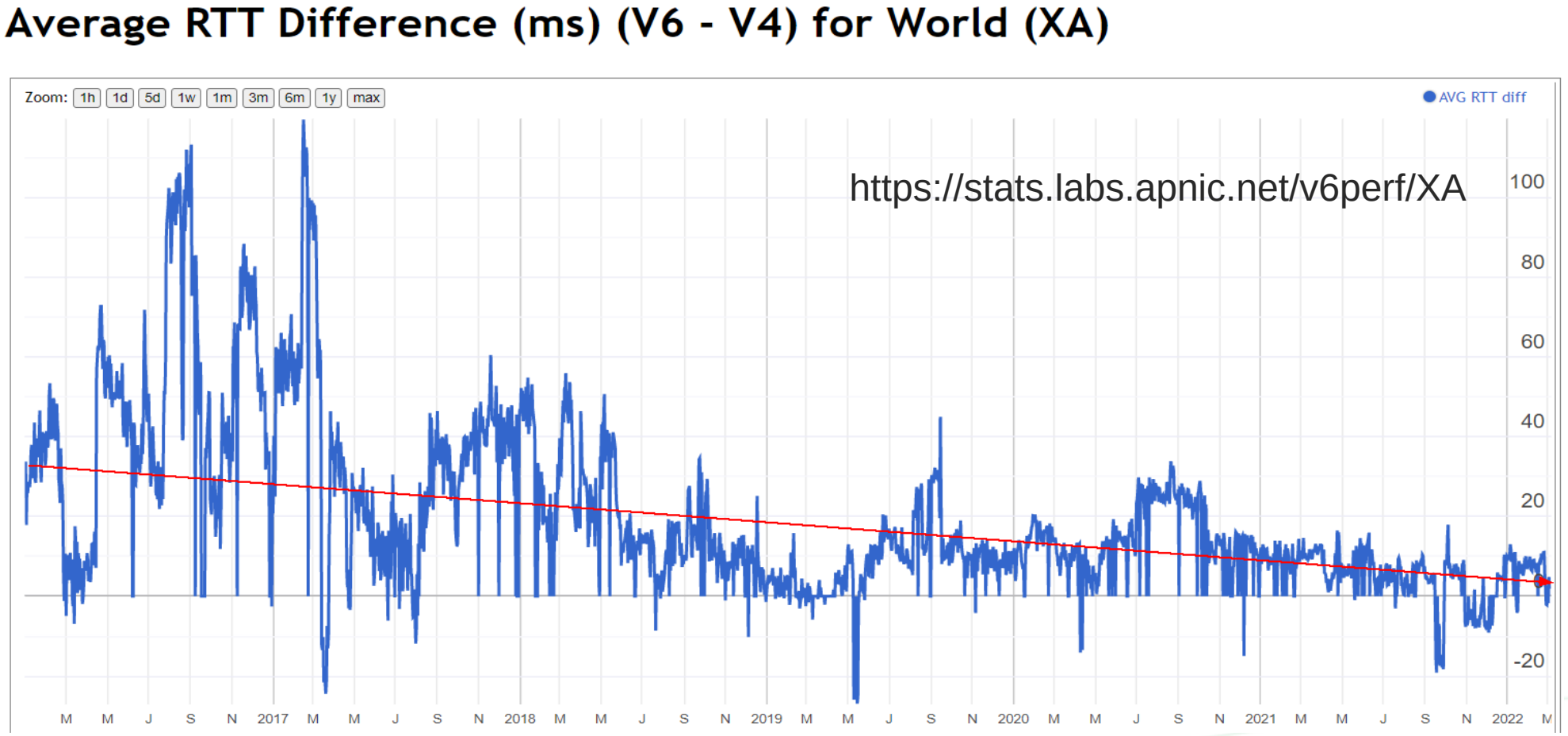
- Subsequent slides focus on technical challenges, especially on IPv6 performance challenges

IETF has Done a lot to Solve IPv6 Challenges and Accelerate IPv6 Adoption

- Specified CPE, router requirements
- Specified various transition solutions
- Specified Happy Eyeballs v1/v2 to favor IPv6 connections
- Specified IPv6 solutions for IoT
- Document various operations & security issues and provide guidelines, e.g. RFCs 9098, 9099
- Specify innovative solutions on top of IPv6, solving remaining issues like HBH processing

- But there are remaining challenges

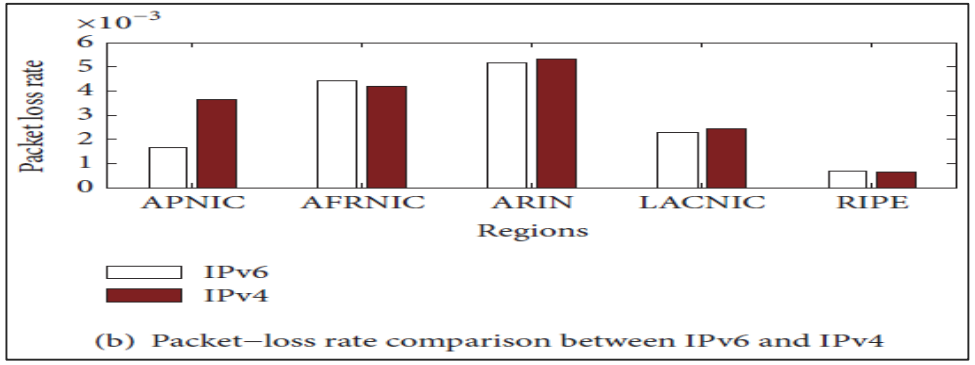
IPv6 Performance Challenge 1: IPv6 RTT Improving but still 6.5ms Higher than IPv4

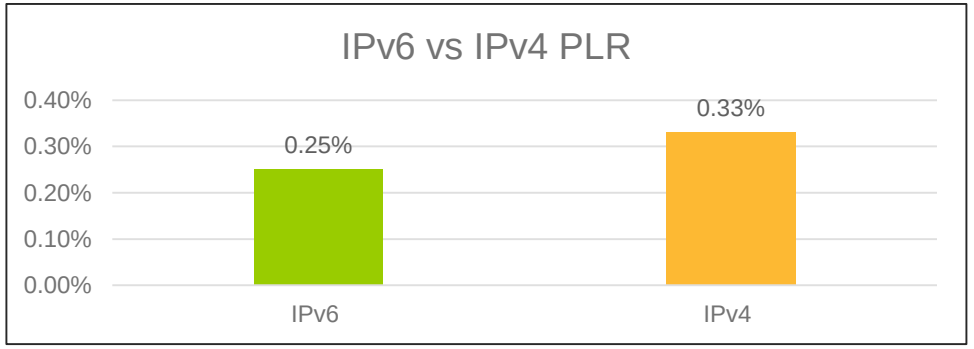


- What are top-3 factors leading to IPv6 RTT improvement?

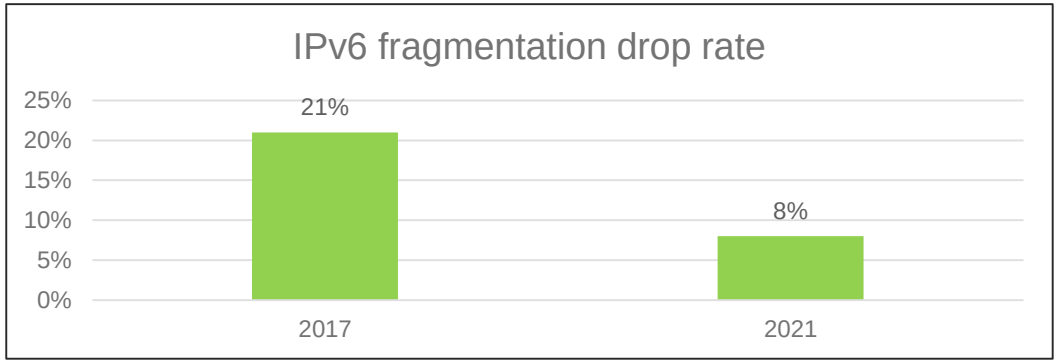
Performance Challenge 2: IPv6 Packet Loss Rate Likely Higher

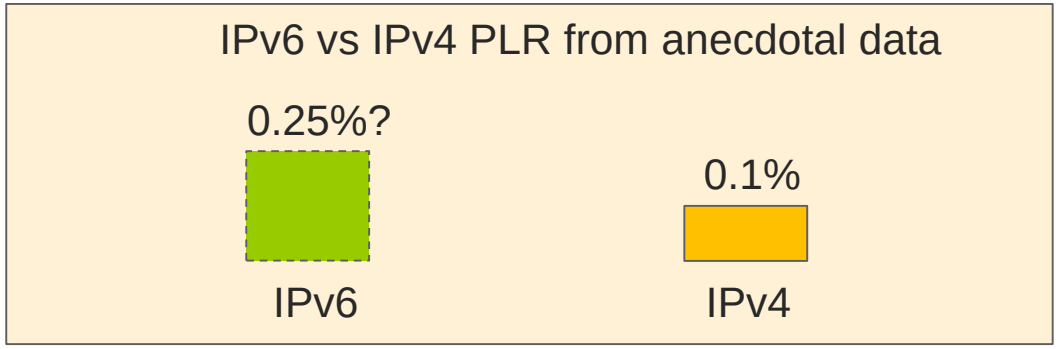
[Hindawi] reported lower IPv6 PLR than IPv4, based on 1-week measurement from China.





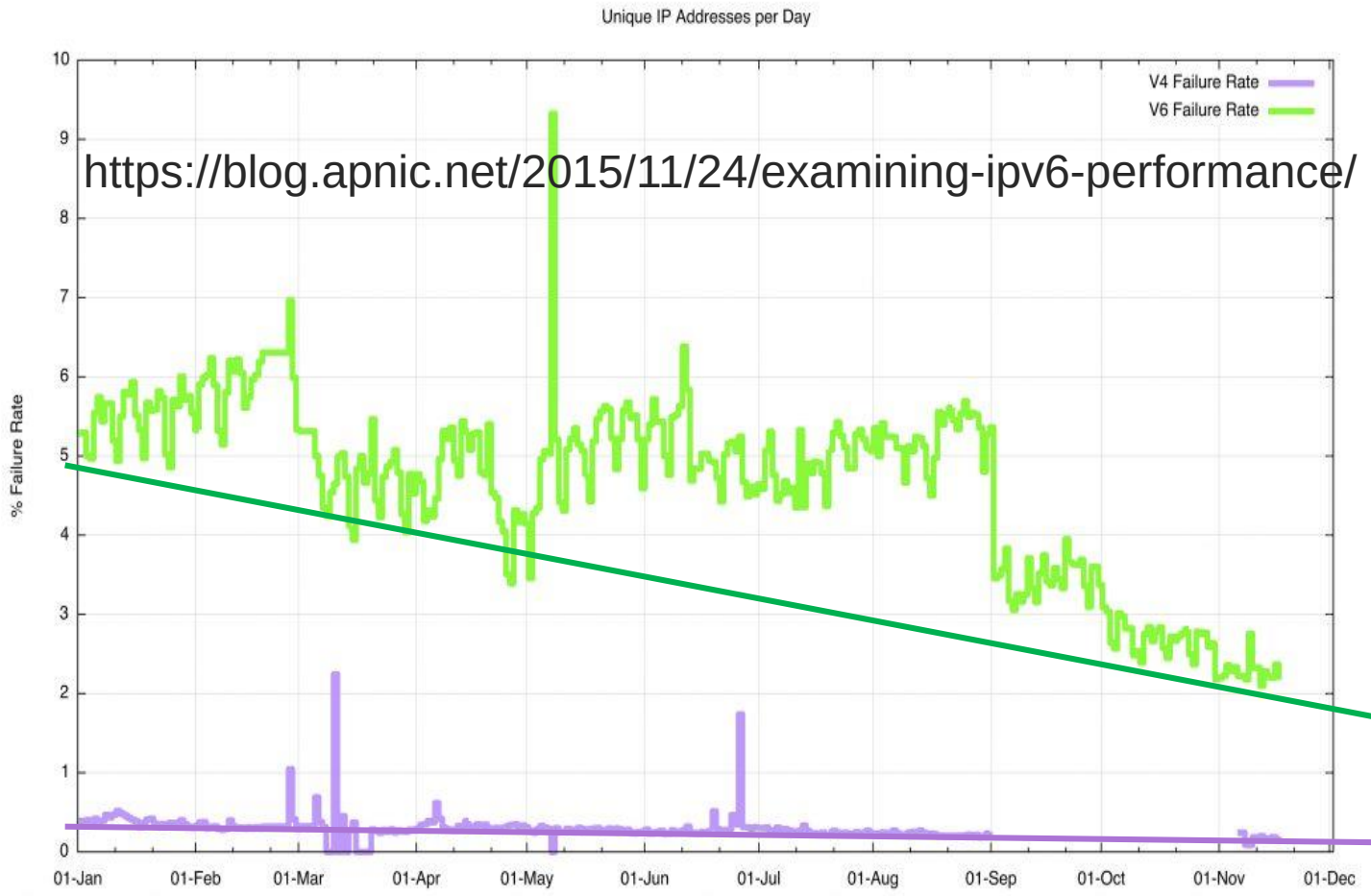
[RFCs 7872/9098] reported very high PLR for IPv6 packets with EHs. Combined with anecdotal data, we believe IPv6 PLR is higher





- How much does high IPv6 packet loss due to EHs, fragmentation, filtering contribute to overall IPv6 PLR?
- Should we measure IPv6 PLR and analyze the causes?

Performance Challenge 3: IPv6 TCP Failure Rate Higher



APNIC

- IPv6: 0.96%
- IPv4: 0.25%

TCP Connection Failure Rates for IPv6 & IPv4, in 2015 in Mar. 2022

- Is higher IPv6 TCP failure rate due to higher IPv6 PLR?
- Should we measure failure rate for QUIC now?

Consequence: Many Operator IPv6 Deployments are in Overlay. Are We Satisfied with (IPv6 Overlay + IPv4 Underlay) Forever?

- IPv6 overlay (i.e. at service layer) sufficient to address IPv4 shortage
- Many operators choose IPv6 Overlay (i.e. IPv6 at UEs & service gateways) + IPv4 Underlay (i.e. packet transport with 6PE, 6vPE over MPLS)
  - Dual-Stack mostly in overlay, not underlay. Many operators reluctant to maintain 2 data/control/management planes for both IPv6 & IPv4. They use tunneling instead.
- OK for now but is it OK forever?

- Caution: the IPv6 performance stats here are Internet stats. In enterprise environment, there are reports that IPv6 perform better than IPv4 [Apple][Facebook]

Possible Solutions to IPv6 Performance Challenges

- Avoid IPv6-in-IPv4 tunneling
- Keep IPv4 and IPv6 paths congruent, e.g. use transit and peer arrangements that are dual stack

- Move content cache closer to users
- Increase link MTU, choose TCP MSS carefully
- Be careful in announcing IPv6 routes; apply IPv6 route filtering best practice [Goering]
- Improve IPv6 packet filtering / ACLs [Gont]
- Use EHs carefully, e.g. only in limited domain with capable devices

- Any other solutions? How to prioritize these solutions?
- Our perception: the industry has some answers, but not completely clear

IPv6 Adoption Summary: Is the Glass Half Full, or Half Empty?

- IPv6 performance can be considered as a proxy indicator for IPv6 adoption
  - When IPv6 performs better than IPv4, companies are more likely to adopt IPv6, or vice versa.
- Half empty: IPv6 performance still not as good as IPv4
- Half full: IPv6 performance almost as good as IPv4
- Can we make IPv6 perform better than IPv4? If yes, a powerful reason to move the world to IPv6
  - Yes at UE side, with IPv4aaS solutions like 464XLAT, DS-Lite, MAP-T/E
  - Yes at cloud side: Apple, Facebook reported better IPv6 performance [Apple][Facebook]
  - Making networks perform better in IPv6 is the next step

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100+ Operators/Enterprises already Have 50%+ IPv6 Users. Time to Consider IPv6-only Networks (with IPv4 as a Service over IPv6)

Source: https://www.worldipv6launch.org/measurements/ as of Feb. 9, 2022. “Rank” indicates IPv6 traffic volume

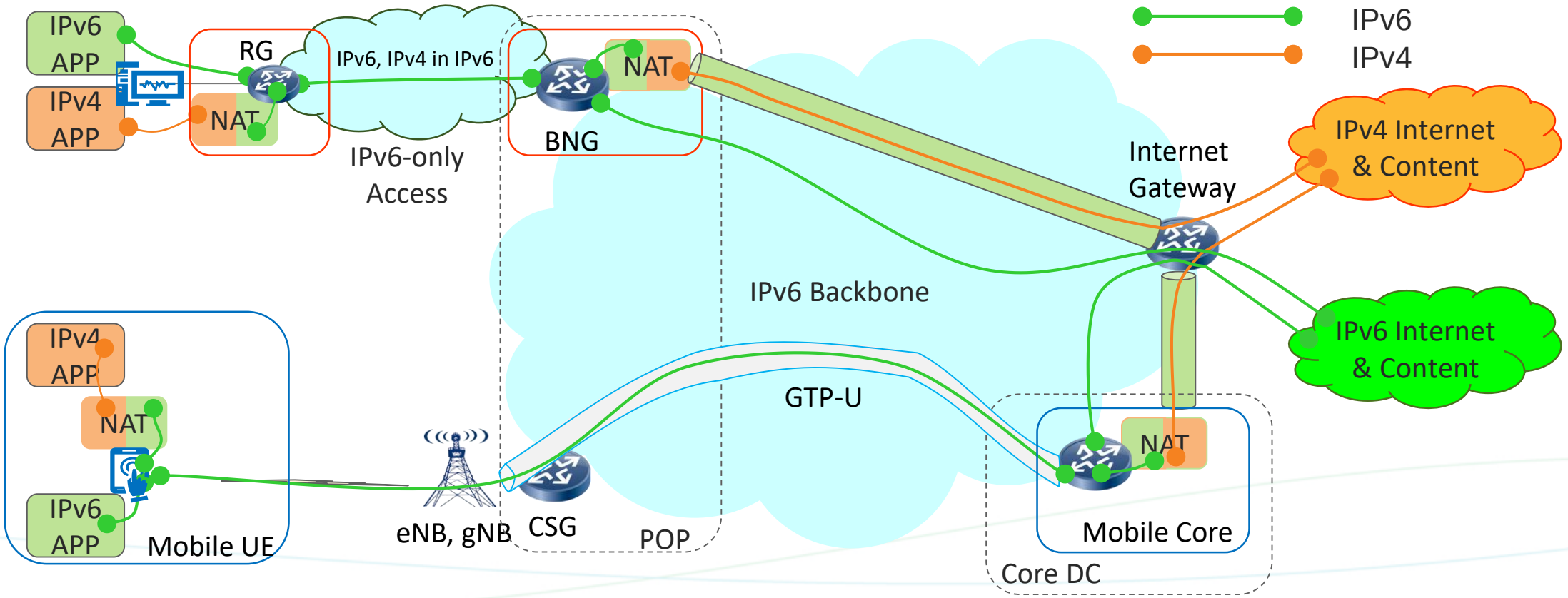
Rank	Participating Network	ASN(s)	% IPv6 deployment
258	CNGI-CERNET2/6IX	23910, 23911	100.00%
353	IPTRON.NET	12757	96.72%
264	Sauk Valley Community College	13953	93.36%
1	RELIANCE JIO INFOCOMM LTD	55836, 64049	93.35%
194	Gustavus Adolphus College	17234	92.71%
292	Critical Colocation	52342	92.33%
6	T-Mobile USA	21928	92.06%
25	Chunghwa Telecom (Mobile)	17421	91.61%
349	AMS-IX	1200	89.78%
19	Free	12322	87.52%
137	Virginia Tech	1312	87.25%
3	Combined US Mobile Carriers	3651, 6167, 10507, 20057, 21928, 22394	87.01%
312	CZ.NIC	25192	86.13%
284	PowerTech Information Systems AS	5381	86.04%
354	snowflake productions gmbh	198249	85.83%
248	Universidade Estadual de Ponta Grossa	53046	85.76%
84	Cosmote Mobile Telecommunications S.A	29247	85.68%
150	University of Pennsylvania	55	85.62%
22	AT&T Wireless	20057	83.17%
9	Verizon Wireless	6167, 22394	82.63%
250	Fundacao Parque Tecnologico Itaipu - Brasil	263083	82.21%
79	Sky Italia	210278	81.61%
106	Community Fibre Ltd.	201838	81.50%
185	Karlsruhe Institute of Technology (KIT)	34878	81.28%
132	University of Minnesota	57, 217	80.22%
93	XS4ALL	3265	79.39%
28	OTE SA	6799	78.03%
16	British Sky Broadcasting	5607	77.90%
46	MEO - SERVICOS DE COMUNICACOES E MULTIMEDIA S.A.	3243	77.75%
355	LeaderTelecom B.V.	58272	77.71%
39	Telecentro S.A.	27747	77.63%
37	Telenet	6848	76.93%
24	Rogers Communications	812, 20453	76.42%
69	VOO	12392	76.28%
175	NYNEX satellite OHG	62023, 200519	76.22%
115	Nettel Telecomunicações Ltda	53135	75.31%
82	Hyperoptic	56478	75.30%
145	Georgia Institute of Technology	2637	74.63%
183	Rensselaer Polytechnic Institute	91	74.06%
67	3 Scandinavia	44034	73.71%
5	ATT	6389, 7018, 7132	73.05%
52	DNA	16086	73.00%
78	Hughes Network Systems	6621	72.83%
128	NET.COM TELECOMUNICAÇÕES LTDA EPP	28131	72.83%
335	SIDN	1140	72.48%
10	Claro Brasil	4230, 28573	72.02%
12	KDDI	2516	71.75%
280	VentraIP Group (Australia) Pty Ltd	45638	71.60%
7	Deutsche Telekom AG	3320	71.42%
8	Orange Business Services	3215	71.22%
182	University of Twente	1133	71.13%
240	UFSCar	52888	70.67%
2	Comcast	7015, 7016, 7725, 7922, 11025, 13367, 13385, 20214, 21508, 22258, 22909, 33287, 33489, 33490, 33491, 33650, 33651, 33652, 33653, 33654, 33655, 33656, 33657, 33659, 33660, 33661, 33662, 33664, 33665, 33666, 33667, 33668, 36732, 36733	70.46%
30	PJSC Mobile TeleSystems	8359, 28884, 29497, 35473, 39811	69.69%
13	Vivo	10429, 11419, 18881, 19182, 26599, 27699	69.20%
80	Mytel (Telecom International Myanmar Co., Ltd.)	136255	69.08%
34	VTR Banda Acha	22047	67.97%
21	BT	2856, 25127	67.50%
31	KPN	1136, 2043, 5615, 8737, 13111, 21286, 59524	67.37%
90	Digicel Trinidad & Tobago	27800	66.04%
41	Maxis Broadband Sdn Bhd	9534	65.55%
26	TELUS	852	64.82%
55	Dialog Axiata PLC	18001	64.17%
11	TELMEX	8151	63.96%
66	Forthnet	1241	63.68%
71	eircom	5466	63.53%
96	EPT Luxembourg	6661	63.37%
97	inexio KGaA	42652	63.02%
222	Aristotle University of Thessaloniki	5470	62.92%
57	Chubu Telecommunications	18126	62.82%
165	University of Vermont	1351	62.13%
345	mc.net	6479	61.84%
60	SKTelecom	9644	61.62%
267	SPAWAR	22	61.51%
171	Jiří štrohalm	197307	61.01%
15	Cox Communications	22773	60.87%
160	Cisco	109	60.54%
45	TIM Brasil	26615	60.23%
135	Sea Net	53222	59.87%
35	Belgacom	5432	59.45%
111	Net Barretos	262983	58.50%
62	Midcontinent Communications	11232	58.38%
215	JIFFY CABLE AND DATACOM	134944	57.64%
99	DIRECTV COLOMBIA LTDA	262928	57.38%
147	University of Iowa	3676	57.33%
117	Justweb Telecomunicacoes LTDA	264552	57.32%

100%

57.32%

IPv6-only Network Means both IPv6 Overlay & IPv6 Underlay. IPv4 will be a Service over IPv6

- IPv6 overlay = UEs & service gateways only have IPv6 address
- IPv6 underlay = IPv6-based packet transport (IPv4 traffic tunneled inside IPv6)



IPv6-only Provides an Exit Strategy to a Single-Protocol World

- (IPv6 overlay + IPv4 underlay) provides no exit strategy
- IPv6-only requires solving the IPv6 challenges
- IETF and leading operators should take the lead

Summary

- IPv6's "UEs – networks – applications" value chain is ready. It has reached the inflexion point
- IPv6 still has performance challenges. IETF can lead to make IPv6 perform better than IPv4
- Better IPv6 performance can lead to IPv6-only networks
- We are documenting the IPv6 challenges & solutions. Please contribute by sending your input to Xipengxiao@huawei.com. Thank you!
  - Measurement or analysis on IPv6 & IPv4 PLR
  - IPv6 vs IPv4 performance for QUIC
  - Analysis of top-5 contributing factors to IPv6's performance improvement
  - Problems encountered, or insights learned from your IPv6 deployment & operations
  - Practice & suggestion on IPv6 route advertisement & filtering, peering
  - Practice & suggestion on IPv6 packet filtering
  - Innovations on top of IPv6
  - IPv6 & IPv4 performance comparison for enterprises

Acknowledgement & References

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Thank You.

Internet Routing Table Comparison: IPv4 vs IPv6

	IPv4	IPv6	Comment
BGP prefix count	906000	147000	16%
Average AS PATH length	5.3	4.8	Surprising: (1) IPv6 < IPv4; (2) IPv4's going down, while IPv6's going up.
Average AS connectivity degree	3.3	3.1	No surprise. Both going up
Total AS	72800	28140	39%
Transit AS	45800	10800	42%

Source
https://blog.apnic.net/2022/01/06/bgp-in-2021-the-bgp-table/

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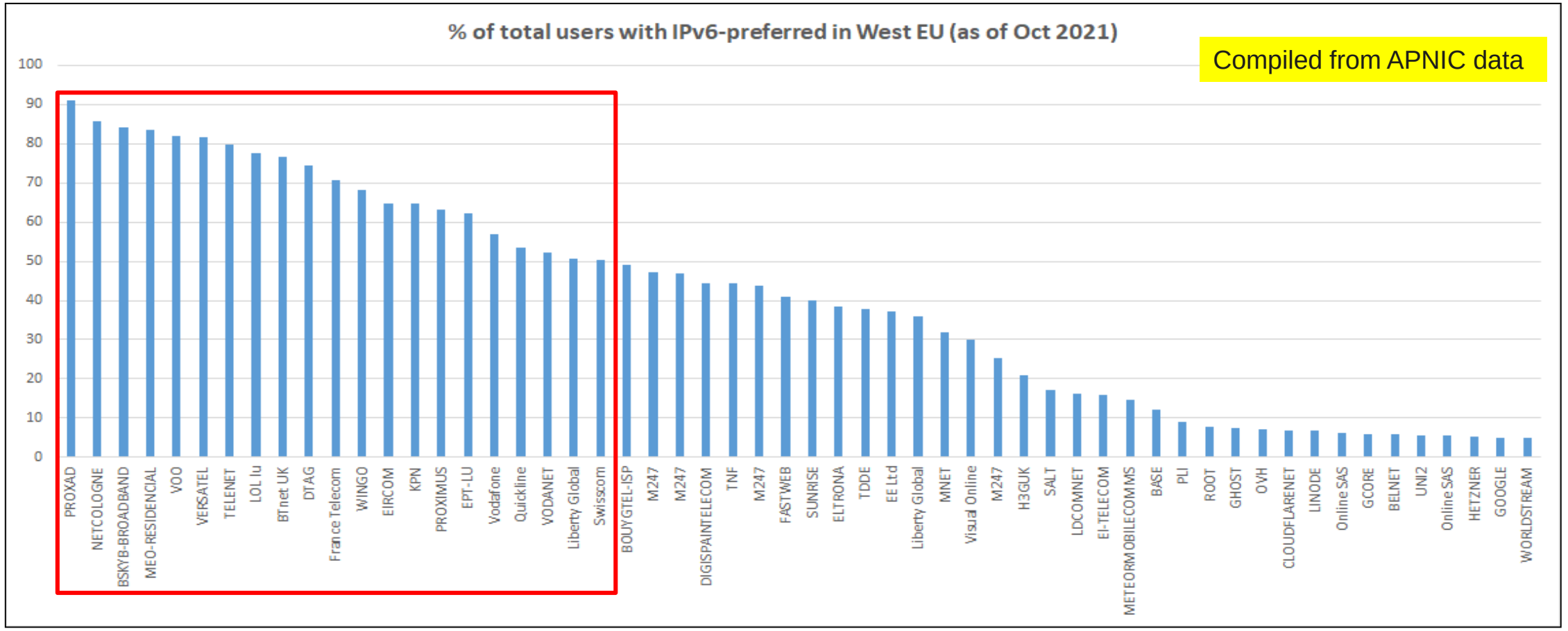
Many Operators already Have 50%+ IPv6 Users. Time to Consider IPv6-only Networks



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