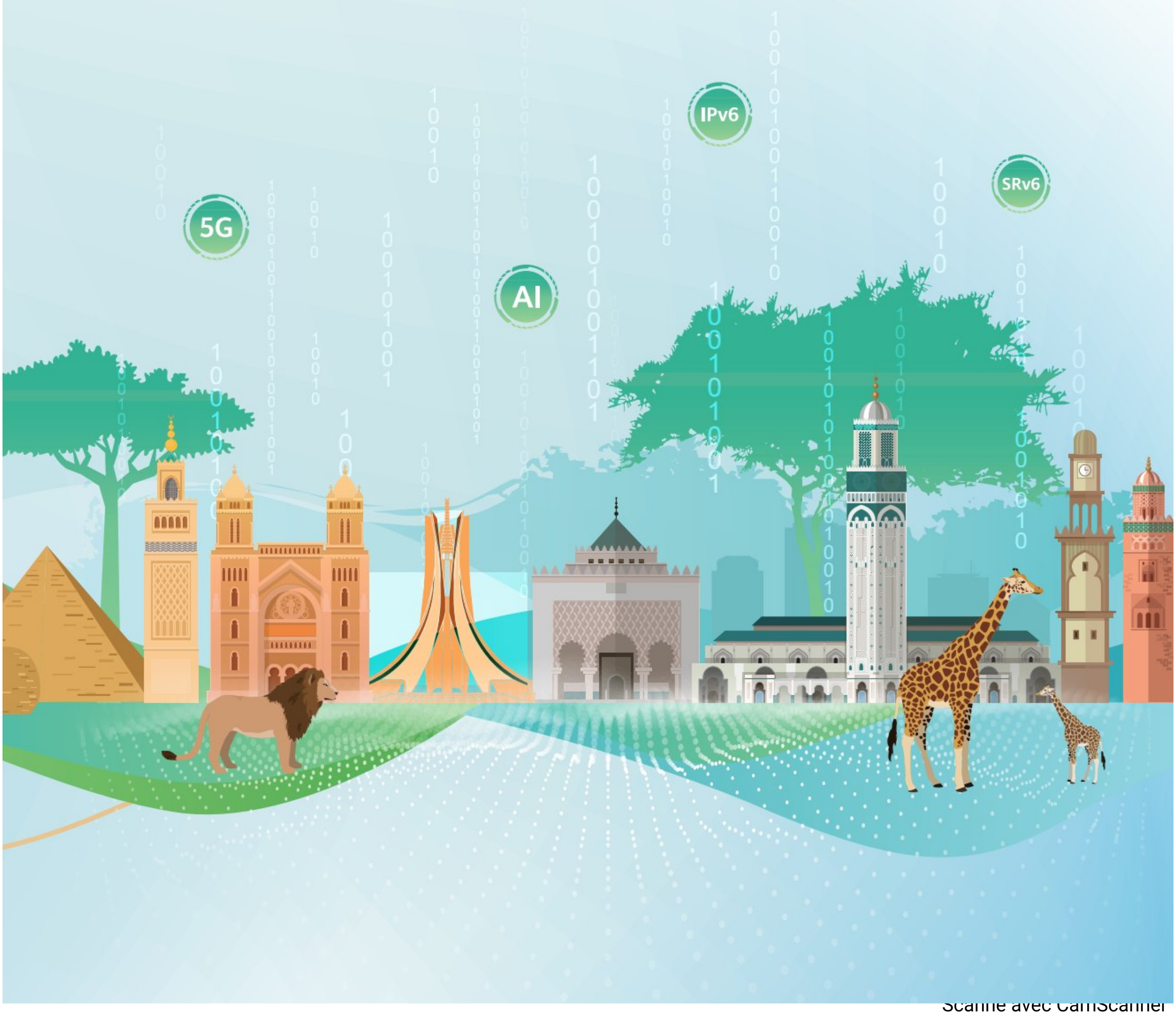
Arab-Africa IPv6 Development White Paper

IPv6: Trends, Innovations, and the Way Forward in the Digital Economy Era



Preface I (African Telecommunications Union)

The Internet Protocol (IP) is the fundamental of Internet today, which has changed the world over the past 30 years. The previous version of IP, version 4 (IPv4), was designed in the 1980s to handle a maximum number of only 4.3 billion addresses at a time when no one could imagine the rapid growth of the Internet today. It is predicted that by the year of 2025, more than 30 billion devices will be connected to Internet. Therefore, it was important that IP version 6 (IPv6) was introduced to solve the problem of address shortages: with the large address space provided, IPv6 can assign every grain of sand on the earth with an IP address. The vast address space makes IPv6 the ultimate choice for the Internet of Things (IoT) and 5G era.

IPv6 not only resolves the address space problem, it is also the basis for innovation and security of the Internet. In 2016, the Internet Architecture Board (IAB) stopped requiring IPv4 compatibility in new or extended Internet protocols. In other words, new protocols for the Internet would be optimized for and depended on IPv6. This means that the IPv4 networks will stop evolving and updating. It also

means that the IPv4 networks will be more vulnerable to new security threats.

It is important for governments and operators to start the transition to IPv6 to guarantee the sustainability of the Internet, which is the foundation of our digital economy today. Currently, most African countries still lag behind the IPv6 deployment. Considering the large population in Africa and limited IPv4 addresses distributed to the continent (most of African countries have only tens of IPv4 address per 1K people, compared to 5,000 addresses/1K people in the US), this portends risks to the sustainable development of Internet. At the African Telecommunications Union, we are working closely with regional and global partners like AICTO and IPv6 Forum to promote the IPv6 deployment in Africa. This is in line with our mission of promoting the rapid development of info-communications in Africa in order to achieve universal access, and full inter-country connectivity.

We should see that some countries in Africa has released the IPv6 migration strategy. In July 2022, Kenya published its *IPv4 to IPv6 Migration Strategy*, requiring only devices with the IPv6 capability to be the type approved for use in Kenya (effective as of July 2023) and encouraging IPv6 Enhanced innovations such as SRv6, IoT, and network slicing. With protocol innovations, we can provide differentiated high-quality services compared to traditional best-effort services. And with AI, we can achieve fast provisioning and greater customer satisfaction. In the 5G and cloud era, IPv6 Enhanced is fundamental to improving service experience.

This white paper presents the importance of IPv6 to regional digital strategies and provides global policy experience. I encourage everyone to interact with the White Paper closely and engage in conversations with colleagues and other stakeholders from the industry so that they can understand the importance and approaches for IPv6 migration and adoption. This is critical to the continued success of the Internet in transforming the lives of Africans. If we can achieve the migration to IPv6, it will unlock new opportunities to do even more with the Internet and have even greater impact in Africa for the digital future.

John OMO

Secretary-General

African Telecommunications Union

Preface II (AICTO)

The wave of digitalization is changing the world today. New technologies like the Internet of Things (IoT), could computing, 5G networks, and Artificial intelligence (AI) bring us the "smart" lifestyle – all those are based on the connected world with Internet.

With more and more devices connected to the Internet and the requirement of an intelligent network that can bring better quality of service, we need to migrate from the old version of the Internet Protocol, IPv4, to its new generation, IPv6. It provides not only larger address space, but also extensibility for the future network evolution. IPv6 and IPv6 Enhanced technologies are the key to the stable delivery of ubiquitous computing power, an increasing number of connections and the enabler of better and smart acceleration of digital transformation.

The deployment status of the IPv6 in the Arab region is extremely unbalanced where few countries have started the migration process. To support the Arab strategy of the information society, AICTO actively moves to help the regional countries to migrate to IPv6 to keep the pace of the global IPv6 transition and not be left behind. For the two consecutive years in 2022 and 2023, we held the Regional IPv6 Summits in Tunisia with stakeholders from the public sector, private sector, civil society, and standards bodies to discuss the policy and direction. This year, together with the IPv6 Forum, we set up the Arab IPv6 Council to increase the IPv6 deployment rate of the Arab Region and minimize IPv6 deployment imbalance among Arab member states.

With joint efforts from our partners, we are happy to release the 2nd version of the regional IPv6 white paper: *IPv6: Trends, Innovations, and the Way Forward in the Digital Economy Era*.

I believe this white paper will provide the most updated vision of IPv6 in the region and give the readers a clear idea about IPv6 migration strategies for a better connected world.

H.E.Mohamed Ben Amor

Director General, AICTO

Executive Summary

The Internet has changed the world over the past 30 years. With the advent of new network innovations, the world is becoming more connected thanks to one protocol: the Internet Protocol (IP).

IP version 4 (IPv4) was designed in the 1980s when no one could imagine the rapid growth of the Internet today. It provides 4.3 billion addresses, which 40 years ago was a huge number, but today is far from enough to connect every person (7 billion) and everything (50 billion or more). To solve the address shortage problem, IP version 6 (IPv6) was proposed. It provides 3.8*10^38 addresses, meaning an IPv6 address can be assigned to every grain of sand on Earth. The vast address space makes IPv6 an ultimate choice for the Internet of Things (IoT) and 5G era.

Providing more addresses is not the only advantage of IPv6. It is also the base of innovation and security of the future Internet. In 2016, the Internet Architecture Board (IAB) stopped requiring IPv4 compatibility in new and extended Internet protocols. In other words, new Internet protocols will be optimized for and depend on IPv6. Consequently, IPv4 networks will no longer evolve or be updated, and in turn will become more vulnerable to new security threats.

To guarantee the sustainability of the Internet, which is the foundation of today's digital economy, governments and operators have initiated the transition to IPv6 on a massive scale. Numerous countries, including France, Germany, the US, China,

and India, have released policies to accelerate IPv6 deployment. Not only does IPv6 provide a vast address space, but more importantly, its scalability and extensibility offer the possibility of enhanced features. With protocol innovations, we can provide differentiated high-quality services compared to traditional best-effort services. And with AI, we can achieve fast provisioning and greater customer satisfaction. In the 5G and cloud era, IPv6 Enhanced is fundamental to improving service experience. It allows IP networks to meet new requirements — including high bandwidth and on-demand network acquisition — with technologies such as industrial digital private network, converged transport network (with slicing), hyper-converged DCN, 10 Gbps campus network, and more.

This white paper first describes the major role that IPv6/IPv6 Enhanced plays as a key enabler for the digital economy and it being the only viable option to support digital transformation and generate value. To this end, we introduce the IPv6 framework developed by the IPv6 Enhanced Council that lays out the blueprint for what an "IPv6-driven digital transformation ecosystem" as a generic IPv6 framework should look like. We also outline the main areas where this innovative Internet is likely to have some impact and the opportunities it opens up from two complementary IPv6 policy perspectives — society-oriented and business/market-oriented — where related policymakers can act in unison but with different expectations and in response to different needs. The instantiation and operationalization of this IPv6-driven digital transformation framework can help regional stakeholders implement both Arab Digital Strategy 2030 and Digital Transformation for Africa (2020-2030).

The white paper then explains the development of IPv6 around the world and in the Arab and African regions, drawing on consolidated publicly available IPv6 adoption statistics. As government policies play a critical role in IPv6 deployment, we analyze the experiences that various countries — such as France, the US, China, India, Saudi Arabia, UAE, and Kenya — have with industry policies. We then provide a policy toolbox, based on those successful experience, to help policymakers adapt their IPv6 migration strategies. This white paper also introduces the essential role of the IPv6 Enhanced Council in sharing experiences and both IPv6 deployment guides and frameworks from regions around the world through the regional sub-alliances, with a special focus on the newly created Arab IPv6 Council.

Despite Arab and African countries currently having a relatively low IPv6 adoption rate, some of them are gradually exploring the industrial application of IPv6 and IPv6 Enhanced. The benefits and value created are measured and assessed through business scenarios that are of particular interest to operators and their stakeholders, attracting very positive and encouraging feedback. Some noteworthy case studies are presented toward the end of the white paper to pave the way for larger-scale deployment of IPv6 and IPv6 Enhanced in the future in both the Arab and African regions to support their digital strategies.

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1 IPv6/IPv6 Enhanced as a Key Enabler of the Digital Economy

Over the years, society has inevitably entered the era of digital economy and realized that IPv6/IPv6 Enhanced with unlimited capabilities is the only choice. IPv6/IPv6 Enhanced is a key enabler for and the only viable option to support digital transformation and generate value. This is because GDP growth is directly correlated to the IPv6 deployment index1. According to this analysis, IPv6/IPv6 Enhanced deployments can create $7.3 trillion by 2025. As such, policymakers in regions where the IPv6 deployment rate is below the world average should take IPv6 Enhanced seriously.

Governments must formulate IPv6 policies to help stakeholders across countries, regions (e.g., Arab and Africa), and sectors (both public and private) to fully harness the "worldwide Internet revolution".

This revolution must allow every person around the world to get an IPv6 address as a personal ID free of charge and be granted the right to access, benefit from, and contribute to the Internet in an end-to-end fashion, without any intermediary or any man-in-the-middle on the borders of the global digital economy. It will allow our network to meet

[1] Roland Berger, Global IPv6 Deployment Report 2022.

new requirements — including high bandwidth and AI-oriented and on-demand network service acquisition — by using technologies such as industrial digital private network, converged transport network (with slicing), hyper-converged DCN, and more. This also facilitates the ability to trace cyber attacks and crimes, something that is not possible for a shared IPv4 address. As such, IPv6/IPv6 Enhanced contributes to building trust and confidence to meet the "secure and safe society" requirement that a digital society places on the IPv6-based Internet.

Once people activate the IPv6 addresses attached to each of their personal devices (e.g., smartphones, tablets, and other connected objects), those people become "prosumers" (i.e., both providers and consumers) of this huge worldwide open dataspace by connecting (exchanging personal and professional messages/data) with other people and transacting with applications (e.g., banking, insurance, entertainment, gaming, health, and education) that support IPv6. This open dataspace becomes a strategic data hub — with appropriate data governance (ownership, provenance, sovereignty, and more) — from which we can continuously derive updated valuable knowledge (patterns, insights, recommendations, actions, and plans of action) thanks to various powerful data processing by AI/ML algorithms. Such data processing can be locally performed in an enterprise or even on a person's smartphone if the service and associated regulation/legislation in force require no external transfer of data. It can also be performed on the cloud for use cases and applications that are not sensitive and involve little risk. The derived knowledge can be made available and consumable to serve various purposes, such as creating value and new markets, improving people's lifestyle, and operationalizing and achieving Sustainable Development Goals (SDGs) — such as the ones defined within the UN's 17 SDGs and promoted by the United Nations and by ITU Data4Good — in some key practical areas.

Everyone is granted the right to access the global Internet and become an active actor of the digital economy. This requires moving away from the current saturated IPv4-based Internet to an IPv6-based one characterized by unlimited capabilities. Moreover, we must know that owning this unique ID (IPv6 address) empowers everyone to take part in the governance of the IPv6-based Internet, hence becoming responsible and accountable for its development and reputation. Their behavior will, therefore, directly impact the sustainability of the digital economy.

2 IPv6-Driven Digital Transformation Framework

The methodology adopted by the IPv6 Enhanced Council was to first explore and analyze how the advent of IPv6 and IPv6 Enhanced — as a major evolution of the IPv6-based Internet standard — will foster the development and use of the Internet in the digital economy. To this end, the IPv6 Enhanced Council of the Global IPv6 Forum developed a framework that emulates what an IPv6-driven digital transformation ecosystem should look like — we briefly describe this framework here. Then we outline the main areas where this innovative Internet is likely to have some impact and the opportunities it opens up from two complementary IPv6 policy perspectives — society-oriented and business/market-oriented — where associated policymakers can act in unison but with different expectations and in response to different needs. Figure 1 depicts these two perspectives.

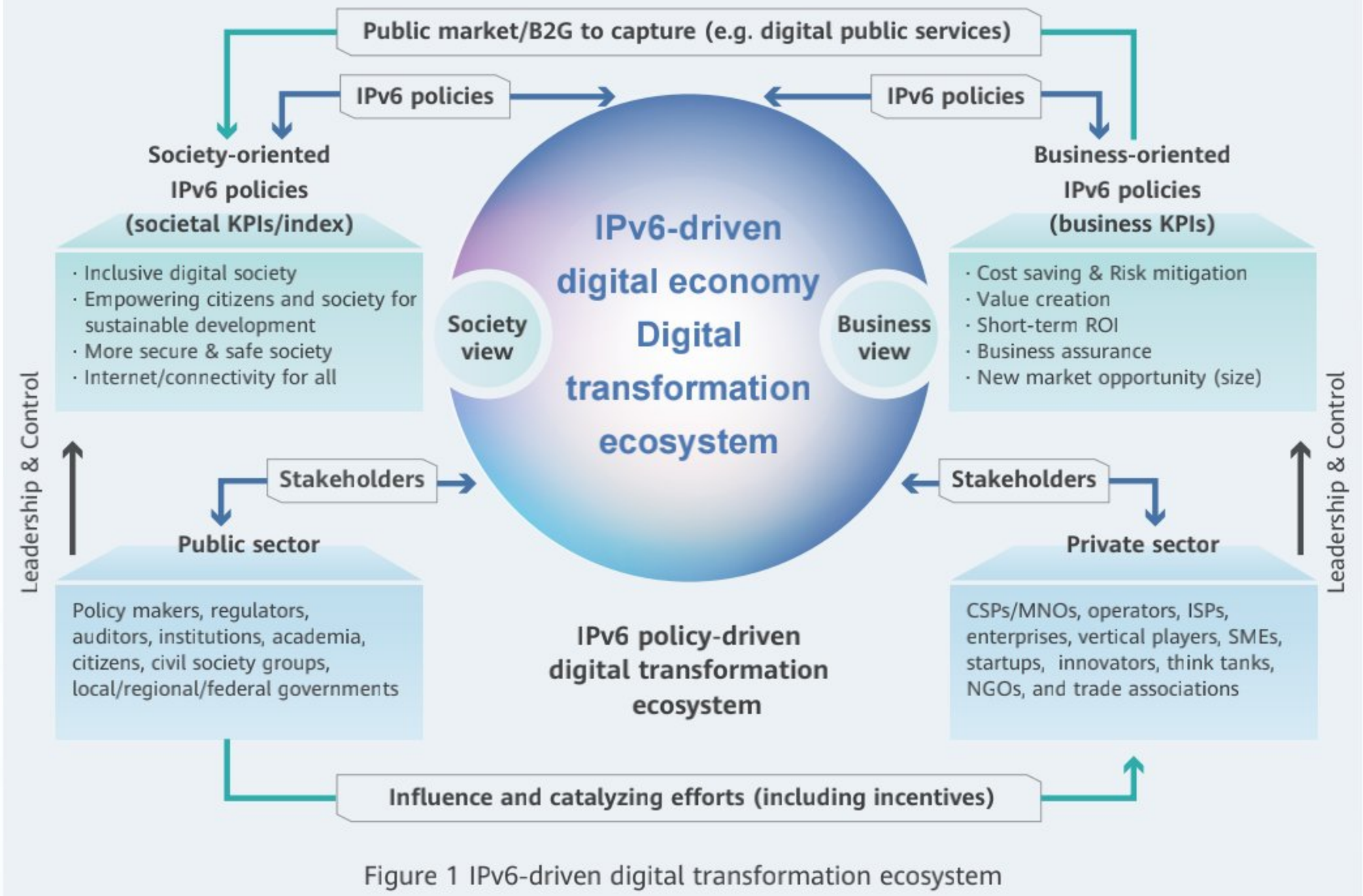


Figure 1 IPv6-driven digital transformation ecosystem

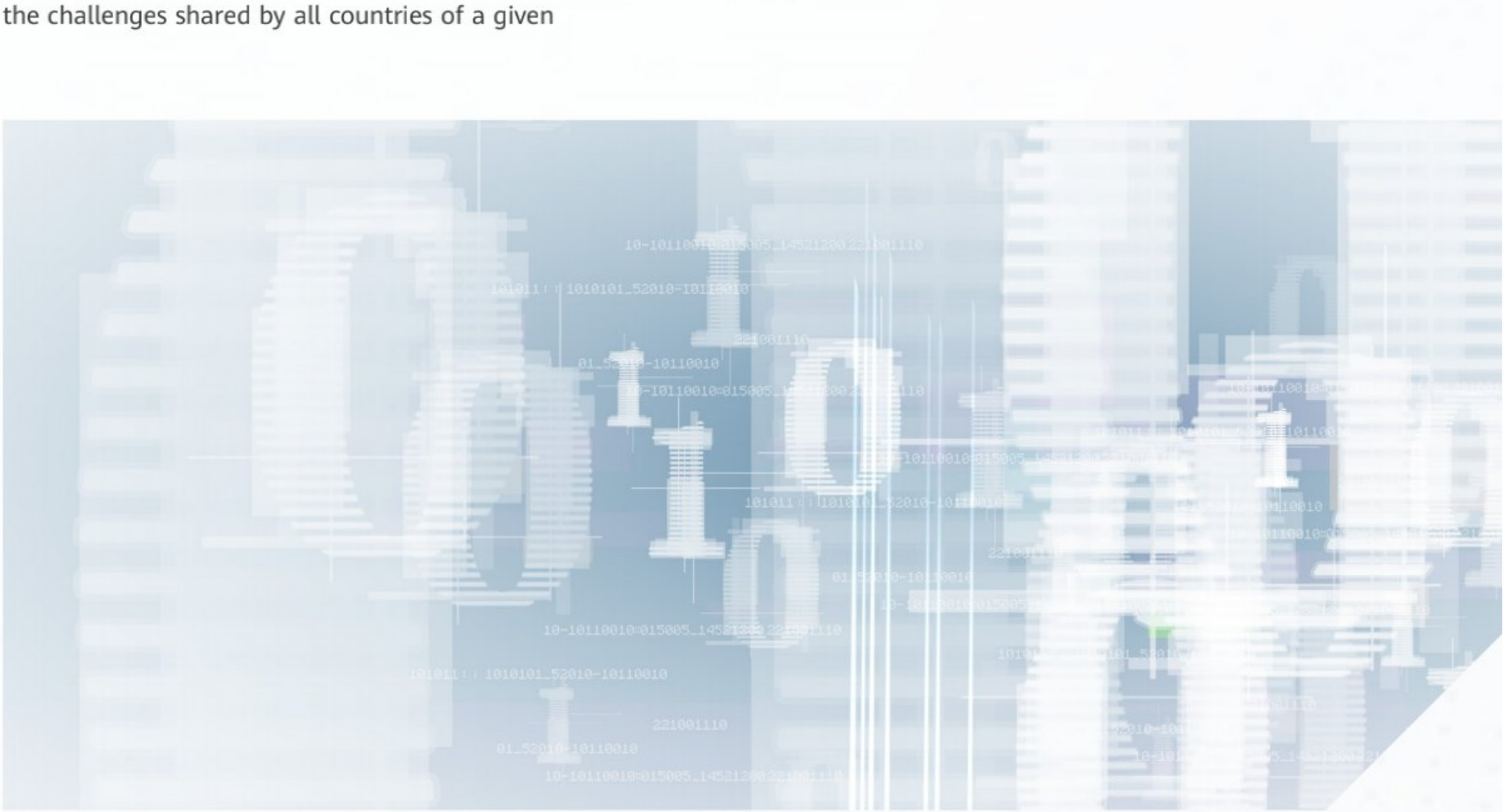
(a) The society-oriented perspective is under the leadership and control of the public sector and its listed associated stakeholders, with KPIs such as the inclusive digital society agenda to empower people and societies for sustainable development.

(b) The business/market-oriented perspective is under the leadership and control of the private sector and its listed associated stakeholders, with KPIs such as short-term ROI, value creation, new market opportunity, and business assurance.

Although both perspectives have their respective agendas, roadmaps, timelines, challenges, and readiness assessments, they are not "siloed". Rather, they are complementary to each other. Synergies, complementary relationships, and mutual benefits may exist. Indeed, in most cases, the provisions of the public sector/government IPv6 policies prevail, meaning that any progress and achievements made in the public sector should influence and catalyze the private sector's efforts. This can be achieved thanks to various instruments set out in government IPv6 policies and associated regulatory frameworks, including incentive programs supporting the purchase of products and solutions ready and capable of operating in IPv6-only environments. The other instrument is public procurement calls that are open to actors in the private sector who are aligned with government IPv6 policies, recommendations, and interventions.

On the other hand, private sector stakeholders whose primary focus is on profitable services should not ignore that business-to-government (B2G) services pose an opportunity to seize. This B2G segment encompasses profitable use cases that can enlarge the market space of the IPv6-based products and solution portfolios offered by private sector stakeholders. Note that some stakeholders (suppliers) in the marketplace specialize entirely in the B2G market.

The IPv6-driven digital transformation framework can be instantiated and trialed on various pilots/PoCs at country and regional levels (e.g., Arab region, Africa's four regions) through an IPv6 regional deployment framework. It can be considered a design blueprint that is meant to capture the requirements placed on IP networks and the challenges shared by all countries of a given region as they are targeting the same objective. The IPv6 Enhanced Council is developing an IPv6 regional deployment framework as a dedicated regional platform for dialog and debate on critical issues concerning IPv6 deployment. The primary goal is to help regional stakeholders implement regional digital strategies, such as Arab Digital Strategy 2030 and Digital Transformation for Africa (2020-2030)[2], and to support individual countries in aligning their national digital strategies with the regional one. Indeed, APNIC statistics show that only 11 Arab and African countries have an IPv6 adoption rate of more than 5%, whereas the worldwide average is 30%. This is why there is an urgent need to develop actionable and practical IPv6 frameworks, guidelines, and tools and to enact appropriate and coordinated government IPv6 policies in an attempt to close this huge gap.



[2] The Digital Transformation Strategy for Africa (2020-2030)

https://au.int/en/documents/20200518/digital-transformation-strategy-africa-2020-2030

3 Global IPv6 Development

With the rapid growth of the Internet and emerging applications like IoT, smart home, and industry automation, the deployment of IPv6 has grown significantly over the past 10 years. Given that IP is the fundamental protocol of the Internet, governments must take the lead in uniting all the stakeholders: from user equipment vendors and network device vendors to ISPs and content providers. Therefore, both developed and emerging countries have released industry policies to promote the development of IPv6 and IPv6 Enhanced.

This chapter first introduces IPv6 as the global trend of Internet development. It then analyzes the IPv6 industry policies of some countries, including France, the US, China, and India, and regional countries like Saudi Arabia, the UAE, Egypt, and South Africa. The goal is to illustrate what a policymaker can do to accelerate IPv6 migration and to help ready a country for the digital transition.

3.1 IPv6: Global Trend of the Internet

3.1.1 Global IPv6 Deployment Status

Many Internet bodies provide statistics regarding the deployment status of IPv6 around the world, including Google IPv6 adoption, Akamai IPv6 adoption, Facebook IPv6 adoption, and APNIC, from different perspectives and using different approaches. In this section, we use statistics provided by the French Regulator, ARCEP[3], to build some ranking diagrams.

We chose ARCEP because its methodology is based on aggregation through a median (the arithmetic average of the two central values) of the publicly available data from those four sources (Google IPv6 adoption, Akamai IPv6 adoption, Facebook IPv6 adoption, and APNIC). This approach reduces the "yo-yo" effect. The methodology involves comparing, contrasting, and ranking the adoption of IPv6 among the top 100 countries with the highest number of Internet users. These countries are determined based on data from Wikipedia (as of February 6, 2023)[4].

The IPv6 usage statistics are derived from measurements performed at a content provider that systematically provides IPv6-based services. The statistics are regularly updated every two months, with data collected on the first Friday of even months.

The result is the published ARCEP interactive map depicted in Figure 2. It could be seen as a good compromise.

In addition to this map, ARCEP also published ranking tables per country and per region (11 regions). We can see that many countries where IPv6 was absent have started to enter the IPv6 world. The Top 100 ranking serves as a valuable tool for positioning each country in relation to others, as well as for assessing the progress made and the speed at which it has been achieved.

We use these statistics along with the guidelines we developed in the IPv6 Enhanced Council (Section 5) to help policymakers in Arab and African regions to develop their IPv6 strategies, policies, and deployment plans.

Since the World IPv6 Day event on June 8, 2011, the deployment rate of IPv6 has increased significantly, reaching close to 50% of the Internet by April 2023. This coverage of nearly half of the Internet marks a significant threshold or inflection point where the benefits to society, industry, and the global economy can be clearly observed.

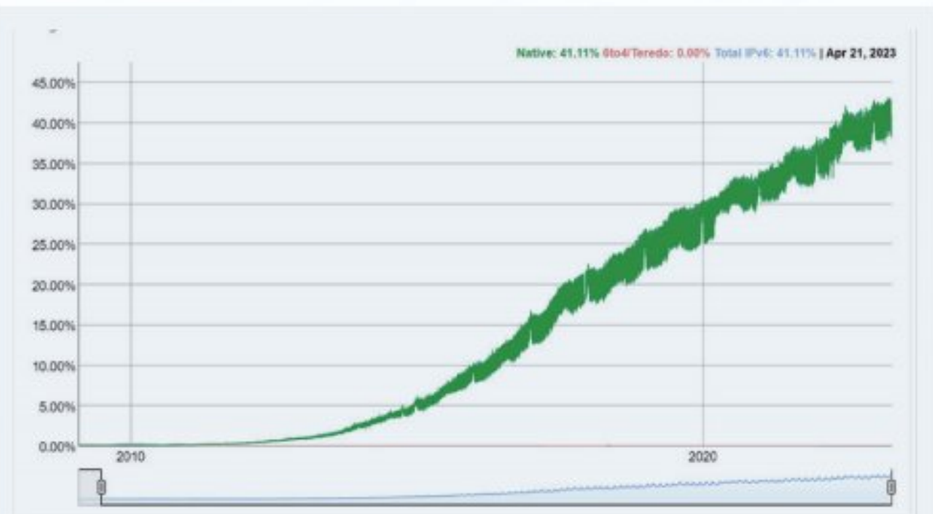


Figure 2 IPv6 adoption rate
[Source: Google IPv6 Statistics, April 2023]

[3] ARCEP, https://carteipv6.arcep.fr/

[4] Wikipedia, List of countries by number of Internet Users

This is due to the joint efforts of equipment vendors, application developers, standardization organizations, content providers, and governments. Some of the significant moves in the industry include:

- **2012**: Akamai, Facebook, and Netflix started IPv6 services.
- **2016**: Apple required iOS App Store apps to support IPv6-only networks.
- **2016**: The IAB announced that it "expects that the IETF will stop requiring IPv4 compatibility in new or extended protocols. Future IETF protocol work will then optimize for and depend on IPv6."
- **2017**: Facebook announced that all new data center clusters would be IPv6-only.
- **2021**: AWS announced the ability to create an IPv6-only architecture on AWS. All GitHub pages support IPv6.

As of May 2022, 80% of user equipment, 42% of metro/backbone networks, and 50% of clouds support IPv6. There is no doubt that the value chain of IPv6 is ready, and the Internet is embracing its new generation of protocols. The IPv6 Enhanced development is also growing rapidly — by April 2023, there were more than 160 SRv6 deployments and more than 30 IP network slicing deployments.

However, the development among countries is extremely unbalanced, as shown in Figure 3, Figure 4, and Figure 5. While some countries like India (69.32%), France (63.43%), and the US (53.22%) have a high IPv6 adoption rate, many others, especially those in Africa, have very limited IPv6 deployment. We can see that the countries with developed ICT industries tend to have higher IPv6 adoption rates.

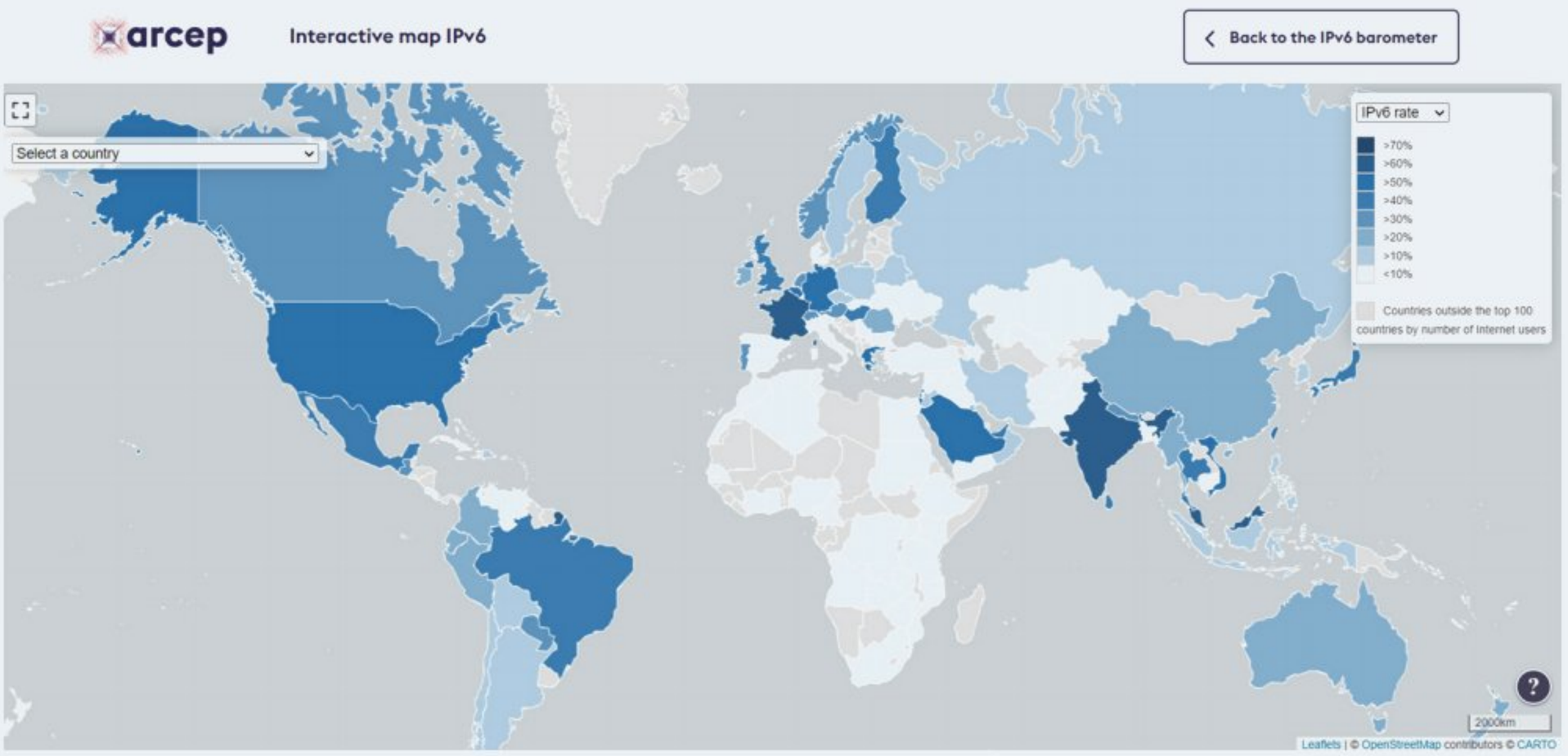


Figure 3 IPv6 adoption rate by country [Source: ARECP, April 2023]

3.1.2 Arab and Africa Regional IPv6 Deployment Status

In 2021, the Arab States region had 15.2 fixed broadband and 75 mobile broadband subscriptions per 100 inhabitants. The percentage of individuals using the Internet was 51.4%, while the household Internet access rate was 57.4%. For Africa, 40% of the population had Internet access, and 60% of them accessed the Internet via mobile phones[5]. These regions still have considerable potential — even though their network coverage grows rapidly — compared to other parts of the world. This will bring significant social and economic values: The International Finance Corporation (IFC) estimated that improving Internet coverage to 75% of the population could create an additional 44 million jobs.

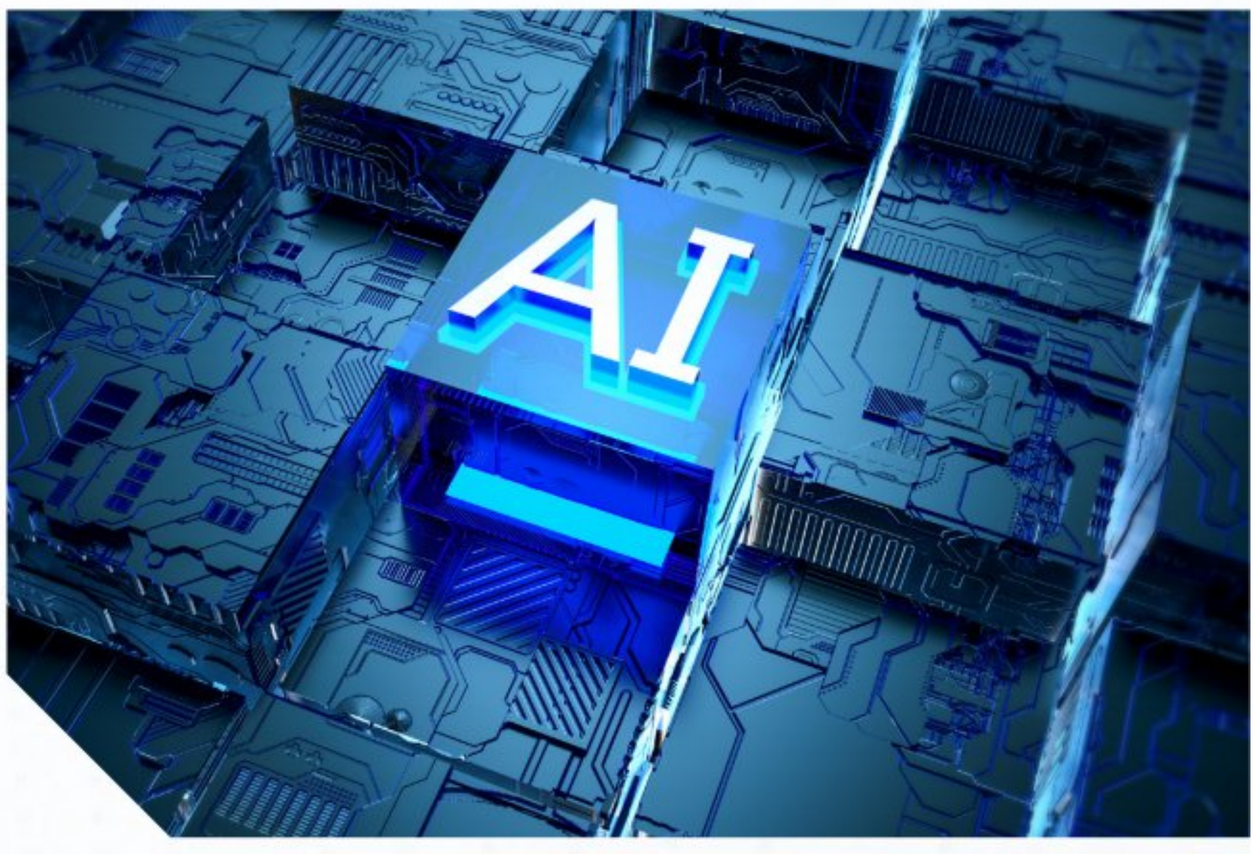
The rapid growth of the Internet requires not only access technologies like 4G/5G and fiber, but also IP as the basic protocol. Given that the IPv4 address pool is already exhausted and the standards around IPv4 will gradually stop evolving, IPv6 has become the only choice for sustainable development of the Internet. However, not every country is aware of the trend.

Based on ARCEP statistics from April 2023, Figure 4 depicts the Arab and African countries with an IPv6 adoption rate of more than 3%. Among the leaders in IPv6 deployment in the two regions, Saudi Arabia (KSA) ranked 6 and the United Arab Emirates (UAE) ranked 16 (both of which are highlighted in green). The three African countries of Zimbabwe, Kenya, and South Africa are highlighted in yellow. In general, most countries still have a low IPv6 deployment rate.

Arab and African Countries	IPv6 Adoption Rate	Ranking
KSA	57,90%	6
UAE	44,70%	16
Kuwait	20,30%	39
Oman	18%	42
Jordan	13,80%	51
Zimbabwe	9,20%	58
Kenya	6,90%	65
Egypt	3,90%	70
South Africa	3,50%	71

Figure 4 Arab and African countries with an IPv6 adoption rate of more than 3% [based on ARCEP statistics, April 2023]

In the 11 well-known regions, regional development falls well below the world average, as illustrated in Figure 5 (based on ARCEP statistics). The data reveals that Western Asia, which is composed of most Arab countries, has a deployment rate of 15.75%, while that in Africa is only 1.42%.



[5] Investment Monitor, African e-Connectivity Index 2021, November 2021

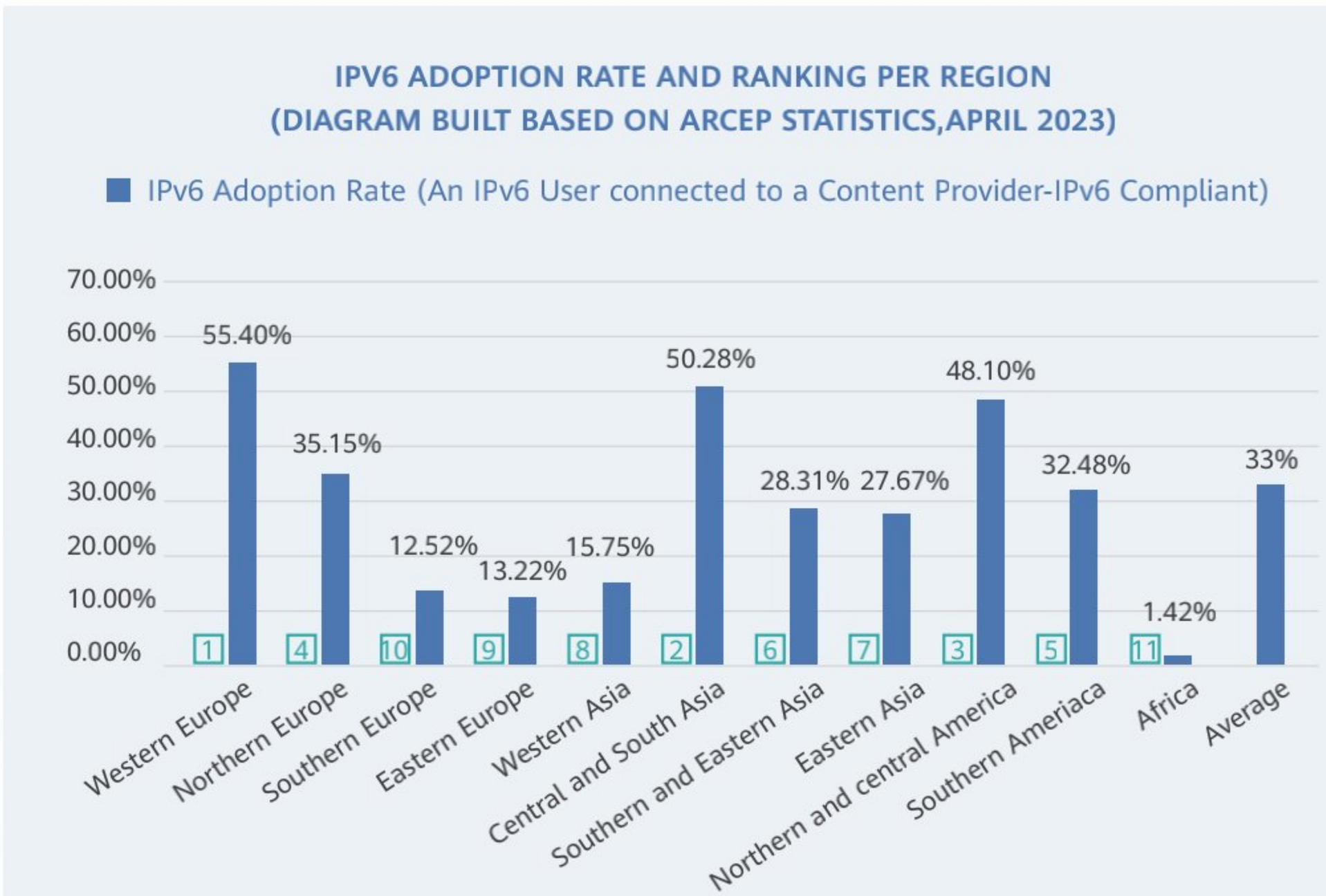


Figure 5 Regional IPv6 adoption rate [based on ARCEP statistics, April 2023]

It is worth noting that some countries in these regions have realized the importance of IPv6 development and started the migration progress. The industry policies will be introduced in the rest of this chapter.

3.2 Global IPv6 Industry Policies

This section introduces some typical policies released by different countries around the world: binding the wireless spectrum with IPv6 (France), promoting IPv6 in the government networks (the US), setting up a national commission for IPv6 promotion (China), and engagement from both government and the private sector (India).

3.2.1 France: Releasing the IPv6-5G Binding Policy

The French telecommunication regulator, ARCEP, confirms that the transition to IPv6 is a major issue for competitiveness and innovation. Major operators

in France (Bouygues Telecom, Orange, and SFR) have already assigned between 93% and 98% of their IPv4 addresses. Sharing IPv4 addresses brings issues like blocking new Internet services and increasing difficulty in identifying cyber crimes.

In November 2019, ARCEP released the regulation on 5G spectrum distribution[6], requiring that:

• IPv6 must be supported to guarantee service interoperability and availability of IPv6-only services.

• The 3.4-3.8GHz 5G spectrum holders must have their network compatible with IPv6 protocol from December 31, 2020.

In addition to the IPv6-5G binding policy, ARCEP publishes Annual IPv6 Barometers[7] every year to follow the deployment of IPv6 in the country and provide suggestions. ARCEP also set up the national IPv6 Task Force[8] to promote the IPv6 deployment in the country. In March 2022, the Task Force published Enterprises: How to Deploy IPv6 to guide enterprises' IPv6 migration.

The actions from both the regulator and operators are boosting the IPv6 deployment in France, as shown in Figure 6. By the middle of 2024, the IPv6-enabled deployment is expected to be close to 100% for major operators like Orange, Bouygues Telecom, and Free. Although SFR is lagging behind, it is catching up.

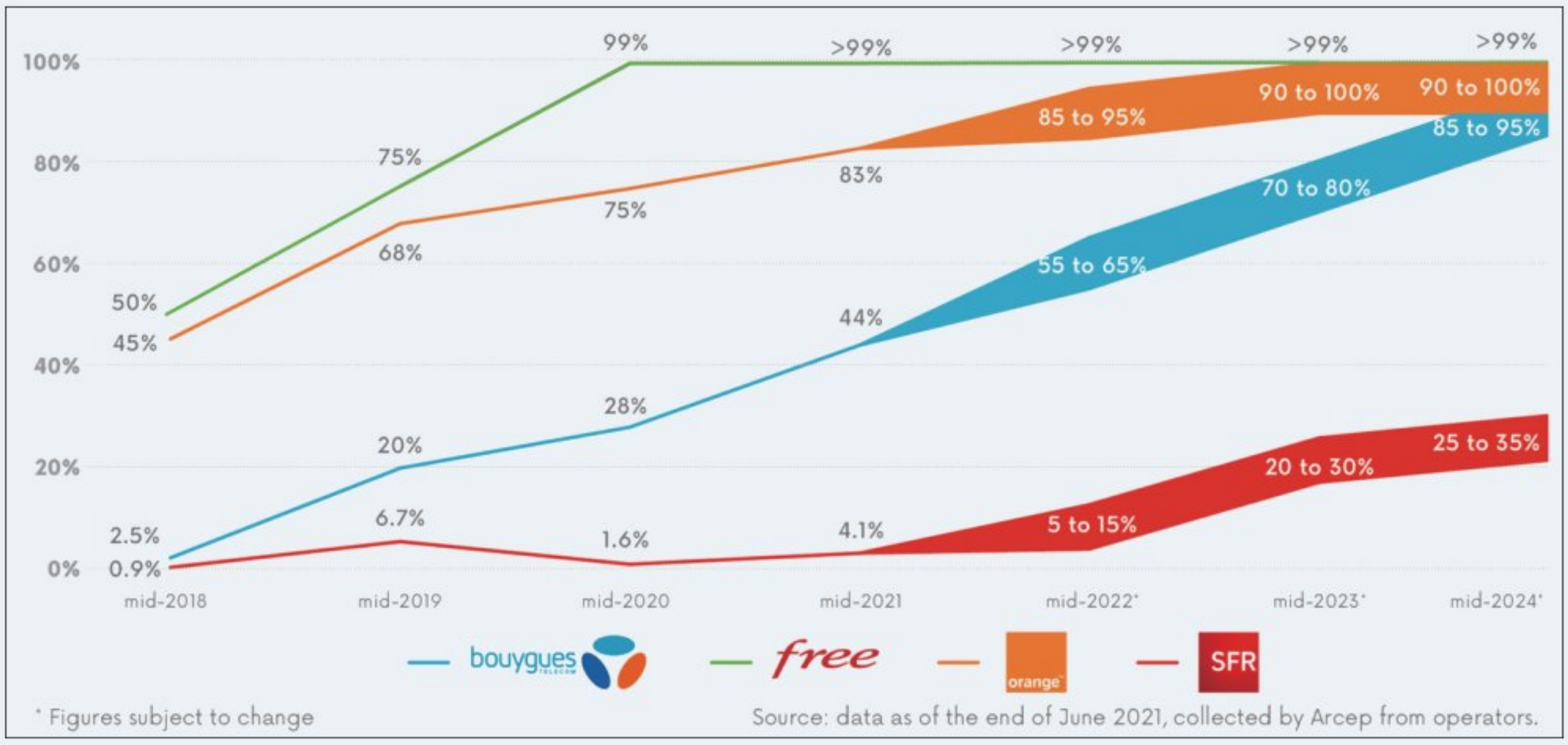


Figure 6 Fixed network evolution for IPv6-enabled customers of major operators in France
[Source: 2021 Annual Barometer of the Transition to IPv6 in France]

[6] ARCEP, Décision n° 2019-1386, November 2019.

[7] ARCEP, ANNUAL BAROMETER OF THE TRANSITION TO IPv6 IN FRANCE, 2019-2022

[8] ARCEP, France IPv6 Task Force https://en.arcep.fr/publications/task-force-ipv6.html

3.2.2 The US: Releasing Multiple Policies Since 2009 and Setting Up an Agenda for IPv6-Only Transition in Federal Networks

As the leading country in Internet technologies, the US is the most active country in IPv6 promotion. The US federal government also released multiple policies to accelerate IPv6 deployment in the public sector. Some key actions include:

• In 2009, the Federal Chief Information Officers (CIO) Council published the Planning Guide/Roadmap Toward IPv6 Adoption within the US Government, clarifying the position of IPv6 as an integrating framework and organizing principle for the next generation of Federal IT Infrastructure.

• In 2012, the CIO Council released the 2nd version of the roadmap, summarizing the federal transition components, business rationale, 'to-be' states, and transition steps within the process.

• In 2020, the Office of Management and Budget (OMB) published OMB-M21-07 (2020), which defines a specific path for agencies' transition to IPv6:

- ➤ At least 20% of IP-enabled assets on federal networks should be operating in IPv6-only by the end of 2023.
- ➤ At least 50% of IP-enabled assets on federal networks should be operating in IPv6-only by the end of 2024.
- ➤ At least 80% of IP-enabled assets on federal networks should be operating in IPv6-only by the end of 2025.

Besides the actions mentioned above, the OMB, CIO Council, and the National Institute of Standards and Technology (NIST) also released multiple guidelines and technical standards. The industry leaders like Cisco, Google, Facebook, and Microsoft from the private sector have also played a significant role in IPv6 adoption to guarantee the competitiveness of the enterprises. More details of the policy actions can be found in the Axon Partners Groups's whitepaper IPv6: Benefits and best practices of public policies[9].

3.2.3 China: Setting Up a National IPv6 Promotion and Deployment Commission to Release Policies and Formulate Development Strategies

As a populous country facing a shortage of IPv4 addresses, China has made IPv6 migration a national strategy. To this end, the Chinese government has established the National IPv6 Promotion and Deployment Commission, which is responsible for releasing IPv6 policies and formulating development strategies. The most recent one was in July 2021, when the government published the Special Action Plan of IPv6 Traffic Promotion (2021-2023), setting up goals for different phases. The final goals of phase 3 include:

• The percentage of IPv6 traffic on mobile networks is over 50%, and the traffic volume of fixed networks is more than three times that of Dec. 2020.

• The IPv6 deployment rate in top 100 commercial websites is over 70%.

• The percentage of fixed terminals using IPv6 addresses is over 80%.

[9] Axon Partners Group, IPv6: Benefits and best practices of public policies, December 2021

3.2.4 India: Promotion from Both Government and Operators

India's Department of Telecommunications has issued relevant documentation for reference at the early stages of IPv6 implementation. The National IPv6 Deployment Roadmap was first released in 2010, followed by a more recent version II in 2013[10]. The main actions outlined in those roadmaps include the two main initiatives taken by the government up until 2013, i.e.:

• Creation of an IPv6 task force (2010)

• Definition of steps for IPv6 proliferation, such as seminars and workshops, and the selection of organizations as IPv6 consultants/facilitators or testbeds

➤ Defined the current status, challenges, strategies, and transition plans for various stakeholders, such as government agencies, service providers, content and application providers, equipment manufacturers, cloud and data center providers, along with security best practices.

➤ Established monitoring mechanisms, both quantitative (measuring throughput, latency, reach, etc.) and qualitative (measuring the number of services, applications, network elements, traffic volume, etc., which is IPv6-based) for future years.

➤ Developed a checklist for IPv6 readiness and a status equipment of manufacturers. Regarding the status of manufacturers, it was very positive towards IPv6 transition even back in 2013, as nearly 80% of network element providers could provide IPv6-capable products.

On the private side, India's transition process was significantly influenced by its service providers, particularly by the operator India Reliance JIO. This operator took the initiative to start its IPv6 transition one year ahead of the average adoption process in India, as IPv4 adoption was already severely limited back in 2013 (with only 36 million IPv4 addresses available for 254 million Internet subscribers in the country). As a result, limited IPv4 adoption served as a catalyst for the IPv6 transition, as the advantages of switching far outweighed the potential problems and risks.

3.3 Arab and Africa Regional IPv6 Industry Policies

IPv6 development is unbalanced in Arab and African regions. In terms of regional deployment, the UAE and Saudi Arabia are leading the field thanks to government-led digital transformation initiatives, such as Saudi Arabia Vision 2030[11] and UAE's Vision 2021, together with other national policies. However, other countries in the regions have relatively low rates of IPv6 adoption. Nevertheless, many countries (including Tunisia, Qatar, Kenya, and Nigeria) have realized the challenges and are in the process of developing national policies or strategies to promote IPv6 deployment.

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[10] Government of India, National IPv6 Deployment Roadmap version-II, 2013

[11] Saudi Arabia Vision 2030 https://www.vision2030.gov.sa/

This section first introduces the experience of Saudi Arabia and the UAE, explaining how they have accelerated their IPv6 deployment in recent years. It then describes some ongoing efforts from other regional countries.

3.3.1 Saudi Arabia: Setting Up KPIs for Service Providers

The IPv6 adoption rate has grown significantly since 2020: from 17% in Q3 2020 to 58% in Q2 2022. This impressive growth can be attributed to the efforts of the IPv6 Task Force led by the Communications and Information Technology Commission (CITC), which is the regulatory body of Saudi Arabia. Since 2008, CITC has started promoting IPv6 transition through guidelines and various initiatives. These initiatives include setting up a national IPv6 Task Force, assessing the current state, and creating an IPv6 strategy roadmap. However, progress was relatively slow until 2018, when the IPv6 Task Force shifted its focus toward involving service providers. CITC organized regular workshops and meetings with stakeholders and obligated the main service providers to report their IPv6 adoption progress. By collecting such data, CITC could set specific targets for service providers to accelerate their IPv6 implementation.

It was a challenge to convince service providers to make investments for wider IPv6 adoption because the business case was not clear. However, demonstrations showing the importance of IPv6 adoption for the emergence of 5G cellular networks and the Internet of Things (IoT) helped raise awareness among service providers. Reports highlighting the centrality of IPv6 to both 5G and IoT were influential in supporting approved business cases for investment[12]. The remaining challenges include mobile handset compatibility, IPv6-only service provisioning, and access to IPv6-only services.

3.3.2 UAE: TDRA Playing a Key Role in IPv6 Migration

In 2012, the UAE's Telecommunications Regulatory Authority (TRA), as it was known at the time, initiated a project to develop an IPv6 strategy, adopting a national action plan to prepare for the eventual transition[13]. The TRA – now known as the Telecommunication and Digital Government Regulatory Authority (TDRA) – has been leading the efforts for more than a decade to nurture a sustainable IPv6 ecosystem. Recently, Mr. Majed Al Mesmar, the Director General of TDRA, shared the UAE's experience in IPv6 deployment[14]: To speed up IPv6 adoption, the authorities studied market gaps and gathered feedback through local Internet registries (LIRs), each of which owns a pool of IP addresses. The reasons for hesitancy included limited knowledge of IPv6, satisfaction with the current IPv4 system, and customers' reluctance to change. To address these knowledge gaps, a series of workshops

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[12] APNIC Mat Ford, Understanding Saudi Arabia's IPv6 boom, June 2021.

[13] Majed Al Mesmar (Director General, TDRA, UAE), Accelerating IPv6 uptake to spur digital transformation, January 2022 https://www.itu.int/hub/2022/01/accelerating-ipv6-uptake-digital-transformation/ .

[14] Accelerating IPv6 uptake to spur digital transformation, January 2022 https://www.itu.int/hub/2022/01/accelerating-ipv6-uptake-digital-transformation/ .

were organized. Successful IPv6 implementation does not solely depend on telecom service providers. Recognizing the need for complementary hardware, the TDRA has synchronized efforts from various public and private sector players to ensure device compatibility for IPv6.

Since the UAE's launch of the updated protocol in 2017, the UAE government has been actively promoting the rapid adoption of IPv6 to create an IPv6-ready ICT market landscape. Testing on the UAE Federal Network (FedNet) was completed in 2018, signifying IPv6 readiness in terms of hardware and software and the possibility to deliver smart government services to all entities and customers across the country.

In 2019, less than two years after the initial launch, the UAE celebrated becoming one of the first countries in the Middle East to make the transition to IPv6.

3.3.3 Kenya: Releasing a National IPv6 Migration Strategy

The Communications Authority (CA) of Kenya published the IPv6 Migration Strategy in July 2022[15], aiming to stimulate the current IPv6 adoption rate in Kenya. The strategy includes:

- **Regulatory intervention**
  - ➤ Only devices with IPv6 capability will be type-approved in Kenya, effective starting in July 2023.
  - ➤ Further assignments of resources, namely, numbering resources, frequency assignments and top-level domain name assignment documents, will contain in them a regulatory requirement for the adoption IPv6 addresses.
  - ➤ Inspection and certification of operator systems and networks will involve a check on the transition to IPv6 components, and those found not to have adopted IPv6 will be deemed non-complaint.
  - ➤ Network readiness assessment reports will be established.
- **Awareness**
  - ➤ Develop an awareness campaign plan targeting operators, vendors, and consumers as appropriate.
- **Training**
  - ➤ Organize hands-on physical training on IPv6 migration and related technologies.
- **Report submissions**
  - ➤ Define reporting templates, and require service providers to report on the steps taken to adopt IPv6.

A set of milestones have been established to measure the progress. Service providers are also encouraged to adopt emerging IPv6 Enhanced technologies to create additional values based on IPv6.

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[15] Kenya CA, IPv6 Migration Strategy

https://www.ca.go.ke/wp-content/uploads/2021/05/Draft-IPv4-to-IPv6-Migration-Strategy-.pdf , July 2022.

4 IPv6 Transition: Recommendations of Industry Policies

The experiences from different countries in the world have shown that a government's industry policy plays a critical role in IPv6 transition. Figure 7 lists a set of policy actions and tools that a government could apply to accelerate the IPv6 migration process from policy preparation to policy enforcement.

Policy Preparation(1st year)	• Set up IPv6 industry organizations • Join international industry alliances • Build the IPv6 awareness campaign and training • Include IPv6 training in university curriculum
Policy Design(1nd year)	• Create high level national strategy with ICT planning • Set up compliance goals for operator and government networks • Encourage IPv6 Enhanced pilots in operator and government networks
Policy Enforcement	• Impose an IPv6 adoption progress reporting obligation for operators • Enforce IPv6 support on newly-built networks • Bind national fund for broadband/mobile coverage projects with IPv6 support • Enforce IPv6 reauirements for new devices in the market • Tax/limit the use of IPv4 address sharing • Bind Frequency and Number Resource Allocation with IPv6 support

Figure 7 IPv6 industry policy tools

4.1 Policy Preparation

- **Set Up IPv6 Industry Organizations**

The IPv6 industry organizations, named like the IPv6 Council or IPv6 Task Force, could bring together stakeholders like government agencies, operators, vendors, consulting companies, and research institutes to build and promote the IPv6 ecosystem. The initiative could be from the regulator, national network information center (NIC), ministry of communication, or major operators in the country. A regional IPv6 council could also be created to address common and shared challenges within a given region as a chapter of the IPv6 Forum. One good example is the newly created Arab IPv6 Council (see Chapter 5 for more details).

- **Build the IPv6 Awareness Campaign and Training**

Competent network architects, engineers, and technicians are key to IPv6 adoption by the industry. Therefore, the government should develop an awareness campaign plan and training sessions through workshops, online platforms, hands-on sessions, and more.

- **Include IPv6 Training in the University Curriculum**

Computer network courses are indispensable in any computer science and computer engineering curriculum. Unfortunately, the examples and hands-on practice in today's network courses are mostly based on IPv4 rather than IPv6. It is important to have IPv6 in network training, which is helpful for university students to get prepared for their future professional careers.

4.2 Policy Design

- **Create a High-Level National Strategy**

The government should identify key public agencies, such as regulators, the ministry of telecommunications, ministry of economy, and ministry of education, to create a high-level IPv6 rollout strategy. It could be an independent IPv6 migration strategy or be combined with other national ICT plans.

- **Set Up Compliance Goals for Service Providers and Government Networks**

For service providers and big enterprises that run complex network infrastructure, migration to IPv6 is not a short-term task, but a journey of several years. The regulators and governments could set up a compliance goal with clear milestones to urge the service providers and government networks to transfer to IPv6 with concrete steps. A reasonable goal is to increase the operators' or governments' IPv6 adoption rate by 20% to 30% every year. This approach has been applied by countries like the US, China, and Kenya. The key performance indicators include:

- ➤ Ratio of IPv6 traffic
- ➤ Ratio of IPv6-capable terminals
- ➤ Ratios of IPv6 content and supported mobile applications

- **Encourage IPv6 Enhanced Pilots on Operator and Government Networks**

IPv6 means more than a larger address space. One of the essential reasons of delayed IPv6 deployment is the lack of business cases (because alternative

approaches such as IPv4 NAT can still be used). As the protocol development based on IPv4 becomes stale, the government can encourage the deployment of IPv6 Enhanced technologies such as SRv6, BIER, network slicing, and IFIT. Those innovations can bring additional values to the business with new services such as digital private network, converged transport network, hyper-converged DCN, and 10 Gbps campus network, thereby facilitating IPv6 deployment. The key performance indicators include:

- Ratio of IPv6-only transport networks
- Readiness of IPv6 Enhanced functions (SRv6, network slicing, etc.)
- Number of IPv6 Enhanced pilot projects

4.3 Policy Enforcement

• Mandate Service Providers to Report IPv6 Adoption Progress

By requiring service providers to report IPv6 adoption progress regularly, the government and regulators can follow the status of IPv6 deployment. This exercise has been adopted by countries like France, Saudi Arabia, and China. Based on the reports, the regulators can set KPIs for the service providers.

• Enforce IPv6 Support by Newly Built Networks

Legacy networks need to deal with devices with inadequate IPv6 support, which may make the immediate migration challenging to achieve. However, for the newly built networks, deploying IPv6 will be a much smoother task. The government and regulators should mandate IPv6 support to guarantee service interoperability, especially for services only available in IPv6. This makes the new networks ready for future evolution. The government should even encourage IPv6-only networks, which is the case required by the US government for its federal networks.

• Bind National Fund for Broadband/Mobile Coverage Projects to IPv6 Support

Many countries have national or department funds to support broadband and mobile network deployment in the country. The government and regulators could use the fund to leverage and motivate the application of IPv6 in those projects.

• Tax or Limit the Use of IPv4 Address Sharing

Although IPv4 address sharing relieved the address shortage in the short term, it is currently the main barrier to the Internet's end-to-end connectivity and IPv6 deployment. The regulator should limit the sharing of one IPv4 address among subscribers. For example, in Belgium, the maximum number of subscribers behind 1 IPv4 address is 16.

• Enforce IPv6 Requirements for New Devices in the Market

The regulators can build IPv6 certification programs and standards requiring equipment compliance for IPv6. This can assist various stakeholders in ensuring that any Internet-compatible products to be used in the national market have the minimum capabilities required to support an IPv6 ecosystem. This approach has been applied by countries like Malaysia and Brazil.

• Bind Frequency and Number Resource Allocation to IPv6 Support

The regulators and NICs can add the IPv6 support requirement while allocating resources such as frequency, top-level domain names, and numbering resources. This method is used by countries like France and Kenya.

5 IPv6 Enhanced Council: What It Brings to Arab and African Regions

At the international level, the IPv6 Enhanced Council plays an essential role in sharing experience in IPv6 deployment and enhanced innovations. It promotes IETF standards by selecting relevant IETF RFCs in IPv6 and IPv6 Enhanced areas as a foundation, and then operationalizes them to deliver applicability guides to various business and deployment scenarios. The Terms of Reference (ToR) of the IPv6 Enhanced Council includes a dedicated regional platform for dialog and debate on critical issues concerning the deployment of IPv6 in the following North America, Asia, Latin America, Middle East, and Africa. The primary goal is to help regional stakeholders implement their regional digital strategies, such as Arab Digital Strategy 2030 and Digital Transformation for Africa (2020-2030), while also supporting individual countries in aligning their national digital strategies with the regional one. By joining the IPv6 Enhanced Council, participants can:

- Obtain the latest advancement in IPv6-related technologies.
- Learn and get help from industry partners working in IPv6.

• Share one's experience and solutions by participating in discussions and co-authoring white papers.

• Join POC projects.

• Participate in alliance workshops.

Therefore, it is highly recommended that all IPv6 stakeholders, including government agencies, operators, equipment vendors, research institutes, and verticals, join the IPv6 Enhanced Council. Currently, the IPv6 Enhanced Council has nearly 100 members from all the continents and domains related to IPv6. The participation is free of charge.

5.1 Arab IPv6 Council: the First Sub-Alliance Created by the IPv6 Enhanced Council

The main objectives of the Arab IPv6 Council are listed below:

• Increase the IPv6 deployment rate in the Arab region to the same level as the top leaders through a clear roadmap and deployment plan to maximize the benefits brought to GDP growth in the region.

• Minimize current IPv6 deployment imbalance among Arab member states.

• Make available a platform for debate on critical issues of IPv6 deployment, with the primary goal of issuing an IPv6 regional framework.

• Coordinate existing IPv6 task force/council policies that fall under the governance and control of the Arab member states to align them with the IPv6 regional framework.

• Capture and include the enacted strategies, frameworks, and policies (including but not limited to ICT regulations, Digital Strategy 2030, digital content, cybersecurity, ICT, sustainable development, and the council of economy) of the main stakeholders of the Arab League. Additionally, identify the main challenges shared by all Arab member states and use such information to derive requirements for IP Networks. These requirements will be used to design an IPv6 regional framework that will serve as an IPv6 regional blueprint for the region.

• Instantiate and operationalize the IPv6 regional framework for business scenarios of high interest to public and private sectors stakeholders in the Arab League Member States.

The structure of the Arab IPv6 Council is depicted in Figure 8. It contains the following building blocks:

• Board

• Technical Committee

• Secretariat

• Member States

• Regional & International Cooperation with Industry Strategic Partners

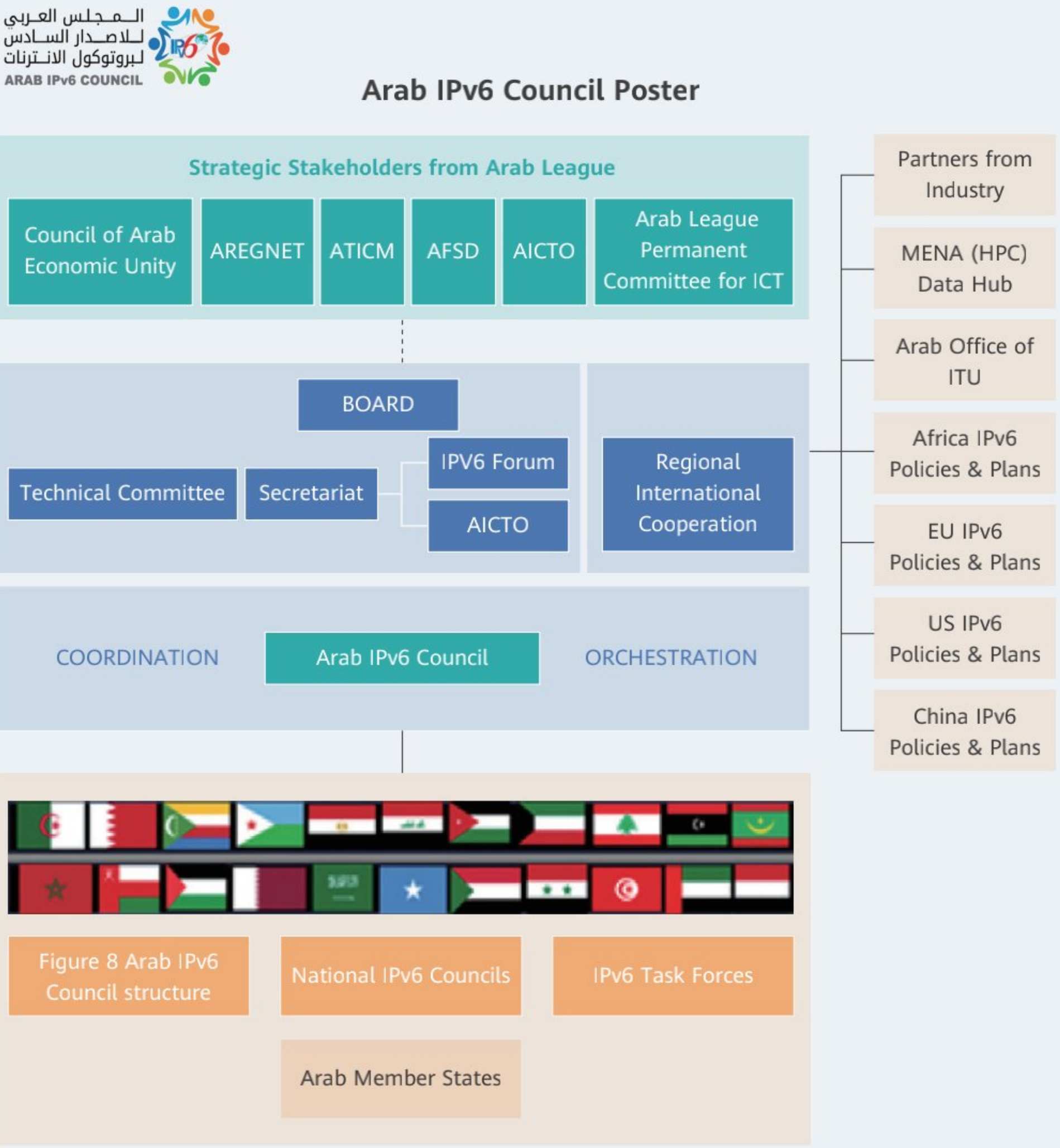


Figure 8 Arab IPv6 Council structure

Figure 8 Arab IPv6 Council structure

6 Africa and Arab Regional IPv6 Enhanced Application Cases

Countries in the African and Arab regions have relatively low IPv6 adoption rates compared with regions that have advanced IPv6 deployment, as depicted in Figure 4. Nevertheless, some of these African and Arab countries are gradually exploring the industrial application of IPv6 and IPv6 Enhanced.

6.1 North Africa Operator A: Using E2E Slicing for Deterministic Experience + SRv6 Minute-Level Service Provisioning + Wi-Fi 6 Full Coverage, Ensuring the Success of the Mediterranean Games

In June 2022, the 19th Mediterranean Games kicked off in city O of country A, with 3,500 athletes from 26 countries and regions participating in the competition. North Africa operator A was responsible for the construction of the entire network infrastructure.

The event posed high requirements on the network infrastructure at the venues, imposing the following major challenges: high-speed and full Wi-Fi coverage, concurrent access by 40,000 terminals, a real-time match score backhaul latency of less than 20 ms for the event management system, and zero frame freezing for live HD videostreaming of the event.

Operator A used slicing + SRv6 + Wi-Fi 6 to improve the entire network quality and ensure service experience.

Figure 9 Operator A's network architecture for the Mediterranean Games

• There were primarily three types of service offered at the Mediterranean Games. The high-speed Internet service required a high network bandwidth, the scoring service required a low latency, and the video conferencing service required good QoE. With the slicing technology, operator A provided three dedicated slice networks over one physical network, with service isolation, on-demand slicing, and automatic control. Operator A is a leading carrier that delivers slicing in Africa. SRv6 enables business paths to be flexibly programmed to meet business requirements. Additionally, SRv6 can work with SDN

to reduce hop-by-hop service configuration, simplifying service provisioning procedures and enabling automatic management of the integrated network.

• Operator A deployed Wi-Fi 6 throughout the venue to accommodate 40,000 terminals accessing the network simultaneously. High-density Wi-Fi 6 APs were installed with small-angle directional coverage to mitigate signal interference in high-density scenarios. Smart Radio Dynamic Turbo was adopted to reduce latency for 4K video applications from 20 ms to 10 ms. Test results showed that this solution offered a download/upload rate 2.5 times higher than that of the traditional solution, increasing from 80 Mbit/s to 200 Mbit/s. This significantly improved audience experience and satisfaction.

The success of the Mediterranean Games proved the maturity of the advanced SRv6 technology and strengthened the confidence of operator A. In its 2023–2024 plan, operator A applies SRv6 advanced technical solutions to the entire network to bring better application experience to its users.

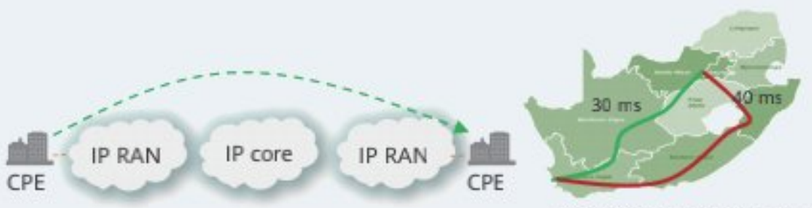
6.2 South Africa Operator C: Using SRv6 + IFIT to Shorten TTM, Guarantee SLAs, and Improve the Overall Competitiveness of Private Lines

In country S, there are three operators, A, B, and C, in the 2B market, and intensive competition exists among them. Due to the high homogeneity of products, price wars are the main form of competition. Operator C, as a traditional leader in the 2B market, needs to strengthen the overall competitiveness of private lines and avoid succumbing to price wars, which will adversely affect its return on investment.

Operator C uses SRv6 + IFIT to improve private line competitiveness:

• SRv6 can reduce cross-department and hop-by-hop service configuration. This simplifies service provisioning procedures and shortens private line TTM. With SRv6 and an SDN controller, service paths can be computed based on diverse SLA requirements.

SRv6-based service provisioning



One-hop direct connection between branches

Providing multiple paths based on committed SLAs

Description:

• Paths can be computed based on multiple factors, such as latency and bandwidth.

• Services are configured only on the CPEs. The network does not need to be changed (SRv6 must be enabled).

Benefits:

• SLA visualization and commitment before service provisioning

• Shorter TTM

Figure 10 Benefits of SRv6-based service provisioning

• IFIT is used to accurately measure and display the SLAs of private line services. In addition, automatic hop-by-hop detection is used to greatly shorten the fault locating time.

IFIT SLA visualization

When the poor quality exceeds a threshold, IFIT automatically starts hop-by-hop detection and demarcates faults within minutes.

Benefits:
• Proactively identifies problems before customers complain
• Shortens the poor-QoE recovery time.

Description:
• Hop-by-hop in-band flow measurement for poor-QoE private lines quickly identifies faulty points.
• 24/7 historical performance snapshot

Figure 11 Benefits of IFIT

By 2023, operator C had upgraded all its traditional MPLS private lines at one mining project to SRv6 private lines. Summarizing the experience of this project, operator C will launch new value-added products for the 2B market to improve the overall competitiveness of its products.

6.3 Middle East Operator Z: Using SRv6 + 400GE + Network Digital Map to Build Ultimate 5G IP Transport Networks

Operator Z, as a 5G pioneer, has consistently led the 5G development and deployment trend in the Middle East and North Africa over the past four years. Operator Z boasts the most extensive 5G business offerings in the region, and its 5G service quality is unparalleled in the Middle East. In 2019, operator Z launched the first 5G FWA in the Middle East. The following year, it launched 5G smartphones and 5G cloud gaming. Then in 2021, it launched 5G VR business. In 2023 to 2024, operator Z plans to launch 5G mobile VPN, private network, and full-scenario IoT, achieving end-to-end 5G service coverage in all business scenarios. This will deliver better experience to customers and create more value.

Currently, operator Z is transforming from a mobile operator to a digital service operator. Its digital service strategy encompasses four major directions: 5G, cloud, gaming, and IoT. In order to support complex 2C, 2H, and 2B services, operator Z needs to build an ultimate IP network.

An increasing number of users are using operator Z's services, such as video conferencing, online gaming, and VR services, all of which require ultra-high bandwidth. Services such as telemedicine and smart manufacturing are particularly sensitive to latency. Low latency can bring better experience and enable more precise services. Additionally, as the number of network devices continues to grow, there is a greater need for management and configuration. As a result, networks need to support visualization and intelligent troubleshooting. In summary, operator Z needs to build an ultimate IP network capable of supporting all 2C, 2H, and 2B scenarios. The typical characteristics of the network are ultra-high bandwidth, ultra-low latency, ultra-strong intelligence, and ultra-high reliability enabled by SRv6, 400G, and network digital map.

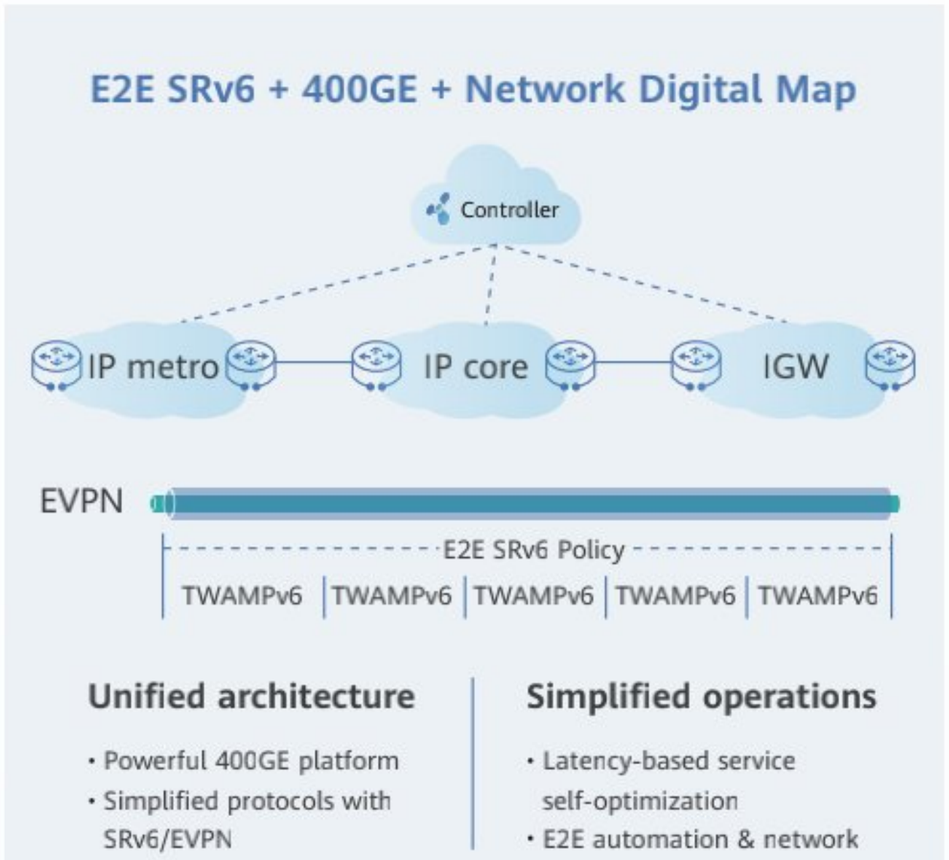


Figure 12 E2E SRv6-based 5G transport network

The ultimate IP network significantly contributes to business success. Over the past few years, operator Z has been vigorously developing 2B and 2H users, posing a challenge to network bandwidth.

• With end-to-end SRv6 deployment throughout the network, network-wide traffic successfully avoids IP best-effort forwarding, resulting in a 30% improvement in network bandwidth utilization. SRv6 enables one-hop cloud access, reduces the number of configuration steps, and shortens new service provisioning time. Specifically, its service TTM is reduced by 24%. Because 90% of the optical fibers in country S are leased, deploying a large number of 100GE bundles on the core side would result in significant rental costs. In response, operator Z opted for a 400GE solution, which allowed it to replace four 100GE fibers with a single 400GE fiber, significantly cutting rental costs. This approach has reduced the per-bit cost by 30%, which is a significant achievement.

• In addition, operator Z uses network digital map to improve its network O&M efficiency, and employs intelligent simulation to enhance overall network reliability and expand the user base. As a result, its network O&M efficiency has been improved by 35%, and its user base has been expanded by 12%, significantly boosting revenue.

Through these efforts, operator Z achieved a 43% increase in ARPU within 5 years and won many awards for its network development. For example, it won the Fastest Fixed Network Award three times in a row, the Fastest and Biggest 5G Coverage Award in country S, and the Fastest Average Speed of 5G Award in city R.

The three cases mentioned above demonstrate the immense potential of IPv6 and IPv6 Enhanced technologies in ensuring optimal user experience. As we move towards the future, we can expect the emergence of newer technologies such as 800GE and WiFi-7, which will further enhance end-to-end QoS. With the ongoing trend of digitalization, the private network for industry digitization presents a new opportunity for operators. IPv6 Enhanced enables operators to offer a range of digital services in addition to connectivity. Industry users can opt for either a private line or a private network and add managed digital services such as Managed LAN/WLAN, Managed Security, Managed DCN, and Managed Cloud Network based on SRv6, slicing, etc. The private network for industry digitization not only enables operators to unleash the power of cloud-network synergy, but also simplifies the lives of vertical industry users by providing a one-stop solution covering both connectivity and cloud services.

7 Conclusion

The IP protocol and IP addresses are the fundamental building block of the Internet. As the IPv4 address space is already exhausted and the protocol innovation stagnates, IPv6 becomes the only way forward for sustainable Internet development to connect everything.

The core values of IPv6 include:

- **Innovation**

From a technology point of view, all new protocol designs are based on IPv6 rather than IPv4. This means that network innovations will be IPv6-based, and IPv4-based networks will gradually stop evolving. From a social point of view, over-priced IPv4 addresses create a high barrier for newcomers to the market, whereas abundant and free IPv6 addresses are much more welcoming for emerging enterprises.

- **Security**

By simplifying the network with end-to-end connectivity, IPv6 supports authentication and encryption during data forwarding. Furthermore, by eliminating shared IPv4 addresses, IPv6 enables every device to have its unique identity on the Internet, facilitating the ability to trace cyber attacks and crimes.

Because of the critical role that IPv6 plays in the digital transformation and the great potential of IPv6 Enhanced, the governments of different countries released various industry policies to accelerate the IPv6 deployment. The policies include but are not limited to: imposing IPv6 adoption progress reporting mechanisms, enforcing IPv6 support on newly built networks, setting up compliance goals for operators/government networks and requiring IPv6 support in national broadband/mobile coverage projects and frequency allocation. These policies have proven to be effective and raised not only the IPv6 adoption rate but also the efficiency of the digital society.

Migration to IPv6 concerns the digital competitiveness of a country in the 21st century. It is crucial for the government and private sectors to cooperate to push the next generation of the Internet forward together.

Appendix: IPv6 and IPv6 Enhanced

With the development of new technologies, such as cloud computing, big data, AI, IoT, and 5G, human society is entering an era of intelligent connectivity of everything. The sudden epidemic has accelerated enterprises' digital transformation by one to three years. Applications such as smart city, online education, telemedicine, and home office are constantly changing the life and work style of every person and every family and have profound impact on enterprises' operation and production modes. According to IDC, more than 55 billion terminals and devices will be connected, and 85% of enterprises' infrastructure will be deployed on the cloud by 2025[16]. As the superhighway of the digital world, the Internet needs to accelerate its development to meet new scenario requirements.

I. IP, IPv4, and IPv6

The IP protocol and IP addresses are fundamental underlying elements of Internet technology. A device cannot access the network without an IP address, and data cannot be transmitted between devices without the IP protocol. It has been more than 40 years since the inception of the last generation of IP protocol, IPv4, which is difficult to adapt to the new digital era. Today, countries and economies have proposed digital strategies and IPv6 promotion plans to promote industrial upgrading and inject new impetus into social development. For example, the US launched a digital infrastructure plan to upgrade at least 80% of networks to IPv6-only networks by 2025; the EU initiated a renaissance plan to set up a dedicated IPv6 promotion team; and China plans to build an advanced and secure digital infrastructure based on IPv6 technology by 2025.

IP is designed for computers to communicate with each other on a network. It defines the rules that computers should follow when communicating. It unifies the "frame" data of various network systems and devices into the IP packet format. With IP, the Internet has rapidly developed into the world's largest and most open computer communication network.

The previous generation of IP, IPv4, was released in 1981 and used 32-bit (4-byte) addresses to provide 4.3 billion addresses. But with the explosive growth of computer devices, IPv4 addresses have been exhausted. Therefore, the Internet standards organization Internet Engineering Task Force (IETF) began to plan the next generation of the IPv4 protocol in 1990. In addition to addressing the shortage of IP addresses, the new protocol needs to develop more extensions. In 1994, the IETF formally proposed an IPv6 development plan. In 1998, IPv6 was officially released by the IETF.

An IPv6 address consists of 128 bits. In order of magnitude, the capacity of IPv6 addresses is about 8 x 1028 times that of IPv4 addresses, reaching 2128 addresses. This not only solves the problem of the number of network address resources, but also provides a foundation for the development of IoT.

[16] IDC, Worldwide Global DataSphere IoT Device and Data Forecast 2021-2025, July 2021

II. Benefits of IPv6

IPv6 not only solves the problem of IPv4 address shortage. By enabling more objects to connect to the Internet and providing protocol extensibility, IPv6 can further release the potential of the Internet, bringing significant social and economic values, especially in technology innovations and network security.

• **Technology Innovations**

On November 7, 2016, the Internet Architecture Board (IAB) released a statement on IPv6, announcing that "The IAB expects that the IETF will stop requiring IPv4 compatibility in new or extended protocols. Future IETF protocol work will then optimize for and depend on IPv6."[17] This means that all Internet innovations will be based on IPv6 while IPv4 will gradually stagnate.

Besides the protocol innovations, IPv6 brings an equal chance to players in the market. In the early days of the Internet, IPv4 addresses were free of charge. This brings extreme imbalance in address allocation: the developed countries and large enterprises can easily obtain large address blocks at no cost. In contrast, emerging countries and new companies have very limited resources. For example, the US has 4911 IPv4 addresses per 1000 population, and most of the Arab and African countries have only tens of IPv4 addresses per 1000 population[18]. With the rapid development of the Internet, IPv4 addresses have become a scarce resource and the price increases significantly: the cost of each IPv4 address doubled in 2021 and passed $50[19]. This brings a high barrier for newcomers and hinders competition.

• **Network Security**

To resolve the address shortage, IPv4 employs techniques that allow multiple users to share an IPv4 address. But this brings two critical security issues: (1) it is hard to identify cyber crimes hiding behind shared addresses, and (2) it is challenging to provide data protection because the Internet was split into pieces.

IPv6 is the ultimate solution: by providing unique addresses to every object connected to the Internet, it is much easier for law enforcement agencies to trace cyber crimes and provide data encryption in data transmission.

By releasing the full potential of connectivity and providing better network security, it is estimated that the total industry value enabled by IPv6 and its innovations can reach $10.8 trillion in 2030[20].

From a more technical perspective, IPv6 has the following advantages:

1. Larger address space: IPv6 has sufficient address space and hierarchical structure. IPv6 increases the length of an existing IPv4 address by four times, from 32 bits to 128 bits, to support a large number of network nodes. The maximum number of IP addresses is 2128. IPv6 supports more levels of address hierarchy. The IPv6 designer divides the IPv6 address space according to different prefixes and

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[17] IAB, IAB Statement on IPv6, November 2017.

[18] IP Address by Country 2022, https://worldpopulationreview.com/country-rankings/ip-address-by-country

[19] IPv4 Prior Sales, https://auctions.ipv4.global/prior-sales

[20] Roland Berger, Global IPv6 and IPv6+ Development Measurement and Analysis on Social and Economic Impact, October 2021

adopts a hierarchical address structure to facilitate the fast forwarding of data packets by routers.

2. Enhanced multicast: IPv6 provides enhanced multicast support and flow control, which can promote the development of Internet multimedia applications and provide a good network platform for QoS control. The format of an IPv6 data packet includes an 8-bit class and a 20-bit flow label. The source node that sends the service flow and the router that forwards the service flow can add labels to the data packet and perform different processing in addition to the default processing.

3. More efficient routing: IPv6 provides flexible routing mechanisms and uses smaller routing tables. IPv6 address allocation follows the clustering principle at the beginning. This enables a router to use an entry to represent a subnet in the routing table. This dramatically reduces the length of the routing table in the router and improves the speed of forwarding data packets.

4. Autoconfiguration: IPv6 implements stateless address autoconfiguration. IPv6 defines both stateless and stateful address autoconfiguration mechanisms. Stateful autoconfiguration uses DHCPv6 to dynamically allocate IPv6 addresses to hosts, and stateless autoconfiguration uses NDP for implementation.

5. Improved security: IPv6 supports authentication and encryption at the network layer, providing higher protection. Encryption and authentication options in IPv6 provide confidentiality and integrity of packets. This dramatically enhances network security.

6. Network simplification: IPv6 simplifies headers, reduces processor overhead, and saves network bandwidth. This makes it easier for routers to handle IPv6 headers. IPv6 uses a new header format with options separate from the basic header, which can be inserted between the base header and the upper layer data if needed. This simplifies and speeds up the routing process.

7. Extensibility: IPv6 facilitates flexible expansion. IPv6 allows extensions to protocols as needed by new technologies or applications. IPv6 defines multiple extension headers, which makes IPv6 extremely flexible, provides strong support for multiple applications, and makes it possible to support new applications in the future.

8. Mobility support: IPv6 can better support mobile communication. Mobile communication is closely connected with the Internet at present. Mobile IPv6 design draws on the experience of mobile IPv4 design and makes use of many new features of IPv6, so it provides more and better features than mobile IPv4.

III. IPv6 Enhanced

Besides larger address space, IPv6 brings extensibility to the Internet. Based on IPv6, IPv6 Enhanced improves IP network capabilities in six aspects: ultra-high bandwidth, ubiquitous connectivity, security, automation, deterministic quality, and low latency.

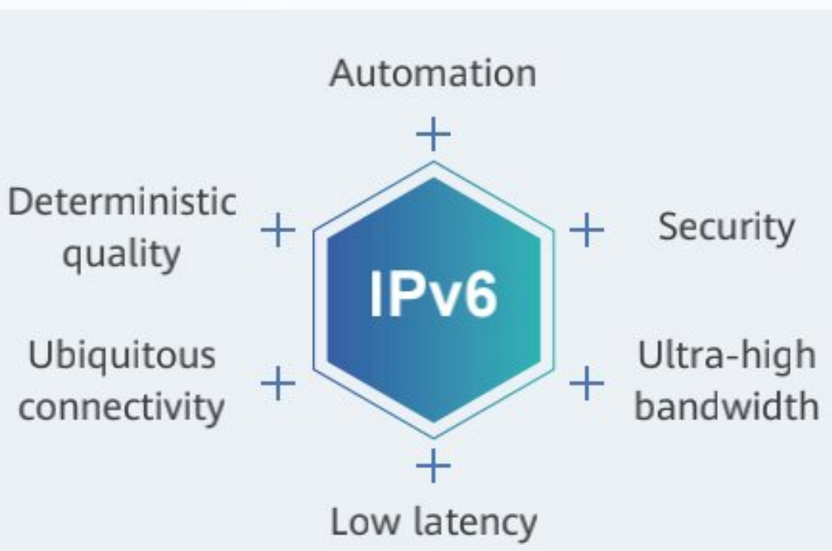

Figure 14 Six key features of IPv6 Enhanced
[Source: ETSI IPE Gap Analysis, August 2021]

Ultra-high bandwidth: continuously releases ultra-high bandwidth to meet the challenges of future service uncertainty.

Ubiquitous connectivity: provides flexible multi-service bearer and service-oriented network capabilities and uses technologies such as SRv6 to implement end-to-end traffic scheduling, protocol simplification, network programmability, and user experience assurance, meeting multi-service convergent experience requirements.

Security: overcomes the defects of IPv4 to effectively defend against broadcast storms, fragment attacks, and scanning attacks. Each device can be assigned a globally unique IP address, implementing traceability of network attacks. In addition, IPv6 Enhanced provides a new platform. New technologies, such as SRv6 and APN6, provide innovative solutions to network security problems.

Automation: enables automatic, self-healing, self-optimization, and autonomous driving networks. With key technologies such as AI, on-demand detection, and knowledge graph, the fault recovery time is shortened from hours to minutes, and anomalies can be intelligently predicted.

Deterministic quality: creates a predictable, deterministic experience for the IP network. The slicing technology is used to provide a secure, reliable, and predictable network environment and achieve jitter from ms to μs/ns. The intelligent lossless network technology is used to achieve zero packet loss in the data center.

Low latency: creates an immersive experience for real-time interaction between people and the virtual world. The end-to-end latency of the MAN reaches 10 ms. In a data center network, the static latency of device-network coordination is reduced from μs to ns, and the single-hop dynamic latency is reduced from 10 to 100 μs to 1 μs, providing efficient data channels.

As shown in Figure 15, the Internet technologies have developed from IPv4 for traditional services like web and voice call to MPLS for multimedia services. Today, the Internet is embracing the IPv6 and IPv6 Enhanced technologies for applications like IoT, industrial automation, satellite communication, autonomous driving, and more.

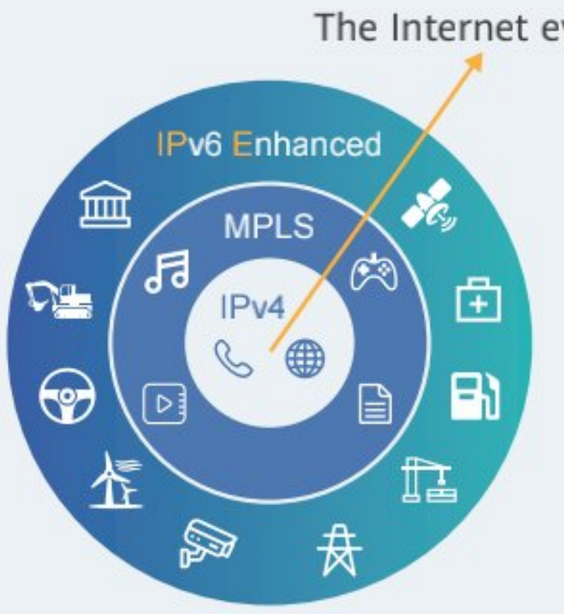

Figure 15 Internet evolution direction: from IPv4 to IPv6 Enhanced