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Periodic Observation Report

Internet Trends as Seen from IIJ Infrastructure—2024

Focused Research

IIJ's LPWA Initiatives —Current State of LoRaWAN® and Outlook for Wi-Fi HaLow™

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Executive Summary

IT news has been brimming with stories about AI in recent years, with the awarding of the 2024 Nobel Prizes in Physics and Chemistry to AI researchers, in particular, being quite a remarkable development.

Nobel Prizes have previously been awarded for IT-related themes, such as semiconductor devices, but the 2024 Physics Prize was awarded for research on artificial neural networks, which lie at the foundations of modern AI. The Chemistry Prize, meanwhile, was awarded for research on AI-based protein structure prediction. Using AI, the researchers were able to predict complex protein structures that were previously difficult to determine. This is an example of innovations made possible by the real-world use of AI.

Although both prizes were AI-related, one recognized achievements in AI development itself, while the other recognized achievements made using AI in a non-IT field. This news serves as a stark reminder of AI's profound impact on our society.

The IIR introduces the wide range of technology that IIJ researches and develops, comprising periodic observation reports that provide an outline of various data IIJ obtains through the daily operation of services, as well as focused research examining specific areas of technology.

Our periodic observation report in Chapter 1 presents our look at Internet trends as seen from IIJ's infrastructure. Every year, we present analyses based on data related to BGP and routes, DNS query analysis, and IPv6 traffic obtained from IIJ's servers and other equipment. Through this periodic analysis, we can identify trends in usage and changes in implementations. The data provide fascinating insights into changes in the Internet that might otherwise go unnoticed.

Our focused research report in Chapter 2 is titled "IIJ's LPWA Initiatives—Current State of LoRaWAN® and Outlook for Wi-Fi HaLow™". LPWA technologies for IoT communications are something IIJ has long been focused on and an area in which it has provided numerous solutions based on LoRaWAN®, an unlicensed-band protocol that is easy to deploy. The 2022 revision of Japan's Radio Act also made it possible to use Wi-Fi HaLow™ in Japan. The report discusses our work with LoRaWAN® to date, describes the features of the new Wi-Fi HaLow™ technology, presents results from our performance evaluations in the field, and discusses future prospects.

Through activities such as these, IIJ continues striving to improve and develop its services on a daily basis while maintaining the stability of the Internet. We will continue to provide a variety of services and solutions that our customers can take full advantage of as infrastructure for their corporate activities.

Junichi Shimagami

Mr. Shimagami is a Director and Senior Managing Executive Officer and the CTO of IIJ. His interest in the Internet led to him joining IIJ in September 1996. After engaging in the design and construction of the A-Bone Asia region network spearheaded by IIJ, as well as IIJ's backbone network, he was put in charge of IIJ network services. Since 2015, he has been responsible for network, cloud, and security technology across the board as CTO. In April 2017, he became chairman of the Telecom Services Association of Japan's MVNO Council, stepping down from that post in May 2023. In June 2021, he also became a vice-chairman of the association.

Internet Trends as Seen from IIJ Infrastructure —2024

Internet services provider IIJ operates some of the largest network and server infrastructure in Japan. Each year, we analyze a year's worth of Internet trends based on information obtained through the operation of this infrastructure and report on it in the IIR. This year, we again analyze changes in trends over the past year from the perspective of BGP routes, DNS query analysis, IPv6, and mobile.

Topic 1

BGP and Routes

We start by looking at IPv4 full-route information advertised by our network to other organizations (Table 1) and the number of unique IPv4 addresses contained in the IPv4 full-route information (Table 3).

The total number of routes reached just under 950,000. While the increase was more than double last year's, it was still the second smallest increase in the past decade (see Figure 1), and that downtrend appears to be ongoing. This year, we observed decreases in all routes with /10–/20 prefixes. This is likely due to the subdivision of address blocks for transfer purposes still being quite prominent. The number of unique IPv4 addresses fell by over 22 million (0.6%), an even larger decline than last year. Combined with last year's decrease, this represents a loss equivalent to about two /8 blocks.

Next, we look at IPv6 full-route information (Table 2) and the number of unique IPv6 /64 blocks in the IPv6 full-route information (Table 3).

Table 1: Number of Routes by Prefix Length for Full IPv4 Routes

Date	/8	/9	/10	/11	/12	/13	/14	/15	/16	/17	/18	/19	/20	/21	/22	/23	/24	total
Sep. 2015	18	13	36	96	261	500	999	1731	12863	7190	12317	25485	35904	38572	60900	52904	301381	551170
Sep. 2016	16	13	36	101	267	515	1050	1767	13106	7782	12917	25229	38459	40066	67270	58965	335884	603443
Sep. 2017	15	13	36	104	284	552	1047	1861	13391	7619	13385	24672	38704	41630	78779	64549	367474	654115
Sep. 2018	14	11	36	99	292	567	1094	1891	13325	7906	13771	25307	39408	45578	88476	72030	400488	710293
Sep. 2019	10	11	37	98	288	573	1142	1914	13243	7999	13730	25531	40128	47248	95983	77581	438926	764442
Sep. 2020	9	11	39	100	286	576	1172	1932	13438	8251	14003	25800	40821	49108	101799	84773	473899	816017
Sep. 2021	16	13	41	101	303	589	1191	2007	13408	8231	13934	25276	41915	50664	106763	91436	497703	853591
Sep. 2022	16	13	39	101	298	592	1208	2064	13502	8292	13909	25051	43972	52203	109071	96909	536520	903760
Sep. 2023	16	14	39	102	298	577	1196	2064	13490	8245	13809	25059	43863	51012	109514	98178	550621	918097
Sep. 2024	16	16	37	93	295	573	1165	2059	13224	8220	13718	24624	43786	51827	111483	99239	579274	949649

Table 2: Number of Routes by Prefix Length for Full IPv6 Routes

Date	/16-/28	/29	/30-/31	/32	/33-/39	/40	/41-/43	/44	/45-/47	/48	total
Sep. 2015	142	771	168	6846	1808	1150	386	990	648	10570	23479
Sep. 2016	153	1294	216	8110	3092	1445	371	1492	1006	14291	31470
Sep. 2017	158	1757	256	9089	3588	2117	580	1999	1983	18347	39874
Sep. 2018	168	2279	328	10897	4828	2940	906	4015	2270	24616	53247
Sep. 2019	192	2671	606	12664	6914	3870	1566	4590	4165	34224	71462
Sep. 2020	205	3164	641	14520	9063	4815	2663	5501	4562	45160	90294
Sep. 2021	223	3628	705	20650	13050	10233	4170	11545	5204	61024	130432
Sep. 2022	298	4247	895	21926	15147	12509	4108	13840	6994	73244	153208
Sep. 2023	316	4357	923	23228	17427	14828	5518	16453	9579	86881	179510
Sep. 2024	322	5360	934	24739	20198	17657	4672	19418	12470	95628	201398

The total number of routes surpassed 200,000. While the increase was smaller than last year, it remained at about the same level as two years ago. Excluding those in the "/41–/43" column, route numbers have been on the rise since we started these periodic observations, but the first ever four-digit increase in /29 routes is noteworthy here. The number of unique /64 blocks also increased by nearly 30%, indicating that the IPv6 rollout and expansion of IPv6 networks continues to progress. As a side note unrelated to BGP, a larger IPv6 address block (/20) has been added for documentation purposes (RFC 9637), as the original block (/32) was deemed inadequate for examples of modern large-scale networks.

Lastly, let's also look at IPv4/IPv6 full-route Origin AS figures (Table 4). In the past year, ARIN and LACNIC were each allocated an additional 1024 32-bit only ASNs.

Eight years have passed since the IANA's 16-bit ASN pool was depleted in 2016. While the nine-year-straight drop in 16-bit Origin ASNs has perhaps been unavoidable, it is also somewhat saddening. The number of 32-bit-only Origin ASNs increased across all categories—IPv4＋IPv6, IPv4 only, and IPv6—though the increases were smaller than two years ago. Notably, IPv4 only still only saw a three-digit rise that was smaller than the decline in 16-bit AS numbers, resulting in a decline in total IPv4 only Origin ASNs for a second year running. Another trend, ongoing since 2021, is that the increase in IPv4＋IPv6 32-bit only ASes has been exceeding the increase in IPv4 only ASes, and as such, we will be watching next year's results with interest.

Table 3: Total Number of Unique IPv4 Addresses in Full IPv4 Routes and Total Number of Unique IPv6 /64 Blocks in Full IPv6 Routes

Date	No. of IPv4 addresses	No. of IPv6 /64 blocks
Sep. 2015	2,791,345,920	31,850,122,325
Sep. 2016	2,824,538,880	26,432,856,889
Sep. 2017	2,852,547,328	64,637,990,711
Sep. 2018	2,855,087,616	258,467,083,995
Sep. 2019	2,834,175,488	343,997,218,383
Sep. 2020	2,850,284,544	439,850,692,844
Sep. 2021	3,036,707,072	461,117,856,035
Sep. 2022	3,068,374,784	532,578,391,219
Sep. 2023	3,055,604,992	700,359,397,494
Sep. 2024	3,033,333,504	896,502,953,452

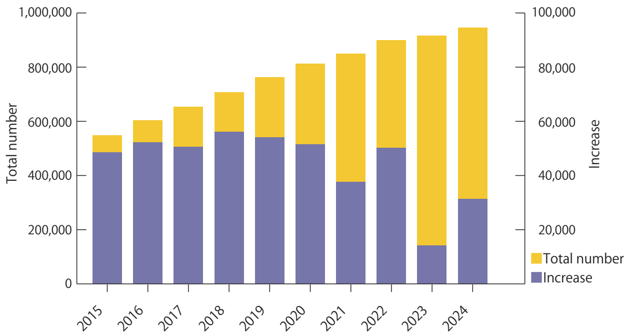

Figure 1: Total Number of Full IPv4 Routes and Annual Increases

Table 4: IPv4/IPv6 Full-Route Origin AS Numbers

ASN	16-bit(1～64495)					32-bit only(131072～4199999999)				
Advertised route	IPv4+IPv6	IPv4 only	IPv6 only	total	(IPv6 -enabled)	IPv4+IPv6	IPv4 only	IPv6 only	total	(IPv6 -enabled)
Sep. 2015	8228	34544	137	42909	(19.5%)	1424	6801	78	8303	(18.1%)
Sep. 2016	9116	33555	158	42829	(21.7%)	2406	9391	146	11943	(21.4%)
Sep. 2017	9603	32731	181	42515	(23.0%)	3214	12379	207	15800	(21.7%)
Sep. 2018	10199	31960	176	42335	(24.5%)	4379	14874	308	19561	(24.0%)
Sep. 2019	10642	31164	206	42012	(25.8%)	5790	17409	432	23631	(26.3%)
Sep. 2020	11107	30374	229	41710	(27.2%)	7653	19668	574	27895	(29.5%)
Sep. 2021	11465	29219	302	40986	(28.7%)	9514	21108	5242	35864	(41.1%)
Sep. 2022	11613	28398	369	40380	(29.7%)	10816	22211	5764	38791	(42.7%)
Sep. 2023	11770	27617	460	39847	(30.7%)	12640	22128	2067	36835	(39.9%)
Sep. 2024	12068	26720	476	39264	(31.9%)	13905	22737	2386	39028	(41.7%)

Topic 2

DNS Query Analysis

IIJ provides a full-service resolver to enable DNS name resolution for its users. Here, we discuss the state of name resolution, and analyze and reflect upon data from servers provided mainly for consumer services, based on a day's worth of full-service resolver observational data obtained on October 9, 2024.

The full-service resolver provides a name resolution function that replies to DNS queries from user devices. Specifically, to resolve a name, it starts by looking at the IP address of an authoritative server for the root zone (the highest level zone), which it queries, and then goes through other authoritative servers to find the records it needs. If the full-service resolver repeatedly queries other servers like this, it can result in increased load and delays, so the information obtained is cached, and when the same query is received again, the response is sent from the cache. Recently, DNS-related functions are implemented on devices that lie on route paths, such as consumer-level routers and firewalls, and these devices are sometimes also involved in relaying DNS queries and applying control policies. Some applications, such as Web browsers, also have their own implementations of name resolver functionality and in some cases resolve names based on a policy that differs from the OS settings.

ISPs notify users of the IP address of full-service resolvers via various protocols, including PPP, DHCP, RA, and PCO, depending on the connection type, and they enable automatic configuration of which nameserver to use for name resolution on user devices. ISPs can notify users of multiple full-service resolvers, and users can specify which nameserver to use by altering settings in their OS, browser, or elsewhere. When more than one nameserver is configured on a device, which one ends up being used depends on the device's implementation or the application, so any given full-service resolver is not aware of how many queries a user is sending in total. When running full-service resolvers, therefore, this means that you need to keep track of query trends and always try to keep some processing power in reserve because changes in behavior or status on the user end can conceivably result in a sudden increase in queries to a given resolver.

Observational data on the full-service resolver provided by IIJ show fluctuations in user query volume throughout the day, with volume hitting a daily trough of about 0.15 queries/sec per source IP address at around 4:25 a.m., and a peak of about 0.32 queries/sec per source IP address at around 9:50 p.m. Overall volume was down 0.02pt vs. the previous year. The breakdown shows that IPv4 accounted for around 59% of queries and IPv6 for around 41%, with IPv6's share having risen by around 1pt from the previous year.

Recent years have seen a tendency for queries to rise briefly at certain round-number times, such as on the hour marks in the morning. As in the past, the number of queries increased around 6 a.m. and 7 a.m. We observed increases in query volume at 14 and 9 seconds before the 6 a.m. and 7 a.m. marks, as was observed in the previous year. This is a pattern we have seen in recent years, with query volume rising sharply at the hour mark and then tapering off gradually, but with the sudden spikes that occur ahead of the hour mark, query volume quickly returns to roughly where it had been. Hence, because a large number of devices are sending queries in almost perfect sync, we surmise that lightweight, quickly completed tasks of some sort are being executed. This year, however, we noticed that these increases at round-number times were smaller than in the past, and we also observed a tendency for query volume over the period from 8 a.m. to 10 p.m. to actually fall at the top of each hour and then gradually increase. We suspect this reflects some implementation changes on client devices that use name resolution.

Turning to protocols, UDP accounted for almost all (98.438%) of the queries. That said, TCP queries have been rising over the last few years, from 0.189% of total in 2021 to 0.812% in 2022, 1.419% in 2023, and 1.561% in 2024. Possibly the main driver of this is an increase in queries using DNS over TLS (DoT). DoT basically uses TCP port 853 to send queries, so an increase in the use of DoT results in an increase in TCP queries.

Looking at the query record types, A records that query the IPv4 address corresponding to the host name, AAAA records that query IPv6 addresses, and HTTPS records used to resolve Web services account for 98% of the total. The trends in A and AAAA queries differ by IP protocol, with more AAAA record queries being seen for IPv6-based queries. Of IPv4- based queries, around 62% are A record queries and 17% AAAA record queries (Figure 2). With IPv6-based queries, meanwhile, A record queries account for around 40% and AAAA record queries around 35% of the total (Figure 3). Compared with the previous year, we observe a 5-percentage-point increase in A record queries for IPv4 and a 2-percentage-point increase for IPv6. Meanwhile, HTTPS record queries, which we started to see in 2020, declined for the first time. They accounted for around 17% of IPv4 and 24% of IPv6 queries, decreases of 3 percentage points for IPv4 and 2 percentage points for IPv6 from the previous year. This may be due to some sort of changes in client implementations. SVCB records, which we started to see in 2022, accounted for 0.30% of IPv4 and 0.57% of IPv6 queries, and while these queries are still only a small fraction of the total, they are progressing steadily. This may be attributable to the use of implementations of Discovery of Designated Resolvers (DDR), a newly proposed protocol designed to allow clients to detect encryption-capable full-service resolvers.

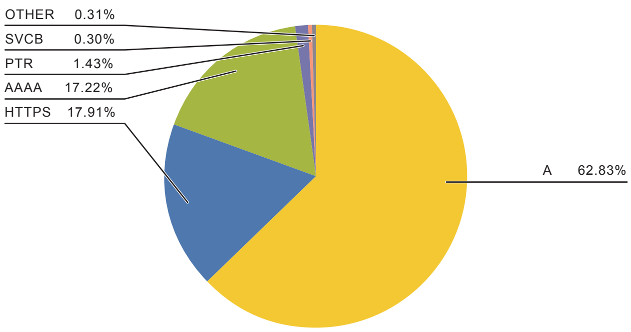

Figure 2: IPv4-based Queries from Clients

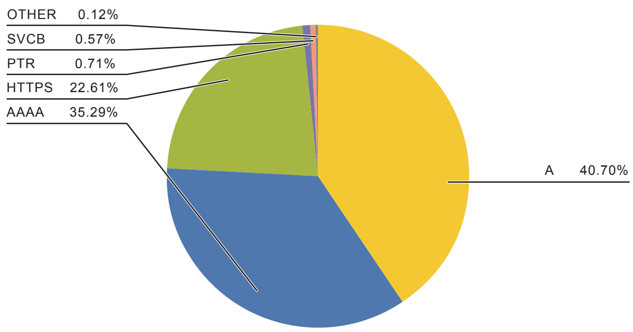

Figure 3: IPv6-based Queries from Clients

Topic 3

IPv6 & Mobile

In this section, we again report on the volume of IPv6 traffic on the IIJ backbone, source ASNs, and the main protocols used. We also go over the state of IPv6 connections on mobile services by device OS.

■ Traffic

Figure 4 shows traffic measured using IIJ backbone routers at core POPs (points of presence—3 in Tokyo, 2 in Osaka, 2 in Nagoya). The data cover the eight months from February 1 to September 30, 2024. Both IPv6 and IPv4 Internet traffic volumes saw a moderate downtrend during that period. Both IPv6 and IPv4 traffic were up when viewed alongside figures for the same day of the previous year (lighter lines on the graph), with IPv6 traffic rising 14.309% and IPv4 traffic rising 14.505% year over year, so almost the same rate of increase for each.

Figure 5 graphs traffic indexed to 100 as of February 1, 2024. As noted, traffic volumes declined mildly from the start of the year, with roughly similar moves for both IPv6 and IPv4.

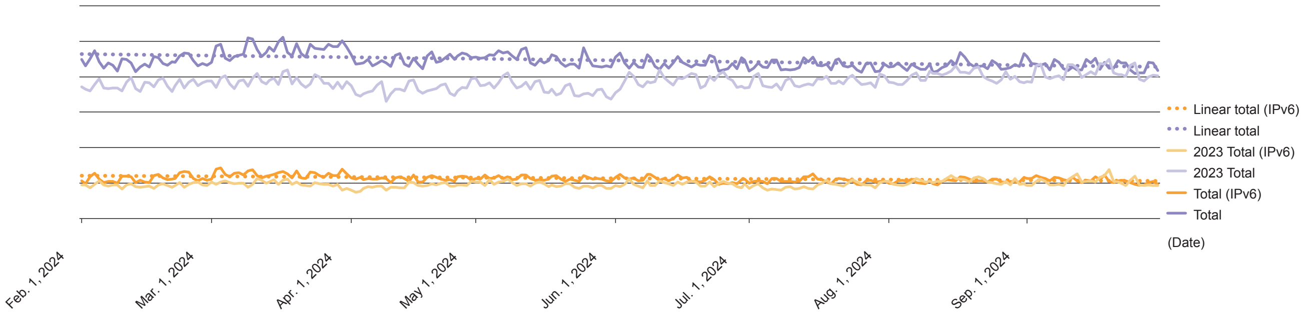

Figure 4: Traffic Measured on Backbone Routes at IIJ's Core POPs

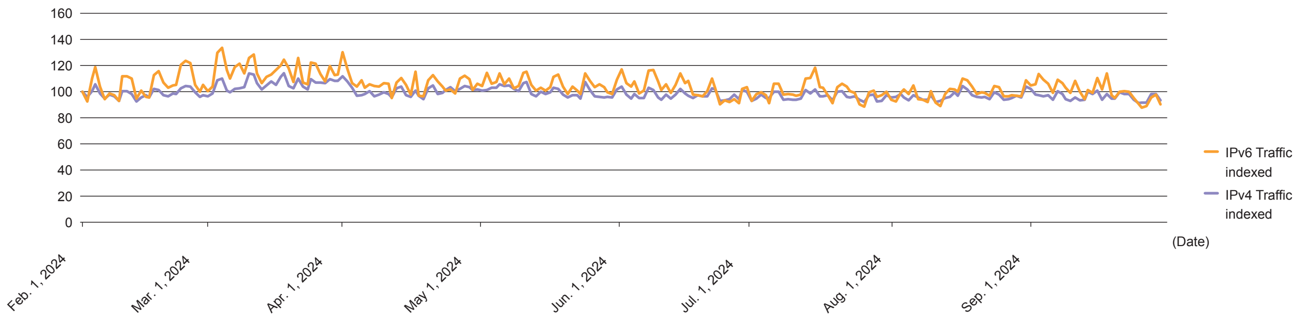

Figure 5: Traffic Indexed to 100 as of February 1

Next, Figure 6 shows IPv6 as a proportion of total traffic. This moves between a minimum of 18.6% and a maximum of 22.5%, averaging 20.16% during the observation period. No major trends are discernible, and the figures are largely in line with those from a year earlier; IPv6 traffic growth perhaps experienced a minor lull.

Table 5 tracks the IPv6 ratio since 2017. It has grown steadily with the exclusion of the Covid period, with this year's ratio being on par with last year's.

■ Traffic Source Organization (BGP AS)

Next, Figures 7 and 8 show the top IPv6 and IPv4 traffic source organizations (BGP Source AS Number) for February 1 – September 30, 2024.

For IPv6, traffic within IIJ accounts for over 60% of the total. Looking at non-IIJ ASes, Company A, a major US search provider, moved up from No. 2 last year to take the top spot with 6% of traffic. At No. 2 with 5% was Company B, a major Japanese content provider, which was in No. 1 last year. While No. 1 and 2 switched places this year, the traffic volumes are neck and neck, so they may well trade places again in the future. At No. 3 is Company C, a US cloud operator, up from No. 8 last year. Having been at No. 16 two years ago, it has increased its IPv6 traffic substantially over the past few years. But at around 2% of total traffic, it is a fair way behind the top two companies, and with volumes for No. 4 and below also being very close, we can expect to see the rankings reshuffled on a yearly basis going forward as well.

Table 5: IPv6 as a Proportion of Total Traffic (Since 2017)

	2017 IIR Vol. 37	2018 IIR Vol.41	2019 IIR Vol.45	2020 IIR Vol.49	2021 IIR Vol.53	2022 IIR Vol.57	2023 IIR Vol.61	2024 IIR Vol.65
IPv6 ratio	4%	6%	10%	10%	11.2%	15.1%	20.1%	20.16%

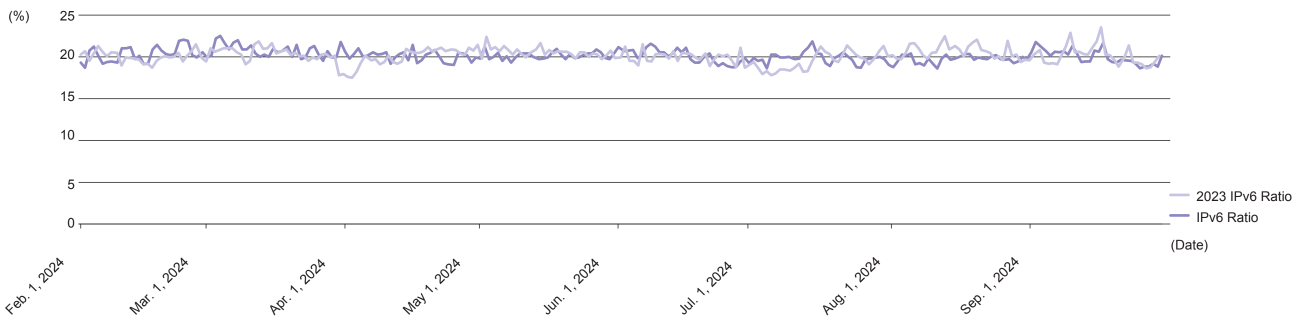

Figure 6: IPv6 as a Proportion of Total Traffic

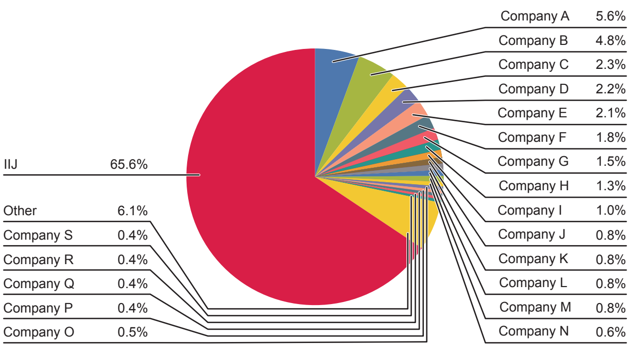

Figure 7: IPv6 Traffic by Source Organization (BGP AS Number)

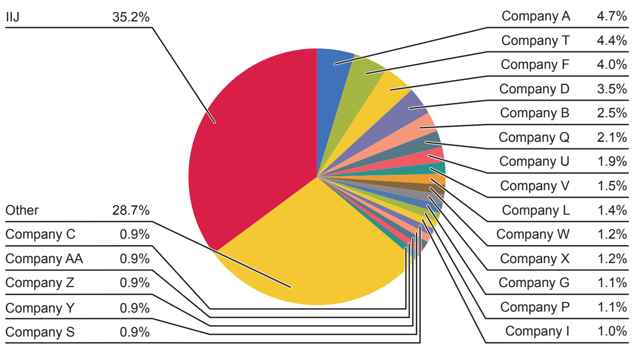

Figure 8: IPv4 Traffic by Source Organization (BGP AS Number)

Protocols Used

Figure 9 plots IPv6 traffic according to protocol number (Next Header) and source port number, and Figure 10 plots IPv4 traffic according to protocol number and source port number (for the week of Monday, September 30 – Sunday, October 6, 2024).

In the IPv6 space, similar to last year, the top four protocols—HTTPS, QUIC, NAT Traversal, and ESP in that order—accounted for 91% of usage. HTTPS accounted for 74% and QUIC 9%, so HTTP-related protocols accounted for over 80%, while VPN-related protocols NAT-T and ESP accounted for 8.4%.

While traffic patterns remain largely similar to last year, there appears to be an overall increase in daytime traffic. IPv6 traffic, in particular, increased during the day on Saturdays and Sundays, suggesting that individual user traffic may constitute a significant portion of the total. In the IPv4 space, UDP443 has now surpassed TCP80, indicating a decline in unencrypted HTTP traffic. Yet while IPv6 HTTP traffic is almost imperceptible on the graph, IPv4 HTTP traffic has only just now been overtaken by QUIC, suggesting that many old servers are still in operation.

IPv6 on Mobile Devices

Following on from our installment of this report in IIR Vol. 57 two years ago (https://www.iij.ad.jp/en/dev/iir/057.html) and in last year's IIR Vol. 61 (https://www.iij.ad.jp/en/dev/iir/061.html), we again look at IPv6-enabled rates on personal IIJmio Mobile Service connections. We also look at differences by device OS and at whether there are differences depending on device manufacturer.

The IPv6-enabled rate for devices connected to the IIJmio Mobile Service was 60.6%. This represents an annual increase of around 2 percentage points, from 58.73% last year and 56.3% the year before that. By device OS, 87.010% of Apple iOS devices had IPv6 enabled, while the figure was 30.235% for Android devices. The Android

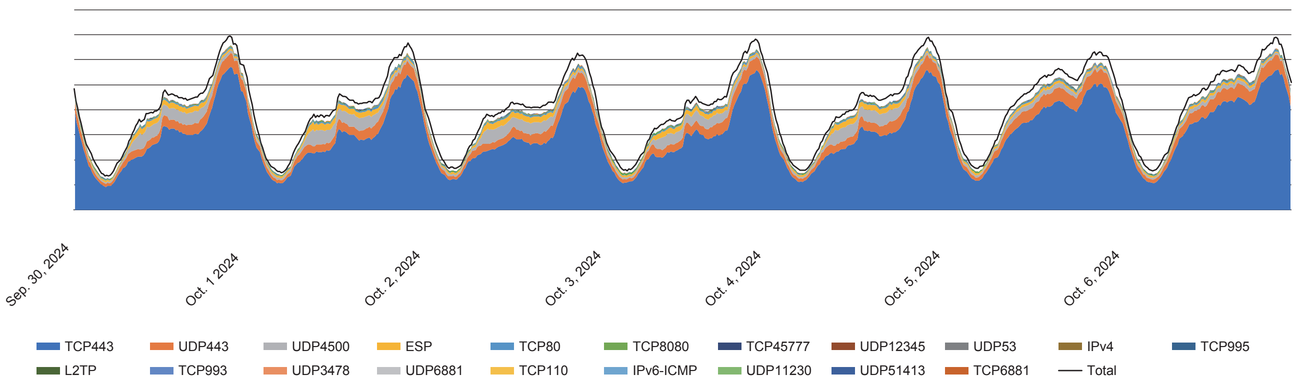

Figure 9: Breakdown of IPv6 Traffic by Source Port Number

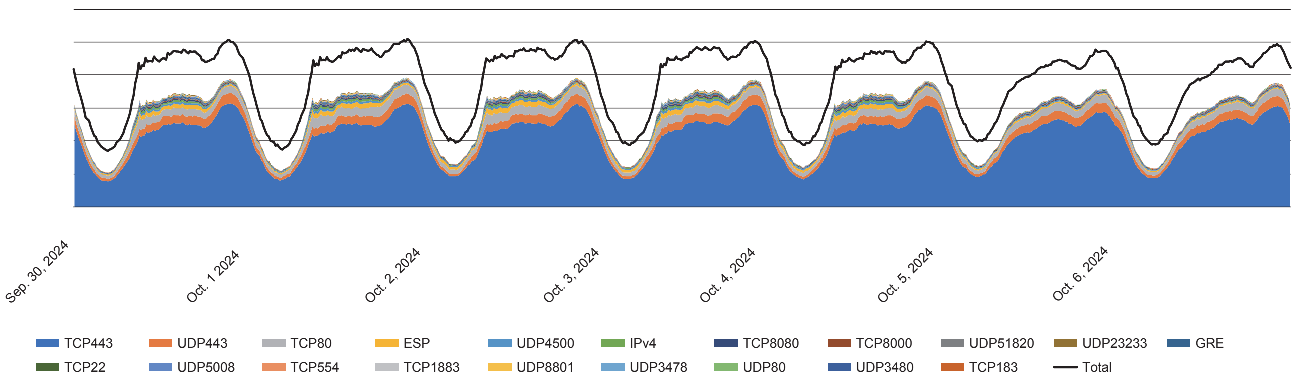

Figure 10: Breakdown of IPv4 Traffic by Source Port Number

IPv6-enabled rate was up a substantial 5 percentage points from last year, which contributed to the overall rise in the IPv6-enabled rate.

Next, we look at IPv6-enabled rates by manufacturer for the top 20 devices connected to the IIJmio Mobile Service. Figure 11 graphs the top 20 spots. Apple products are widely used in Japan and thus account for over 53%. Apple's IPv6-enabled rate was high at around 87%, a slight increase from last year. The manufacturer with the highest IPv6-enabled rate was Motorola Mobility at 91.7%, followed by Apple at 87% and Google in third place at 86%.

Here, we highlight FCNT, which ranks 14th by number of IIJmio-connected devices. FCNT released new products such as the arrows We2 this year, and arrows We2 alone had an IPv6-enabled rate of 97.6%. This is likely because its default APN profile is set to PDP-Type IPv4v6, enabling IPv6 connectivity. Yet the F-51B, also from FCNT and designed for MNOs, had an IPv6-enabled rate of just 7.4%, and so the overall IPv6-enabled rate for FCNT devices was only 31.2%.

Summary

We have examined traffic on the IIJ Internet backbone core, source ASNs, and main protocols used. Traffic volume declined slightly during the observation period but was up by over 14% vs. last year. IPv6 usage remained largely flat at 20.16%, essentially treading water this year. Looking at IPv6 traffic by source AS, No. 1 and 2 traded places but were still neck and neck, while No. 3 and below also remained closely matched at around 1–2% of total traffic each.

As has been the case so far, IPv6 is more widely used on relatively new servers, with encrypted HTTP protocols accounting for over 80% of traffic and unencrypted HTTP only a sliver. As for IPv4 traffic, however, unencrypted HTTP is still fairly prevalent.

In the mobile space, Android OS devices saw a 5-percentage-point increase in the IPv6-enabled rate, while the overall increase was just under 2 percentage points. We are also seeing new devices released with IPv6 enabled via the PDP-Type setting in their APN configuration. It would be good to see the number of devices with IPv6 enabled by default continue to rise ahead.

We will continue to watch the IPv6 situation from a range of angles and provide updates as new developments come to light.

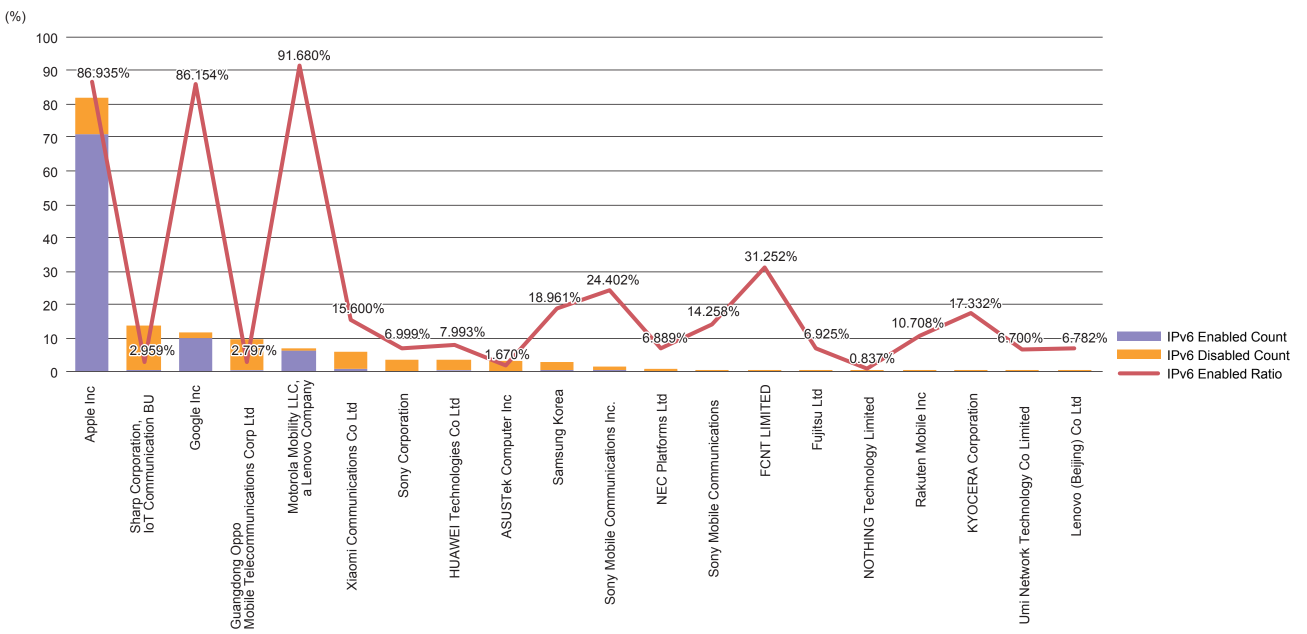

Figure 11: IPv6 Support by UE Manufacturer (Top 20)

Topic 4

Internet Backbone Trends

In this section, we cover recent Internet backbone trends from the perspective of IIJ's internet backbone infrastructure interconnectivity and routing.

Interconnection Interface Trends and Requirements

To facilitate interconnectivity on the Internet, service operators need to adopt standardized interfaces. Currently, IIJ primarily uses 400G-FR4, 100G-LR4, and 10G-LR for interconnection interfaces. There has been a trend in recent years of reviewing interconnectivity between operators that is based on 10G interfaces. The main objectives for establishing interconnectivity are to reduce traffic exchange costs and to improve communication quality through increased efficiency. From a cost reduction perspective, using 10G interfaces for interconnectivity is perhaps becoming less cost-effective. The main reasons for this are improving cost per 100G port on interconnection routers used at the AS boundaries between operators and the relative difficulty of managing 10G interfaces. At IIJ, we also request/select interconnection routers offering both high bandwidth and high port density. Using 10G interfaces on such routers results in lower port utilization efficiency. This is because, in terms of port configuration, the use of 100G and 10G ports is often mutually exclusive. Physical interface ports are a scarce resource, and when they are used for 10G instead of 100G connections, bandwidth is lower and thus less traffic can be carried, which results in reduced port utilization efficiency. And trying to select routers with interface support covering 10G all the way through to 400G for interconnection applications limits the range of options that are satisfactory in terms of functionality and price compared with routers that support only 100G/400G.

At IIJ, therefore, we ask interconnection partners to upgrade from 10G to 100G interfaces when 10G interfaces are not absolutely necessary, when multiple 10G lines are already bundled through link aggregation, or when bandwidth might be increased beyond 10G in the future. Similarly, IIJ also receives requests from its interconnection partners to either switch from individual 10G connections to IXP-based connections or to upgrade ports to 100G interfaces.

By comparing Figures 12 and 13, we can see how the percentage breakdown of interconnection interfaces on IIJ's internet backbone has changed over the past year. Over this period, the use of 10G interfaces declined as a percentage total while the use of 100G interfaces increased.

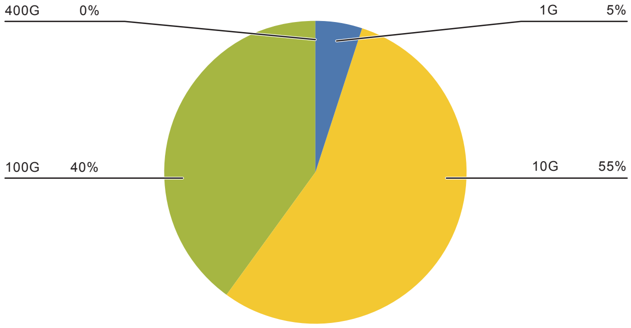

Figure 12:Breakdown of Interconnection Interfaces on IIJ's Internet Backbone (October 2023)

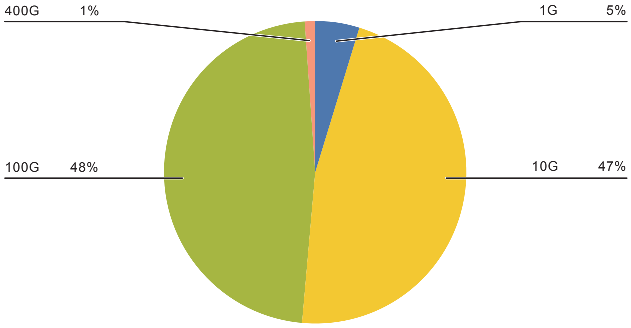

Figure 13:Breakdown of Interconnection Interfaces on IIJ's Internet Backbone (October 2024)

While 400G interfaces are being considered as an interconnection interface requirement for connections of 100G and above, adoption still appears limited. While IXP operators seem to be making relatively decent progress in supporting 400G, it likely remains more of a future consideration for interconnections between service providers, except those with large traffic volumes.

Another new trend we are seeing is efforts to promote the use of 100G-LR interfaces within the 100G category. Compared with the currently widespread 100G-LR4, the 100G-LR specification increases the transmission capacity per wavelength from 25G to 100G. Advantages of this include lower cost per unit due to the number of lasers per unit being reduced from four to one and reduced failure rates due to there being fewer components. The use of 100G-LR on interconnection interfaces has begun primarily at IXPs in Europe and North America, and it is expected to be taken up on interconnections between service providers ahead.

Current State of RPKI

Here, we provide an update on the state of RPKI. We look at current data on ROAs, signed objects that verify which IP addresses are owned by an organization. ROA registration data from the NIST RPKI Monitor (Figures 14 and 15), available online*1, show that among all IPv4 routes on the Internet, 53.38% are Valid (ROAs registered, routing verified), 46.15% are Not-Found (ROA not yet registered), and 0.47% are Invalid (discrepancies in ROA registration, treated as unauthorized routes). In the IPv6 space, 55.30% of routes are Valid, 40.24% are

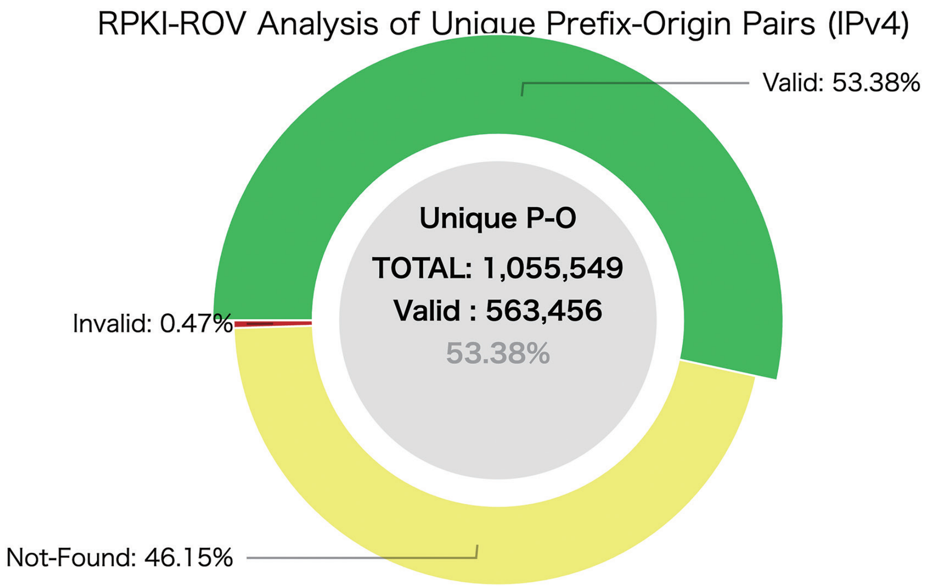

Figure 14:ROA Registration Data from the RPKI Monitor (IPv4) as of 18:00, October 15, 2024

*1 See NIST RPKI Monitor (https://rpki-monitor.antd.nist.gov/).

Not-Found, and 4.46% are Invalid. With the ROA registration rate for IPv4 having surpassed 50%, legitimacy has been established for more than half of all routes, which suggests substantial progress has been made. Meanwhile, over 4% of IPv6 routes are Invalid. Registering an ROA is simple: you register the Origin AS that will generate and advertise the route, prefix and subnet information, and the maximum route length (subnet size). Any of the parameters being inconsistent with the ROA will result in the route being marked as Invalid, so such discrepancies need to be corrected unless they are for testing purposes.

Currently, we have enabled RPKI-ROV for AS boundary BGP peers and perform ROA-based origin validation on routes that peers advertise to IIJ. Since Invalid routes cannot be distinguished from route hijacking attempts, our policy is basically to reject them.

Now let's look at the ROA registration status of Internet routes that IIJ generates and advertises (Table 6). IIJ participates in the Internet using Global AS number AS2497, and thus the Origin AS for routes IIJ advertises is AS2497. As of October 16, 2024, 44.0% of routes originating from AS2497 are Valid.

	No. of routes originated by AS2497	No. of routes IIJ transits and advertises to the Internet
Valid	80	4200
Unknown	102	3757
Invalid	0	3
Valid rate	44.0%	52.8%

Table 6: ROA Registration Data from the RPKI Monitor (IPv6) as of 18:00, October 15, 2024

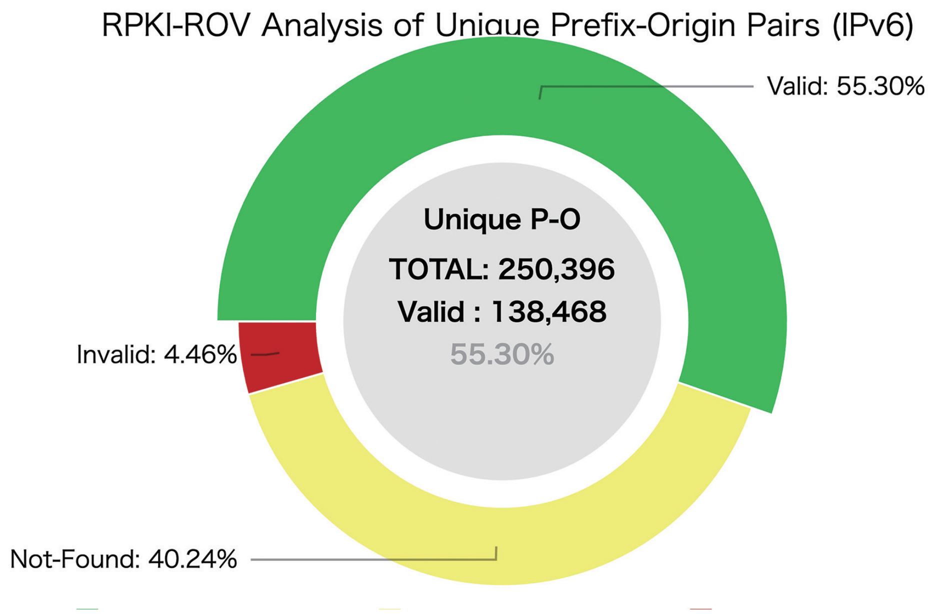

Figure 15: ROA Registration Data from the RPKI Monitor (IPv6) as of 18:00, October 15, 2024

This means ROAs are registered, confirming legitimacy, for just under half. Yet, ROV returns Not-Found for over 50% of the routes, indicating no ROA has been registered. One significant obstacle to ROA registration is the need for organizations that own IP addresses to register and issue their own ROAs. While IIJ has registered ROAs for nearly all IP addresses it owns (excluding special cases), there is evidently a lack of progress among users who bring their own IP addresses to IIJ. Since IIJ cannot currently register ROAs on behalf of users, they must complete the registration themselves. IIJ offers support in this regard, so we encourage you to take advantage of this to help us increase the ROA registration rate for AS2497.

When including routes for which IIJ provides transit service to customers, 52.8% of all routes are Valid according to ROV. This indicates decent progress in terms of ROA issuance within Japan as well.

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IIJ's LPWA Initiatives
—Current State of LoRaWAN® and Outlook for Wi-Fi HaLow™

2.1 Introduction

The term IoT (Internet of Things) has been around for quite some time now, and IoT is undoubtedly one of the key tools we have for addressing contemporary social challenges, including those highlighted by the UN's Sustainable Development Goals. Examples include the use of IoT in smart agriculture and other such efforts to improve productivity amid a declining labor population, and to achieve high energy efficiency in smart cities. As IoT itself is an abstract concept, there are various approaches to deploying it, with one well-known example being the use of sensors and other devices equipped with LPWA (Low Power Wide Area) wireless technology to collect and utilize data.

LPWA, as the name suggests, refers to wireless technologies that provide wide-area coverage with low power consumption. It limits power consumption by reducing communication speed and frequency, and while differences may arise depending on communication methods and operation practices, the sensors and other such devices can run for years even on small batteries. Strategies used to minimize signal degradation over long-distance transmissions include narrowing the wireless frequency band and the use of spread spectrum techniques. LPWA can be broadly categorized into licensed-band LPWA (provided by communication carriers) and unlicensed-band LPWA (freely available to anyone using wireless devices, such Wi-Fi® devices, approved by the Ministry of Internal Affairs and Communications[*1]). Within these categories, there are several communication methods, each with their own characteristics as shown in Table 1.

	Communication method	User-installed base stations	Approx. range	Approx. speed	Main characteristics
Licensed band (uses mobile phone frequency bands)	LTE-M	Not needed	Within base station area	Up to several 100kbps[*3*4]	A major protocol in the licensed-band category as it can use existing LTE infrastructure. Higher power consumption vs. other methods, but supports handover, making it suitable for mobile applications.
	NB-IoT	Not needed	Within base station area	Up to 100kbps[*3]	Reduces power consumption by reducing bandwidth and transmission speed vs. LTE-M. Does not support handover. Limited base station deployment in Japan due to lack of LTE compatibility; only offered by SoftBank at present[*5].
Unlicensed band (mainly 920MHz-band specified low-power radio)[*2]	ELTRES™	Not needed	Up to 100km[*6]	Several 10bps[*7]	A proprietary communications standard developed by Sony that supports ultra-long-distance transmission and mobile applications. Uses GNSS time synchronization and is thus designed for outdoor use. Service including base stations provided by Sony Network Communications.
	LoRaWAN®	Required	Up to 10km	Up to ~5kbps	Uses the LoRa® protocol developed by US-based Semtech. Use of chirp spread spectrum modulation makes it robust to noise. The LoRaWAN® specification defines protocols for the physical layer up (excl. application layer), and because the specification is open, it is used on many devices around the globe among unlicensed LPWA systems[*8].
	Sigfox	Not needed	95% population coverage[*9]	100bps[*10]	Provided by France-based UnaBiz SAS. Uses ultra narrow band (100Hz) technology to minimize radio interference. Speed is limited, but it is cost-effective. In Japan, service including base stations is provided by Kyocera Communication Systems.
	Wi-Fi HaLow™	Required	Up to 2km[*11]	Up to several Mbps[*11]	Standardized as IEEE 802.11ah, based on existing Wi-Fi® (IEEE 802.11 series) technology. HaLow is the designation for devices certified by the Wi-Fi Alliance®. Highest speed among unlicensed LPWA systems; also suitable for streaming communications.
	ZETA	Required	Up to 10km[*12]	Up to 50kbps[*12]	Developed by China-based ZifiSense. Uses ultra narrow band (2kHz) communication. Supports multi-channel communication and mesh networking.

Table 1: LPWA Types and Main Characteristics

*1 In Japan, this generally refers to devices bearing the Technical Conformity Mark (Giteki Mark).

*2 Most unlicensed-band protocols used in the LPWA space use 920MHz-band specified low-power radio. The 920MHz band is considered suitable for IoT applications because, compared with other specified low-power radio bands, it performs well in the presence of obstacles (readily diffracts around them) and offers both communication speed and transmission range. "Keiso Mamechishiki: 920MHz Band Musen Tsushin ni Tsuite" [Instrumentation Tidbits: About 920MHz-band Wireless Communications], MG Trend (https://www.mgco.jp/magazine/plan/mame/b_network/1510/, in Japanese). "Sub-GHz musen towa" [What is Sub-GHz Wireless], TechWeb (https://techweb.rohm.co.jp/product/wireless/sub-ghz/43/, in Japanese).

At IIJ, we are focusing on LoRaWAN®, which is becoming the global de facto standard in the unlicensed-band arena, and we offer a range of services that use LoRaWAN®. We are also conducting technical research and the like with a focus on Wi-Fi HaLow™, which is based on existing Wi-Fi® technology and thus has the benefit of user familiarity. In this article, we discuss IIJ's current LoRaWAN® initiatives, the technical characteristics of Wi-Fi HaLow™, with reference to our own experimental results, and future prospects.

2.2 IIJ's LoRaWAN® Initiatives

LoRaWAN® has the largest global market share among unlicensed-band LPWA technologies, with the number of connections projected to reach around 500 million in 2024 and 750 million by 2026[*8]. While overseas markets have been quicker to adopt the technology in areas such as service metering (e.g., water supply) and smart buildings, adoption is also expanding in Japan in the areas discussed below, with IIJ taking the lead.

■ Agricultural IoT

In 2017, IIJ was commissioned by Japan's Ministry of Agriculture, Forestry and Fisheries to carry out the management entities strengthening project within the ministry's Innovative Technology Development and Urgent Deployment Program. Under the project, we conducted R&D (including demonstration tests) on the use of IoT technologies to improve water management efficiency in paddy fields[*13*14].

We adopted LoRaWAN®, which has the following advantages as an LPWA wireless standard for agricultural IoT[*15].

- End devices (sensors etc.) can run for years even on small batteries if measurement rate is low.
- Base stations can be placed according to usage patterns, so there are fewer service provider constraints (can be used outside other standards' service areas).
- Communication between end devices and base stations is cost-free, so there are cost advantages to be had from using only a few base stations to cover many devices.
- Supports downlink communication, enabling simple device control.
- As an open standard, it makes it easy to create use cases by combining devices from multiple vendors.

Our R&D efforts demonstrated that by using the paddy field sensors and automatic water valves we developed, it is possible to reduce the total time spent on paddy field water management (including opening/closing water valves and travel time) by around 70%[*14].

*3 "Dai yon-ji sangyo kakumei ni okeru sangyo kozo bunseki to IoT/AI-to no shinten ni kakawaru genjo oyobi kadai ni kansuru chosa kenkyu hokokusho" [Research Report on Industrial Structure Analysis and Current Status of and Challenges Related to the Advance of IoT/AI in the Fourth Industrial Revolution] National Diet Library Search (https://ndlsearch.ndl.go.jp/books/R100000039-I11370285, in Japanese).

*4 "Hodo-happyo-shiryo '(oshirase) IoT service-muke tsushin hoshiki 'LTE-M' wo teikyo kaishi'" [Press Release (Notice) Launch of 'LTE-M' Communication System for IoT Services], NTT Docomo (https://www.docomo.ne.jp/info/news_release/2018/09/26_00.html, in Japanese).

*5 "Kokunai yuiitsu, Softbank no NB-IoT senryaku" [Softbank's NB-IoT Strategy: Unique in Japan", Business Network (https://businessnetwork.jp/article/7505/, in Japanese).

*6 "Gaiyo" [Overview], SONY ELTRES™ (https://eltres-iot.jp/overview/, in Japanese).

*7 "ELTRES™ IoT Network Service", NURO Biz (https://biz.nuro.jp/service/eltres/detail/, in Japanese). "[QA shu] Tokucho, tsushin sokudo, area, shiyo, kakaku nado" [Q&A Collection: Features, Communication Speed, Coverage, Specifications, Pricing, etc.", Sony (https://iot.sonynetwork.co.jp/column/column010/, in Japanese). Transmits a maximum 128-bit payload 4 times every 5 seconds.

*8 "Reiwa 6-nen-ban joho-tsushin-hakusho data-shu" [Information and Communications White Paper, 2024 Data Collection], Ministry of Internal Affairs and Communications (https://www.soumu.go.jp/johotsusintokei/whitepaper/ja/r06/html/datashu.html#f00239, in Japanese).

*9 "Service Area", IoT Network Sigfox, KCCS (https://en.kccs-iot.jp/area/).

*10 "LPWA towa" [What is LPWA], IoT Network Sigfox, KCCS (https://www.kccs.co.jp/sigfox/service/lpwa/, in Japanese).

*11 "802.11ah ni tsuite" [About 802.11ah], 802.11ah Promotion Council (https://www.11ahpc.org/11ah/index.html, in Japanese).

*12 "ZETA LPWA Network" Zeta Alliance (https://japan.zeta-alliance.org/zeta.php, in Japanese).

*13 "Suiden mizu kanri ICT katsuyou consortium wo setsuritsu shi, Norin-suisan-sho no kobo jigyo 'kakushinteki gijutsu kaihatsu / kinkyu tenkai jigyo' wo jutaku" [IIJ Establishes Paddy Field Water Management ICT Utilization Consortium and Wins Commission for Ministry of Agriculture, Forestry and Fisheries' Innovative Technology Development and Urgent Deployment Program" IIJ (https://www.iij.ad.jp/news/pressrelease/2017/0619.html, in Japanese).

*14 "Suiden-saku" [Rice Farming], NARO, Bio-oriented Technology Research Advancement Institution (https://www.naro.go.jp/laboratory/brain/h27kakushin/keiei/result/suidensaku.html, in Japanese).

*15 "Focused Research (1): IIJ's Efforts to Promote LoRaWAN® in Agricultural IoT", Internet Infrastructure Review (IIR) Vol. 47, IIJ (https://www.iij.ad.jp/en/dev/iir/047.html).

Currently, we are using the insight gained to provide services such as the IIJ Water Management System Platform for Paddy Fields and MITSUHA paddy field sensors. Beyond paddy field water management, we are also engaged in a range of initiatives to address regional community challenges centered on agriculture, such as those below*16. We currently support around 70 basic municipalities in Japan, with plans to expand this further.

- Monitoring of soil moisture to improve fruit and other crop yields
- Automatic tractor steering in areas without cellular coverage
- Monitoring of rivers etc. for disaster prevention
- Detection of trap sensor activation for wildlife damage control

■ Temperature Control for Cold Storage Items

With the 2018 revision of Japan's Food Sanitation Act, which systematized food hygiene management in line with HACCP principles, the practice of temperature control is spreading to a variety of industries. Drawing on the expertise gained from agricultural IoT, IIJ has been offering a LoRaWAN®-based solution for food temperature control since 2020*17. This solution helps reduce the workload associated with temperature control in refrigerators and freezers in fresh food markets, seafood processing plants, and the like as well as in food preparation and processing workplaces such as restaurant central kitchens.

Beyond hygiene management, there is also a growing trend of late toward the monitoring of storage temperatures in an effort to properly manage the disposal cycle in order to reduce food waste.

The need for temperature control is also expanding beyond food to the following applications.

- Pharmaceutical quality control in the medical industry
- Cold-storage item quality control in logistics warehouses

Something common to all these use cases is that it is not always possible to run power to the location where sensors are to be installed inside refrigerators, pharmaceutical storage systems, and logistics warehouses. It is also crucial that communications between the inside and outside of such storage systems be maintained even when the doors are closed.

With LoRaWAN®, temperature control sensors can run for years even on small batteries, making it easy to install them in places where power is unavailable. As it is regarded within Japan as being for private LPWA systems, LoRaWAN® makes it easy to create wireless environments tailored to the use case, even inside of buildings or storage units. And because it is designed for long-distance communication, connectivity can be maintained even when the doors, which act as obstructions, are closed, provided the distance is short. With these features being utilized, we can expect to see an increasing number of LoRaWAN® temperature control applications being deployed in the IoT/LPWA market.

■ Monitoring at Construction and Civil Engineering Sites

Japan's construction industry faces a number of challenges—chronic labor shortages, workplace accidents, and the stagnation of efforts to increase efficiency. In addressing these issues, sensors can be useful in understanding the current state of affairs and taking action accordingly. Yet the environment at construction sites changes daily as work progresses, and this means collecting wireless sensor data is no easy task. LoRaWAN® is suitable even in such environments. Indeed, proof-of-concept (PoC) testing we performed in collaboration with a construction company showed it was possible to reliably collect sensor data throughout the construction period at a roughly 30,000m^2 logistics facility*18.

The PoC work also demonstrated that remote monitoring of the following items led to improved efficiency during the construction period.

*16 "Smart nogyo setsumeikai" [Smart Agriculture Briefing', IIJ (https://www.iij.ad.jp/news/pressrelease/2024/pdf/handout_20240917.pdf, in Japanese).

*17 "IIJ LoRaWAN(R) Solution for HACCP Temperature Management", IIJ (https://www.iij.ad.jp/en/biz/haccp/).

*18 "Zenitaka-gumi to kensetsu genba ni okeru LoRaWAN® wo katsuyo shita genba kankyo data no shushu/bunseki shisutemu no jissho jikken wo jisshi" [Conducting demonstration testing with Zenitaka Corporation on a system for collecting and analyzing data on construction site environments using LoRaWAN®], IIJ (https://www.iij.ad.jp/news/pressrelease/2024/1106.html, in Japanese).

- Heat stress index (WBGT)
- Worker safety management via monitoring of security guard skin temperature and heart rate
- Images showing construction progress
- Construction machinery operation status
- Construction machinery location (work zone)
- Location of construction machinery keys

Recently, we have also been receiving requests about monitoring factors such as lights being left on, windows left unclosed, and amount of rainfall, and we can thus expect LoRaWAN® to be widely used in construction site monitoring applications ahead.

Beyond construction, there is also demand for worker safety management on civil engineering sites where LTE connectivity is unavailable, such as tunnels. Such locations are another field in which LoRaWAN® can help thanks to its long-range communication capabilities and battery-powered operation.

■ Building LoRaWAN® communication Environments

As mentioned earlier, LoRaWAN® is regarded within Japan as being for private LPWA systems, so base stations must be installed to receive data from the end devices. Because LoRaWAN® radio uses spread spectrum technology, communication can be transmitted even when the received signal strength is below the noise level (even when SNR is negative, as discussed later)[*19]. This is a major advantage of LoRaWAN®, in many cases making it possible to set up a communications system fairly effortlessly simply by placing devices wherever users want them. That said, when there is a need for signals to propagate over several kilometers outdoors, for instance, or when end devices need to be located in complex building interiors, we may conduct some preliminary environmental assessment before considering base station placement. Below, we offer a technical perspective on the factors to consider when assessing the communications environment in such situations, based on our experience working with LoRaWAN®.

The main points to check when assessing communication conditions are as follows.

- Received Signal Strength Indicator (RSSI)
- Signal-to-Noise Ratio (SNR)
- Interference from other wireless systems in the 920MHz band

In the case of RSSI, differences across products due to the performance of device antennas, signal processing circuitry, and the like make it difficult to set universal standards for this metric, but based on our operational experience, as long as we can keep it at -100dBm or above, even when packet losses occur, the packets can generally be recovered via end device automatic retransmission functionality. For extra assurance, it is ideal to have a margin for error and ensure around -80dBm. Incidentally, and this is not limited to LoRaWAN®, in open outdoor environments (no buildings or other obstacles), RSSI can be roughly estimated using a two-ray model. As Figure 1 shows, the two-ray model takes into account both free space path loss and the interference between the direct ray and the ground-reflected ray[*20]. While the model itself

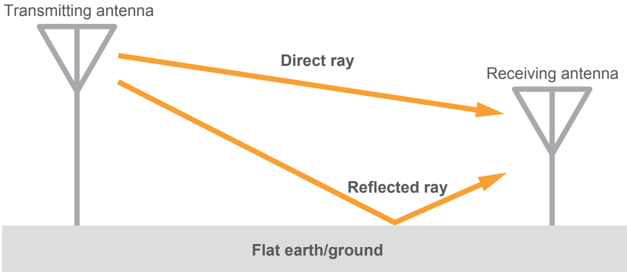


Figure 1: Conceptual Diagram of Two-ray Model

*19 "RSSI and SNR," The Things Network (https://www.thethingsnetwork.org/docs/lorawan/rssi-and-snr/).

*20 "Jun-ichi Takada, "Fundamentals of Radiowave Propagation", Journal of the Institute of Image Information and Television Engineers, vol. 70, no. 1, pp. 142–148 (2016) (https://www.jstage.jst.go.jp/article/itej/70/1/70_142/_article/-char/en).

is too simple to fully simulate real-world environments, it is suitable for getting a rough idea of signal behavior as it only uses a few parameters (radio frequency, transmission power, antenna height and gain, and distance) and is easy to calculate. Figure 2 shows the computed results for a two-ray model. The lower the antenna height, the more susceptible it is to flat earth effects, so if you want to transmit LoRaWAN® signals over 1km, for example, an antenna height of 2m or more should enable good signal transmission. Once antenna height reaches around 8m, it exceeds the (first) Fresnel zone radius, reducing the impact of flat earth effects, such that signal attenuation can be expressed almost entirely by free space path loss alone. The Fresnel zone, incidentally, is the area that determines line-of-sight between antennas, and any obstacles within this zone can significantly affect propagation characteristics through reflection, diffraction, and the like.

Turning to SNR, as shown in Figure 2, LoRaWAN® specifies threshold values for each data rate (DR)[*19][*21]. DR2 is often used for very small amounts of data such as sensor data[*22], so theoretically even an SNR of -15dB would be acceptable[*23], but as with RSSI, it is ideal to maintain a margin for error (5–10dB). From experience, when the RSSI is good, SNR is also usually not a problem, but because SNR values can vary depending on the environment, examining both RSSI and SNR together makes quantitative assessments easier.

Since 920MHz-band specified low-power radio is used not only for the LPWA standards in Table 1 but also for other systems such as RFID, the LoRaWAN® communication specifications state that, before transmitting, devices must check that the frequency channel they are about to transmit on is not being used by other systems in

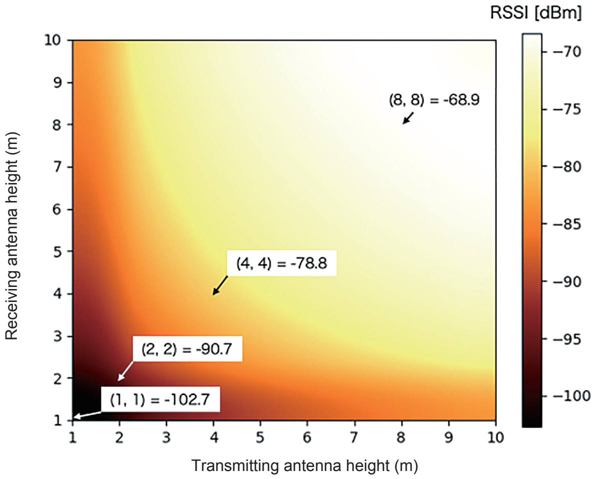


Figure 2: Two-ray Model Computation Example (Frequency: 920MHz, Transmission Power: 13dBm, Antenna Gain: 2.14dBi, Antenna Distance: 1km)

DR	Communication speed [bps]	Required SNR [dB]
DR0	250	-20
DR1	440	-17.5
DR2	980	-15
DR3	1760	-12.5
DR4	3125	-10
DR5	5470	-7.5

Table 2: Communication Speeds and Required SNR Values by LoRaWAN® Data Rate (DR) (125kHz Bandwidth in All Cases)

*21 "RP002-1.0.4 Regional Parameters", LoRa Alliance (https://resources.lora-alliance.org/home/rp002-1-0-4-regional-parameters).

*22 As radio transmission time exceeds 400ms, DR0 and DR1 are rarely used in practice due to the complexity of operating in accordance with Japan's Radio Act.

*23 LoRaWAN® uses spread spectrum technology, so communication is possible even when SNR is negative.

accordance with the ARIB STD-T108 regulation, based on Japan's Radio Act[*21][*24]. Thus, if communication is not established as expected even in the absence of obstacles, there may be radio congestion, so we sometimes check whether other 920MHz-band wireless systems are in use nearby.

Incidentally, IIJ also provides measurement devices[*25] for assessing LoRaWAN® radio conditions. These devices work as shown in Figure 3, aggregating and displaying measurements (average RSSI/SNR and communication success rate) based on downlink information returned from gateways. Because all the user needs to do is power on the device and check the displayed measurements, these devices are widely used in the field.

2.3 Characteristics and Future Prospects of Wi-Fi HaLow™ (IEEE 802.11ah)

Japan's Radio Act was amended in September 2022, enabling full-scale domestic use of IEEE 802.11ah/Wi-Fi HaLow™. HaLow is the designation for devices incorporating IEEE 802.11ah ("11ah") technology that have been certified by the Wi-Fi Alliance®. As the name suggests, it is a Wi-Fi® standard, but it is designed specifically for IoT and thus also categorized as an LPWA technology.

■ 11ah as an LPWA Technology

Viewed as an LPWA technology, 11ah has the following characteristics.

- Like other unlicensed-band LPWA technologies, it uses 920MHz-band specified low-power radio.
- 11ah supports communication over IP.
- 11ah uses OFDM for modulation, enabling relatively high speeds for an LPWA technology, ranging from hundreds of kbps to on the order of Mbps depending on communication conditions.
- As an LPWA technology, 11ah uses wide bandwidth (over 1MHz, vs. 125kHz for LoRaWAN®), making ultra-long-distance communication difficult. Relatively careful attention must also be paid to interference.

The characteristics of LoRaWAN® data communications mean it is not well-suited for real-time, bidirectional exchange of relatively large amounts of data. A key distinguishing

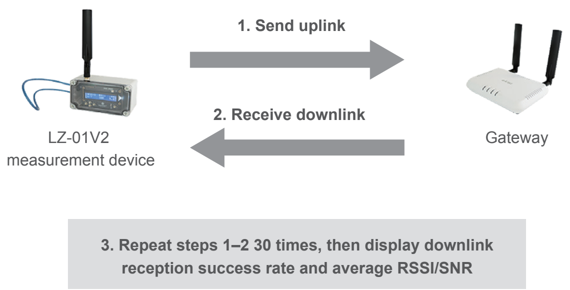


Figure 3: Operation of LoRaWAN® Measurement Device

*24 This is known as carrier sense or LBT (Listen Before Talk).

feature of 11ah is that it supports communication over IP and can achieve transmission speeds suitable for video, making it promising for use cases such as surveillance cameras and remote firmware updates. Conversely, factors such as bandwidth and overhead at the MAC layer and above mean 11ah is likely to be eclipsed by LoRaWAN® from a device power budget perspective, so it seems unlikely that 11ah will be a drop-in replacement for LoRaWAN®. Thus if 11ah-compatible sensor devices do become available, they may primarily be of the type that transmit measurements continuously (non-battery-powered). In any case, it is important to distinguish between LoRaWAN® and 11ah as appropriate to the use case based on their respective characteristics.

Technical Characteristics of 11ah

As mentioned, 11ah is part of the Wi-Fi® series, and the experience from a user's perspective is virtually the same as with conventional Wi-Fi® protocols. Specific examples include the following.

- It uses SSIDs/BSSIDs.
- Client devices (STA) connect to access points (APs).
- Security is provided through WPA2/3.

From a technical standpoint, while 11ah is based on the Wi-Fi® 5 (IEEE 802.11ac) specifications, modifications have been made to enable its use for LPWA in the 920 MHz band. The main modifications are described below[*26].

Narrowband Operation

While 11ac specifies bandwidth options of 20, 40, 80, and 160 MHz, available bandwidth in sub-gigahertz bands is limited by country regulations—in Japan's 920MHz band, only 7.6MHz is available. 11ah uses bandwidths of one tenth those of 11ac (2, 4, 8, and 16 MHz) and also supports 1MHz bandwidth. Due to the aforementioned regulations, however, only the 1, 2, and 4 MHz channels are currently permitted in Japan.

Note that using narrower bandwidth in 11ah allows for greater transmission range, as shown in Figure 4. This is primarily because narrower bandwidth helps prevent interference and increases power density per frequency. Narrower bandwidth, however, reduces the number of OFDM subcarriers, which means that for the same Modulation and Coding Scheme (MCS, discussed later), transmission speed will be lower.

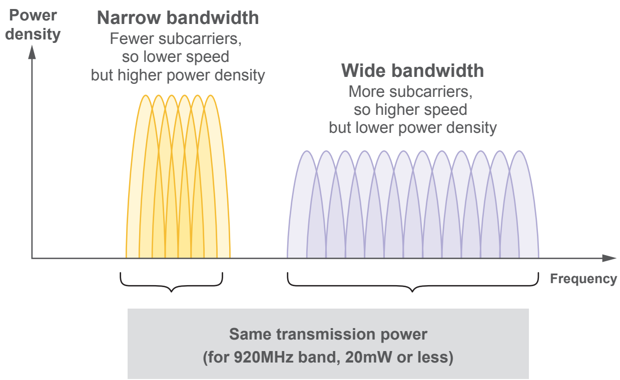


Figure 4: Conceptual Diagram of Bandwidth and Power Density

*25 "LZ-01V2 – IIJ LoRaWAN® Solution", IIJ (https://www.iij.ad.jp/biz/lorawan/device2/sencor_15.html, in Japanese).

*26 Tadao Kobayashi, "Private wireless network nyumon: Wi-Fi® 6, 802.11ah, local 5G tettei kaisetsu" [Introduction to Private Wireless Networks: Comprehensive Guide to Wi-Fi® 6, 802.11ah, and Local 5G], RIC Telecom, 2021

■ **Improved Multipath Resistance**

To narrow the bandwidth, 11ah specifies an OFDM subcarrier spacing of 31.25kHz, one tenth that in 11ac. This choice was made with the idea that the spacing would be achieved by lowering the clock speeds of 11ac wireless chips to one tenth. Thus, as Figure 5 shows, the OFDM symbol time is 32μs, which is 10 times longer than for 11ac. The guard interval (GI) can also be set to be more than 10 times longer than for 11ac, enabling stable transmission even in outdoor and long-distance scenarios. This is because, as illustrated in Figure 6, when the delay time of multipath delayed waves falls within the GI length, the effects of inter-symbol interference can be eliminated when demodulating the OFDM signall[*27].

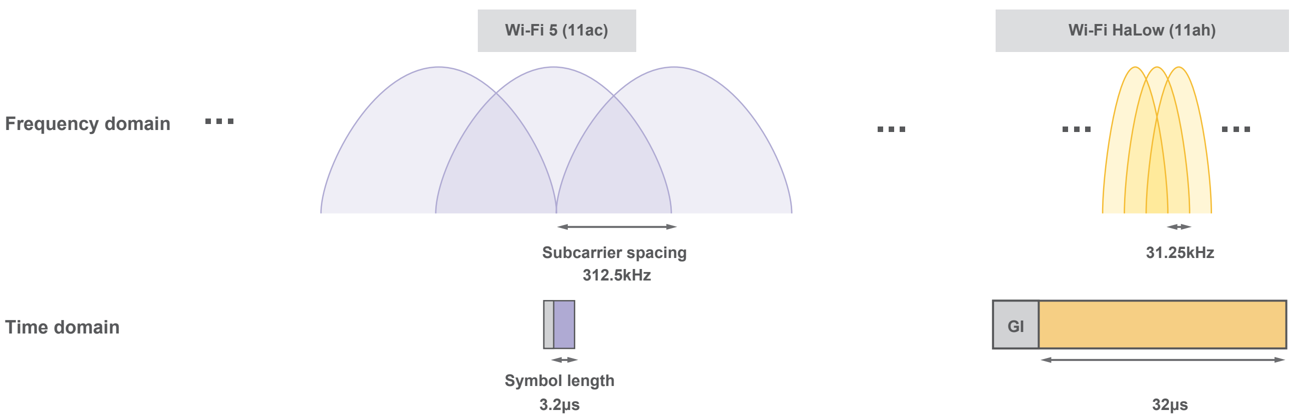


Figure 5: Conceptual Diagram of OFDM Subcarrier Spacing and Symbol Length

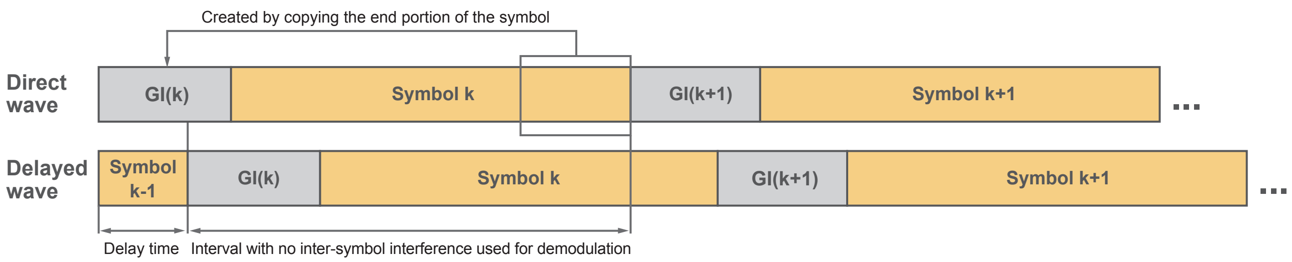


Figure 6: Effect of Guard Interval

*27 Makoto Itami, "OFDM no kiso to oyo-gijutsu" [Fundamentals and Application Technologies of OFDM], IEICE Fundamentals Review, vol. 1, no. 2, pp. 35–43, 2007 (https://www.jstage.jst.go.jp/article/essfr/1/2/1_2_2_35/_article/-char/ja/, in Japanese).

Modulation and Coding Scheme (MCS)

Table 3 shows the Modulation and Coding Scheme and physical layer data rates for 11ah. The MCS in 11ah is based on 11ac, with modulation methods and coding rates for MCS Index 0–9 being identical to those in 11ac. So within MCS Index 0–9, higher indices allow for more bits to be modulated at once, resulting in faster data rates. But as bandwidth is, as mentioned, one tenth that for 11ac, data rates are also one tenth compared with 11ac. MCS10 was created specifically for 11ah and is only supported in 1MHz mode. MCS10 is essentially MCS0 with 2× repetition, which, while reducing speed, ensures communication stability.

Incidentally, many devices have the ability to automatically switch MCS, and it seems that in many cases they check wireless RSSI and SNR values to do this.

Note that the data rates in Table 3 represent theoretical maximum values at the physical layer, so actual speeds will be lower. In particular, since 11ah often involves use cases with (for an LPWA system) relatively high-capacity continuous communication, such as camera video streaming, more attention must be paid to the 920MHz-band 10% duty cycle rule specified in the Radio Act than with other LPWA standards. The 10% duty cycle rule, in simple terms, ensures that everyone can make efficient use of limited available frequency bands by restricting each device's transmission time to no more than 360 seconds (10%) per hour. So to ensure continuity of communications, transmissions must be broken into smaller segments (keeping speed at one tenth)[*28]. As a result, when 11ah is used for continuous communication, actual speeds fall to less than one tenth (or 1/100 compared with 11ac) of the data rates shown in Table 3.

Other Features

Due to space limitations, we cannot cover all aspects of 11ah here, but below are some of its other features. Incidentally, the power-saving functionality and BSS Coloring were also adopted in the subsequent Wi-Fi® 6 (IEEE 802.11ax) standard.

- Power-saving (sleep function using Target Wake Time, or TWT)
- Reduction of inter-channel interference using BSS Coloring
- Relay function at APs (optional)

MCS Index	Modulation	Coding rate	Data rate (1MHz bandwidth) [Mbps	Data rate (2MHz) [Mbps]	Data rate (4MHz) [Mbps]
0	BPSK	1/2	0.3	0.65	1.35
1	QPSK	1/2	0.6	1.3	2.7
2	QPSK	3/4	0.9	1.95	4.05
3	16-QAM	1/2	1.2	2.6	5.4
4	16-QAM	3/4	1.8	3.9	8.1
5	64-QAM	2/3	2.4	5.2	10.8
6	64-QAM	3/4	2.7	5.85	12.15
7	64-QAM	5/6	3.0	6.5	13.5
8	256-QAM	3/4	3.6	7.8	16.2
9	256-QAM	5/6	4.0	N/A	18.0
10	BPSK x 2	1/2 x 2	0.15	N/A	N/A

Table 3: MCS and Physical Layer Data Rates in 11ah (Number of Spatial Streams = 1, GI Length = 8μs)

*28 In many cases, devices include configuration settings that allow for continuous communication at reduced speeds. If continuous communication is not required, speed restrictions can be dispensed with as long as communications comply with the rule limiting transmission time to 360 seconds per hour.

■ Establishing 11ah Communications

When building 11ah systems, in addition to what it has in common with LoRaWAN®, you also need to take into account factors such as bandwidth and MCS. RSSI and SNR are crucial, as with LoRaWAN®, and while it depends on the equipment used, you should generally aim for at least -85dBm and 15–20dB or higher. When it comes to RSSI, based on Figure 2, you need antenna heights of 3–4m or more to achieve outdoor communications with a range of around 1km in the absence of obstacles.

As for SNR, while you can adjust the acceptable operating parameters to an extent by changing bandwidth or MCS, such adjustments need to be made while monitoring actual communication conditions, taking into account communication speed in line with the aforementioned 10% duty rule.

Since 11ah, as part of the 802.11 series, uses CSMA/CA, it should not interfere with other 920MHz-band systems. But because the 11ah standard uses relatively wide bandwidth, in cases in which channels are congested, the 11ah side may experience increased waiting times, so it is useful to check for channel congestion in advance. Another important point is that in cases such as connecting multiple cameras to communicate continuously with a single AP, the presence of too many devices may cause communications to fail.

Some AP devices support relay functionality, which offers one means of establishing communication area coverage when achieving single-hop transmission distance is difficult or when line-of-sight between antennas is hard to maintain. As for the task of monitoring communication status, some devices, depending on their specifications, come with such functionality as standard.

■ 11ah Performance Evaluation Tests

At IIJ, we conducted performance evaluation tests of 11ah in an outdoor setting (Arakawa riverside area) over 2023–2024*29*30.

The first test used iPerf to measure speeds with non-continuous communication (no 10% duty cycle speed restriction), while the second test involved both iPerf measurements and continuous video transmission (with the 10% duty cycle speed restriction applied). Table 4 shows a summary of the test results.

#	10% duty cycle speed restriction	Antenna height (dipole equivalent)	4MHz bandwidth	2MHz bandwidth	1MHz bandwidth
1st round (up to 1000m)	No speed restriction (communication stops once duty cycle reached)	Transmitting antenna: 3m Receiving antenna: 1.8m	• ~2.2Mbps at 100m • ~590kbps at 500m • ~80kbps at 800m • Almost no communication at 1,000m	• ~1.7Mbps at 100m • ~420kbps at 500m • ~380kbps at 800m • ~200kbps at 1,000m	• ~1.3Mbps at 100m • ~840kbps at 500m • ~150kbps at 800m • Almost no communication at 1,000m
1st round (1,100m and beyond)	No speed restriction (communication stops once duty cycle reached)	Transmitting antenna: 3m Receiving antenna: ~4m	• ~120kbps at 1,200m	• ~220kbps at 1,300m	• ~230kbps at 1,300m
2nd round	Speed restriction applied	Transmitting antenna: 4m Receiving antenna: 4m	• 913kbps at 200m • 416kbps at 400m • Unmeasurable at 800m	• 436kbps at 200m • 313kbps at 400m • Unstable at 800m, ~100kbps	Not tested

Table 4: Performance Evaluation Test Results Summary

*29 “Wi-Fi HaLow™ no seino hyoka jikken wo okonaimashita” [We Conducted Performance Evaluation Tests of Wi-Fi HaLow™], IIJ Engineers Blog (https://eng-blog.iij.ad.jp/archives/21601, in Japanese)

*30 “Wi-Fi HaLow™ no seino hyoka jikken dai-ni-dan—dokomade ikeru!? Douga check shitemita!!” [Wi-Fi HaLow™ Performance Evaluation Test Round 2—How Far Can It Go!? We Tested Video Transmission!!”, IIJ Engineers Blog (https://eng-blog.iij.ad.jp/archives/25458, in Japanese)

The first test results showed that signal speed did not necessarily decrease inversely with distance, partly due to reflections from roads. With a 4MHz bandwidth, speeds exceeded 2Mbps at 100m but fell below 100kbps at 800m, indicating difficulties with long-distance transmissions. Also, because the devices were set to select MCS automatically, communication tended to become unstable when RSSI and SNR fluctuated. For distances up to 1,000m, we used a receiving antenna height of 1.8m, and with this setup, estimated RSSI in the two-ray model drops below -85dBm at around 800m. So the finding that communication quality deteriorates around this distance made sense. Note that when receiving antenna height was manually adjusted to around 4m, we were able to achieve connectivity at 1km or more.

The second set of test results show that at the 200m point, reasonable speeds were achieved even with the 10% duty cycle restriction, as the system was using MCS7. But because MCS was set to automatic, as in the first test, MCS tended to become unstable with distance, making communication difficult beyond 800m. Given that the average RSSI measurement at this point was around -82dBm, and considering the two-ray model estimates, this distance threshold seems reasonable.

As for video transmissions, frame drops occurred when, for example, vehicles passed through the Fresnel zone, but the system would likely be sufficient for surveillance applications not requiring high image quality (e.g., river water level monitoring) even at 800m. Higher speeds at greater distances could potentially be achieved depending on the selection of antenna, bandwidth, and MCS.

■ Challenges and Future Outlook

Potential use cases for 11ah beyond video transmission include those below. Generally, 11ah lends itself to situations in which conventional methods would be challenging for reasons to do with communication specs or because communication line installation and running costs are infeasible.

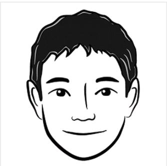
- Extension of in-building communications (wired / existing Wi-Fi®) in factories and similar facilities
- Replacement of LTE to reduce communication line running costs
- Multicast communication for municipal disaster preparedness and related applications
- Long-distance voice communication in tunnels and underground facilities

While price is a key factor for adoption in social infrastructure, 11ah-capable products (devices, communication modules, chips, etc.) are still not widely available in the market. They thus remain relatively expensive compared with existing Wi-Fi® products. In Japan, the 802.11ah Promotion Council, of which IIJ is a regular member, is leading market stimulus efforts, and with the cooperation of overseas vendors as well, the product lineup is gradually expanding. Interoperability of different vendors' devices remains a challenge, however. This issue is also being addressed within the 802.11ah Promotion Council framework, and so usability can be expected to improve ahead.

The use of the 850MHz band will also bear watching ahead[*31]. Currently, this band is allocated to digital MCA in Japan but will become available when that service ends in 2029. If this band is allocated to 11ah, this would enable broader bandwidth communications and likely make it possible to operate without the 10% duty cycle rule, further expanding the range of potential use cases. Using the 850MHz band would also help in avoiding conflicts with other systems, making it easier to use 11ah alongside other LPWA technologies like LoRaWAN®, and possibly enabling it to function as their backbone network. While this is still five years away, there apparently are plans to make portions of the band available in stages. According to the Ministry of Internal Affairs and Communications' schedule, technical requirements were to be compiled by around autumn 2024, so more specific information may already be available by the time this article is published.

2.4 Conclusion

This article has discussed IIJ's LPWA initiatives in the areas of LoRaWAN® and Wi-Fi HaLow™ (IEEE 802.11ah). LoRaWAN® is already used worldwide, and as an open standard offering ease of connectivity, we can expect it to make further inroads in Japan as well. While it is still early days for HaLow, it does offer advantages such as support for communication over IP and easy migration from existing LAN and Wi-Fi systems, so while keeping an eye on developments in this area, we will continue to work toward incorporating these technologies into new services.



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*31 "802.11ah no riyou shuhasu no kakudai ni muketa, Soumushou '900MHz-tai jieiyou musen system kodoka sagyohan' ga kaishi" [Ministry of Internal Affairs and Communications 'Working Group on Enhancement of 900MHz Band Private Radio Systems' Begins, Aiming to Expand Frequency Range for 802.11ah], 802.11ah Promotion Council (https://www.11ahpc.org/news/20240412/index.html, in Japanese).

Internet Initiative Japan

About Internet Initiative Japan Inc. (IIJ)

IIJ was established in 1992, mainly by a group of engineers who had been involved in research and development activities related to the Internet, under the concept of promoting the widespread use of the Internet in Japan.

IIJ currently operates one of the largest Internet backbones in Japan, manages Internet infrastructures, and provides comprehensive high-quality system environments (including Internet access, systems integration, and outsourcing services, etc.) to high-end business users including the government and other public offices and financial institutions.

In addition, IIJ actively shares knowledge accumulated through service development and Internet backbone operation, and is making efforts to expand the Internet used as a social infrastructure.

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