IoTeX

Decentralized Physical Infrastructure Networks

A Modular Infrastructure Thesis

IoTeX Research

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Abstract. Decentralized physical infrastructure network (DePIN) is currently one of the hottest narratives in Web3. In this report, we present a new thesis of DePIN, namely the modular DePIN infrastructure. By retrospecting the evolution of software development platforms for building physical infrastructure networks, we describe the new technology trend of building DePIN applications on top of a community-owned modular DePIN infrastructure and highlight the characteristics of this new DePIN thesis from both technical and economic perspectives.

Keywords: DePIN · Infrastructure · Modularity · Community-Driven · Platform Economy

1 Introduction

As one of the hottest narratives in Web3, decentralized physical infrastructure network (DePIN) [1] has received a lot of attention recently. DePIN leverages blockchain, Internet of Things (IoT) and tokenomics to incentivize communities to build real-world physical infrastructure networks and machine economy from the bottom up across a wide range of categories, such as mobility, energy, logistics, mapping, telecommunication, and more. DePIN can be classified into two categories [2], namely physical resource networks (PRNs) and digital resource networks (DRNs). While PRNs focus on providing non-fungible goods and services such as wireless connectivity, mobility and energy, DRNs mainly offer fungible digital resources such as compute, storage and bandwidth. When compared to traditional physical infrastructure network constructions, DePINs can be built in a more efficient and cost-effective manner [3].

While the number of DePIN startups have increased steadily since the past year, the newcomers are facing multiple challenges. Due to the lack of funds and technical competence, it usually takes long time for a DePIN startup to bring its idea to market. In particular, majority of DePIN projects in the market today are still largely centralized, which contradicts with the ultimate vision of DePIN. To address these challenges, we present the modular DePIN infrastructure, a new thesis for DePIN, in this report. The modular DePIN infrastructure can not only help DePIN startups to address their technical challenges and accelerate their go-to-market strategy, but also bring new platform economy and encourage collaboration of the DePIN community towards the common goal of building a community-owned DePIN infrastructure.

The rest of the report is organized as follows. Section 2 describes the past, present and future of physical infrastructure networks, followed by the presentation of a modular infrastructure thesis for DePIN in Section 3. Section 4 provides a number of design patterns for building DePIN applications using the modular DePIN infrastructure. In Section 5, we give a state-of-the-art overview of the modular DePIN infrastructure landscape. Section 6 discuss the new platform economy enabled by the modular DePIN infrastructure. The valuable venture capital insights are summarized in Section 7. Finally, we conclude this report in Section 8.

2 Physical Infrastructure Networks: The Past, Present and Future

In this section, we describe the system architecture evolution of physical infrastructure networks.

2.1 Physical Infrastructure Networks - The Past

In this past, physical infrastructure networks are highly centralized and usually built upon cloud and/or enterprise infrastructure. An example of centralized physical infrastructure network is illustrated in Fig. 1.

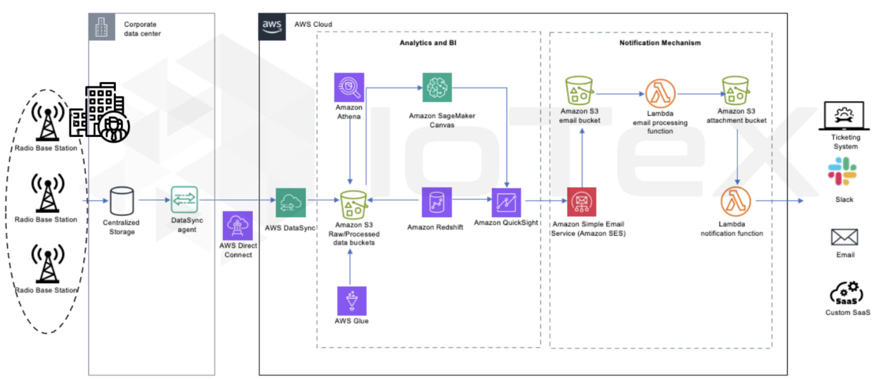

Fig. 1. An example of centralized physical infrastructure network [4]. The physical infrastructure network is deployed and managed by a corporate data center and the AWS infrastructure is used to realize analytics and monitoring applications.

In such a centralized architecture, physical infrastructure networks are typically deployed and orchestrated by centralized organizations and cloud platforms. As a result, a substantial amount of value is captured by centralized entities that deploy physical infrastructure networks and provide cloud platforms.

2.2 Physical Infrastructure Networks - The Present

The emergence of blockchain and cryptocurrency makes it possible for building token-incentivized, community-driven physical infrastructure networks. Many physical infrastructure networks deployed today are based on a hybrid architecture, as illustrated in Fig. 2.

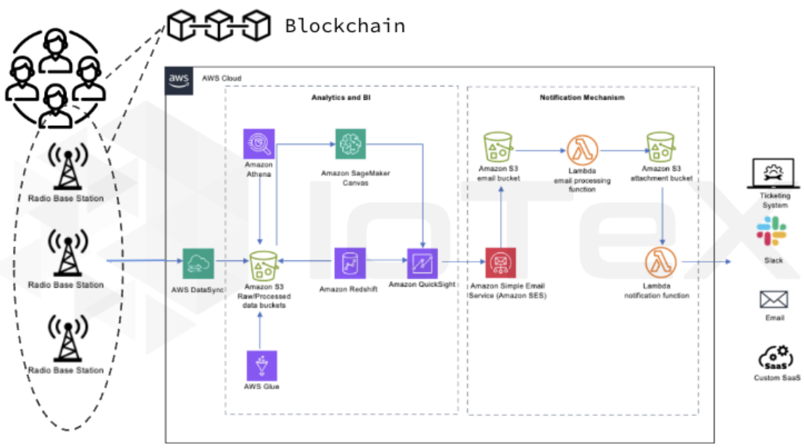

Fig. 2. An example of hybrid physical infrastructure network. The physical infrastructure network is deployed by community members via token incentives and the AWS infrastructure is used to manage physical resources and realize analytics and monitoring applications.

In such a hybrid architecture, community members are rewarded by crypto tokens via a smart contract on blockchain to deploy physical infrastructure networks in a decentralized manner. Meanwhile, the physical infrastructure networks are still orchestrated by centralized cloud platforms. Note that community members are able to capture certain amount of value along the value chain.

2.3 Physical Infrastructure Networks - The Future

Since Messari coined the term "DePIN" in the seminal report, Web3 communities have been making the effort towards realizing the ultimate vision of community-driven and community-owned physical infrastructure networks, as shown in Fig. 3.

In such a decentralized architecture, community members are rewarded by crypto tokens via a smart contract on blockchain to deploy physical infrastructure networks in a decentralized manner. Moreover, the physical infrastructure networks are orchestrated by community-owned, decentralized platforms, the components of which are developed and owned by different Web3 development

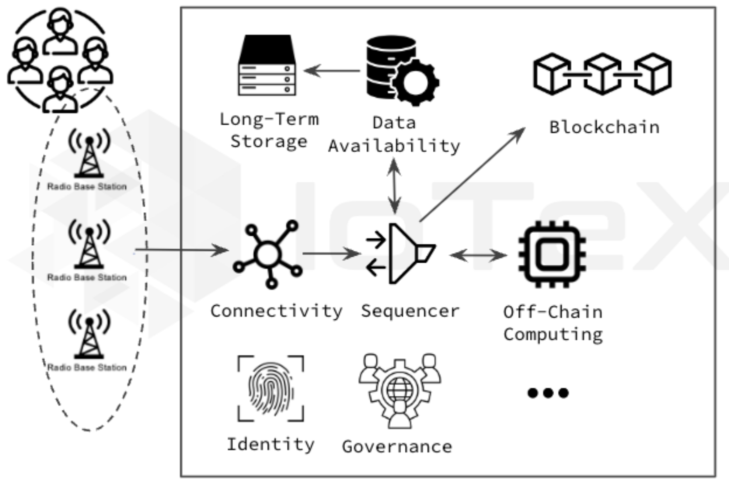

Fig. 3. An example of decentralized physical infrastructure network (DePIN). The physical infrastructure network is deployed by community members via token incentives and a community-owned, decentralized infrastructure is used to manage physical resources and build a variety of applications.

teams in lieu of centralized entities (e.g., cloud service providers). As a result, the community members are able to capture significant amount of value along the value chain.

3 A Modular Infrastructure Thesis for DePIN

We envision that an emerging DePIN infrastructure is the collection of community-driven hardware and software elements to build DePIN applications and a high-level architecture is shown in Fig. 4. There are four major categories of stakeholders:

- **Device Manufacturers**: The device manufacturers are responsible for manufacturing various DePIN devices.
- **Miners**: The miners are incentivized to deploy DePIN devices (physical or virtual) and rewarded by crypto tokens.
- **Builders**: The builders have two sub-categories:
  - **Infrastructure Builders**: The infrastructure builders develop core components and services that can be used by application builders to create DePIN application.
  - **Application Builders**: The application builders develop DePIN applications using various components built by the infrastructure builders.
- **Users**: The users use the utilities provided by DePIN applications and pay for their actual usage.

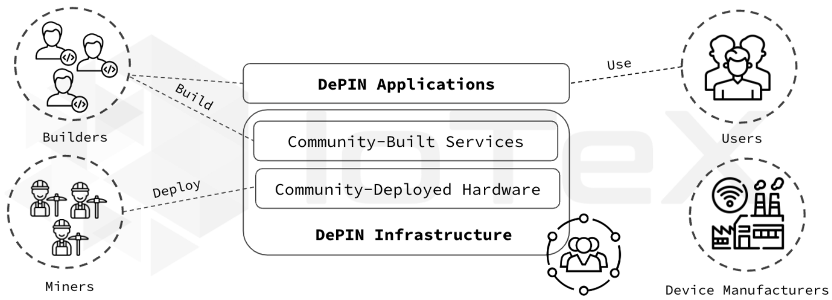

Fig. 4. A high-level architecture of emerging DePIN infrastructure and applications.

3.1 The Modular DePIN Infrastructure Overview

A typical DePIN application could be built out of nine modules, namely hardware abstraction, connectivity, sequencer, data availability, long-term storage, off-chain computing, blockchain, identity, and governance. Depending on the requirements of a DePIN project, all or a subset of those modules could be utilized. Moreover, some modules may be combined in specific implementations.

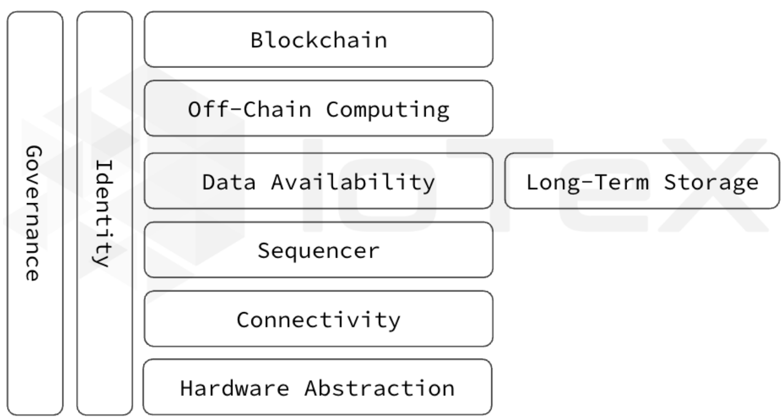

Fig. 5. An overview of the modular DePIN infrastructure

Hardware Abstraction Module: The Hardware Abstraction module features a lightweight embedded SDK that facilitates a wide range of smart devices (big or small) to securely connect with entities in the Connectivity module. The Hardware Abstraction module should realize best industry practices with respect to device security and enable smart devices to securely interact with other entities (e.g., people and servers) in a decentralized setting. In practice, the Hardware

Abstraction module that supports popular microcontroller families (e.g., ESP32, Arduino, STM32, etc.), single-board computers (e.g., Raspberry Pi, ODROID, Rock Pi, etc.), and smartphones (e.g., Android and iOS) is highly desirable.

Connectivity Module: The Connectivity module might be a centralized service or decentralized network that reliably passes data collected from smart devices to the sequencer module. The Connectivity module should support one or multiple communication protocols (e.g., HTTP(s), MQTT, WebSockets, Bluetooth, LoRa, etc.) and enable secure two-way communications between smart devices and the sequencer. Moreover, the connectivity module should scale automatically with the number of connected devices.

Sequencer Module: The Sequencer module might be a centralized service or decentralized network that authenticates and sorts data packets received from smart devices before storing them to the Data Availability module. The Sequencer may also retrieve data in batch from the Data Availability module and send it to another module (e.g., the off-chain computing module) for further processing.

Data Availability Module: The Data Availability module might be a centralized service or decentralized network that stores data temporarily for a project-specified time period. Ingest into the Data Availability module is flexible and can come from either on-chain or off-chain sources. Once this period expires, the stored data might be deleted or moved to the Long-Term Storage module. Based on a project's configuration, the Data Availability module may also commit data sets to the Blockchain module from time to time.

Long-Term Storage Module: The Long-Term Storage module might be a centralized service or decentralized network that is able to store data for long-term retention, depending on the requirements of DePIN projects. The stored data can be retrieved from the Long-Term Storage module for other purposes via storage APIs. While implementation of the Long-Term Storage module varies by network, but it involves uniquely identifying a piece of data (bytes, files, directories, etc.) by some content-addressable, immutable hash representation of the underlying data. The storage timeline can be permanent or time-bound (e.g., many years), and novel sampling mechanisms are employed to ensure the data exists for subsequent retrieval.

Off-Chain Computing Module: The Off-Chain Computing module might be a centralized service or decentralized computing resource (e.g., CPU, GPU, FPGA, etc.) pool that is able to perform project-specific business logic on the data stored in the Data Availability module and (optionally) generating validity proofs (e.g., zero-knowledge proofs, TEE-based attestation reports, etc.) of the computations executed. A validity proof, which is essential to ensure integrity of off-chain computations, is then verified on-chain by a corresponding verifier smart contract.

Blockchain Module: The Blockchain module serves as the trust anchor of a DePIN application for identity management, device management, data attestation, crypto asset management, etc. The Blockchain module is mainly responsible for verifying the validity of off-chain computations and distributing token rewards to DePIN miners. The Blockchain module could also be used for realizing on-chain governance.

Identity Module: The Identity module is responsible for managing on-chain and/or off-chain identities (e.g., account abstraction (AA) wallet, decentralized identifiers (DIDs), etc.) for all the entities (e.g., smart devices, users, servers, etc.) in DePIN applications. While an on-chain identity allows users to manage their DePIN assets, an off-chain identity allows machines to securely interact with each other in a decentralized setting.

Governance Module: The Governance module, which could be realized on-chain/off-chain or in a hybrid manner, is responsible for defining and enforcing the policies and procedures for each modules in a modular DePIN tech stack. The Governance module allows token holders to make decisions regarding various aspects (e.g., usage of the project treasury, protocol upgrade, etc.) of a DePIN project, typically through a community voting process.

3.2 Characteristics of the Modular DePIN Infrastructure

When compared to centralized platforms used for building conventional physical infrastructure networks, the emerging modular DePIN infrastructure has the following salient characteristics:

- **Community-Owned Platform**: Each infrastructure module (i.e., computing, connectivity, storage, etc.) is built and owned by a developer team. As a result, the entire infrastructure platform is jointly owned by the DePIN community.
- **Multi-Vendor Marketplace**: Each infrastructure module could be provided by multiple developer teams. All the infrastructure modules form a free and dynamic marketplace that allows application developers to choose best modules that can suit their needs.
- **Module-Specific Economy**: For each infrastructure module, the developer team has its own economy model design for aligning benefits of all stakeholders.
- **Composability**: An application developer can choose modules provided by different teams to build end-to-end DePIN applications.

With the community-owned modular DePIN infrastructure in place, application developers can easily build applications via the combination of various infrastructure modules and achieve the similar user experience as they use centralized cloud platforms today.

4 Design Patterns

In this section, we describe a number of design patterns for building typical DePIN applications with the modular DePIN infrastructure.

4.1 Sensor Networks

Sensor networks represent a category of DePIN applications (see DIMO [5], Hivemapper [6], WeatherXM [7], etc., for examples) that allow community members to monetize data collected from the physical world. A reference system architecture for building this category of DePIN applications is shown in Fig. 6.

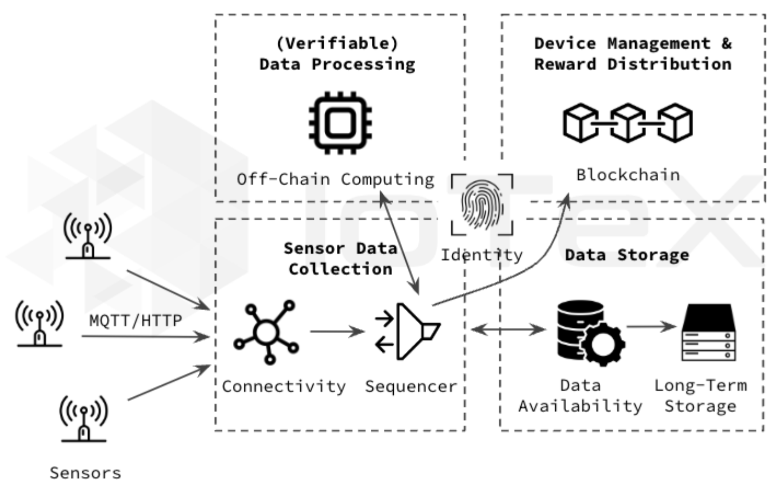

Fig. 6. A Reference System Architecture for Decentralized Sensor Networks

The above reference system architecture contains five major phases:

1. **Device Management**. In this phase, the ownership between sensor and its owner is established and then managed by the blockchain module.
2. **Sensor Data Collection**. In this phase, sensor data is collected via the connectivity module and pre-processed by the sequencer module.
3. **Data Storage**. In this phase, sensor data is cached using the data availability module and optionally stored with the long-term storage module.

4. **(Verifiable) Data Processing**. In this phase, the off-chain computing module processes sensor data according to a pre-defined business logic and outputs the computation result and (optionally) a validity proof.
5. **Reward Distribution**. In this phase, token rewards are distributed to sensor owners whose sensors contribute to computations.

The identity module will be used across the different phases to ensure trustworthy interactions among various system entities.

4.2 Connectivity Networks

Connectivity networks represent a category of DePIN applications (see Helium [21], Nodle [20], Wicrypt [23], etc., for examples) that allow community members to monetize bandwidth of various wireless communication technologies (e.g., LoRa, Bluetooth, WiFi, 5G, etc.). A reference system architecture for building this category of DePIN applications is shown in Fig. 7.

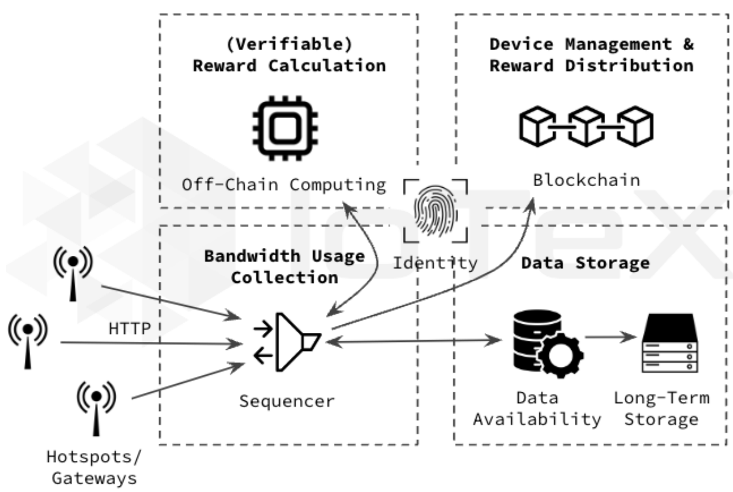

Fig. 7. A Reference System Architecture for Decentralized Connectivity Networks

The above reference system architecture contains five major phases:

1. **Device Management**. In this phase, the ownership between hotspots/gateways and its owner is established and then managed by the blockchain module.
2. **Bandwidth Usage Collection**. In this phase, bandwidth usage is reported by hotspots/gateways and pre-processed by the sequencer module.
3. **Data Storage**. In this phase, bandwidth usage data is cached using the data availability module and optionally stored with the long-term storage module.

4. **(Verifiable) Reward Calculation**. In this phase, the off-chain computing module calculate token rewards based on the bandwidth contribution and outputs the computation result and (optionally) a validity proof.
5. **Reward Distribution**. In this phase, token rewards are distributed to hotspot/gateway owners whose devices contribute their bandwidth.

The identity module will be used across the different phases to ensure trustworthy interactions among various system entities.

4.3 Computing Networks

Computing networks represent a category of DePIN applications (see Render Network [48], Akash Network [49], io.net [45], etc., for examples) that allow community members to monetize computing resources (e.g., CPU, GPU, FPGA, etc.) that are either hosted in the cloud or owned by community members. A reference system architecture for building this category of DePIN applications is shown in Fig. 8.

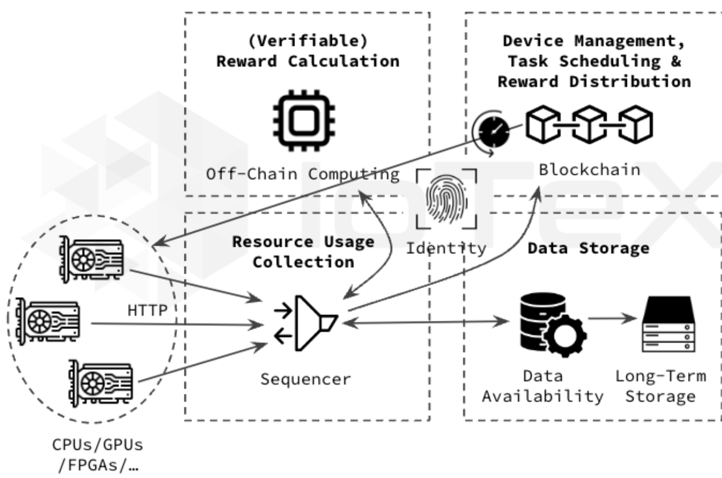

Fig. 8. A Reference System Architecture for Decentralized Computing Networks

The above reference system architecture contains five major phases:

1. **Device Management**. In this phase, the ownership between computing resources (i.e., CPUs, GPUs, FPGAs, etc.) and its owner is established and then managed by the blockchain module.
2. **Task Scheduling**. In this phase, computing resources are scheduled based on a pre-defined rule implemented by a smart contact on the blockchain module.

3. **Resource Usage Collection**. In this phase, computing resource usage data is reported by the chosen machine(s) and pre-processed by the sequencer module.
4. **Data Storage**. In this phase, computing resource usage data is cached using the data availability module and optionally stored with the long-term storage module.
5. **(Verifiable) Reward Calculation**. In this phase, the off-chain computing module calculate token rewards based on the usage of computing resources and outputs the computation result and (optionally) a validity proof.
6. **Reward Distribution**. In this phase, token rewards are distributed to owners whose machines contribute their computing resources.

The identity module will be used across the different phases to ensure trustworthy interactions among various system entities.

5 The Modular DePIN Infrastructure Landscape

During the past years, Web3 community has built various infrastructure modules that could be directly used by or easily adapted to serve DePIN applications. In this section, we describe the state-of-the-art modular DePIN Infrastructure landscape. An overview of the modular DePIN infrastructure landscape is shown in Fig. 9.

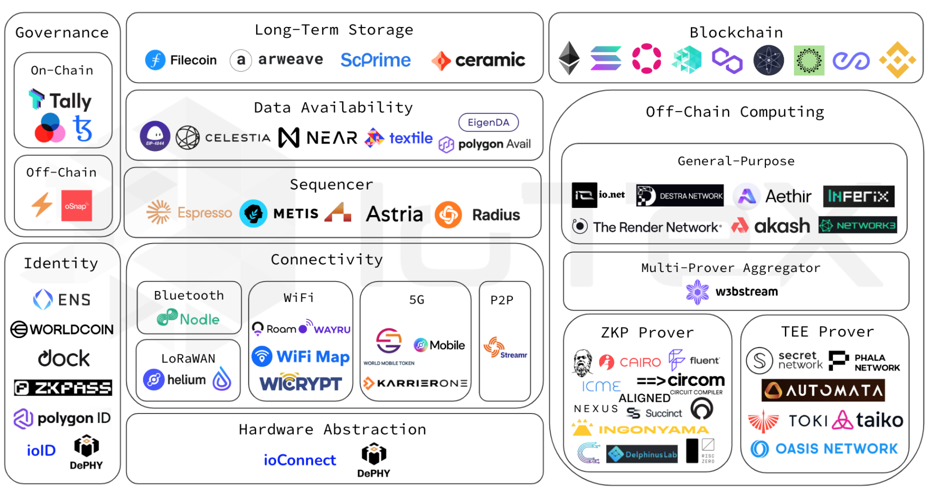

Fig. 9. An Overview of the Modular DePIN Infrastructure Landscape

Hardware Abstraction Module: While all the semiconductor companies provide SDKs for their chipsets and development boards, those SDKs are lack of key functionalities to enable smart devices to interact with decentralized networks. To the best of our knowledge, ioConnect [14] developed by IoTeX is the first universal embedded SDK for connecting a wide range of smart devices (e.g., Raspberry Pi, Arduino, ESP32, smartphones, etc.) to Web3. The ioConnect SDK realizes key security and identity technologies (e.g., Arm's PSA Certified Crypto API [15], Decentralized Identifiers [16], Verifiable Credentials [17], DIDComm Messaging [18], etc.) to ensure trustworthy connection between smart devices and Web3 networks. DePHY's hardware SDK [19] also works on the same direction for certain device.

Connectivity Module: A number of DePIN projects aim to build decentralized connectivity networks for people and devices. These projects have explored various wireless communication techniques, including Bluetooth (e.g., Nodle [20]), LoRaWAN (e.g., Helium [21] and Drop Wireless [22]), WiFi (e.g., Wicrypt [23], WiFi Map [24], Roam [25], and Wayru [26]), 5G (e.g., Karrier One [27], Helium Mobile [28], and World Mobile Token [29]), and P2P network (e.g., Streamr [30]). These connectivity modules facilitate smart device and people to connect to Web3 networks in different ways.

Sequencer Module: While a number of decentralized or shared sequencer projects (see Espresso [31], Metis [32], Astria [33], and Radius [34], for examples) exist, these sequencer solutions were built in the context of Layer-2 rollup networks. However, it is not difficult to adapt the exiting sequencers to serve DePIN applications.

Data Availability Module: Quite a few data availability projects have been built during the past few years. Those solutions might realize data availability by leveraging the existing Layer-1 blockchain (e.g., EIP-4844 [35] and Near [37]), using a separate blockchain (e.g., Celestia [36] and Polygon Avail [39]), building upon decentralized storage (e.g., Textile [97]), or resorting to restaking-based approach (e.g., EigenDA [40]). The existing solutions make different security assumptions and implementation trade-offs.

Long-Term Storage Module: Long-term storage solutions (e.g., Filecoin [41], Arweave [42], ScPrime [43], ceramic [44], etc.) have been built since the early days of Web3. Those solutions can serve the long-term storage requirements of DePIN applications well.

Off-Chain Computing Module: The off-chain computing can be roughly classified into two categories, namely the general- and special-purpose computing networks. While the general-purpose computing networks (e.g., io.net [45], Destra Network [46], Aethir [47], The Render Network [48], Akash [49], Inferix [50], Network3 [93], etc.) aim to provide decentralized computing resources (e.g., CPUs, GPUs, FPGAs, etc.) for various applications, the special-purpose computing networks focus on attesting integrity of a specific computation process.

The special-purpose computing networks can be further divided into two subcategories, namely ZKP- and TEE-based prover networks. On the one hand, the ZKP prover networks contain zkVM (e.g., Risc0 [51], Succinct [52], ICME [53], Nexus [54], etc.), zkWasm (e.g., Delphinus Lab [55], fluent [56], etc.), hardware-accelerated prover (e.g., Cysic [57], Ingonyama [58], etc.), domain-specific language (DSL) based prover (e.g., Circom [59], ZoKrates [60], etc.), and zkAggregator (e.g., Aligned [61], Nebra [62]). On the other hand, the TEE prover networks contain multiple projects (e.g., Oasis Network [63], Toki [64], Taiko [65], Automata [66], Secret Network [67], Phala Network [68], etc.) that build upon the Intel SGX technology. In addition, W3bstream [69] developed by IoTeX aims to become a multi-prover aggregator for verifiable off-chain computing.

Blockchain Module: The leading blockchains that are widely used for building DePIN applications include Ethereum [70], Solana [71], Polkadot [72], IoTeX [73], Polygon [74], Cosmos [75], Eclipse [76], Peaq [77], and BNB Smart Chain [78].

Identity Module: A number of projects have been built to provide identity for people and devices in Web3 applications, among which ioID developed by IoTeX and DePHY [19] focus on device identity based on self-sovereign identity technology. Web3 ID by Dock [79] applies the same technique to offer people's identities. Polygon ID [80], zkPass [81] and Worldcoin [82] leverages zero-knowledge proofs and/or secure multi-party computation to protect users' privacy. In addition, ENS [83] is an on-chain domain service which can also be utilized as an identity system.

Governance Module: Two types of governance systems have been explored in the Web3 community, namely on-chain (see Tally [84], Commonweath [85], tezos [86], etc., for examples) and off-chain (see Snapshot [87], oSnap [88], etc., for examples) governance. Those governance systems could be directly applied to each component in a modular DePIN infrastructure to make various decisions.

6 New Platform Economy

In this section, we describe the new platform economy that is enabled by the modular DePIN infrastructure.

6.1 From Single to Diversified Economy

The conventional software development infrastructure (e.g., cloud computing platforms) that are used to build physical infrastructure networks has a single fixed economic model, as illustrated in Fig. 10.

Fig. 10. The Single Fixed Economy in Cloud Computing Platforms

Since all the modules and components are primarily built by cloud service providers, it is up to them to determine the pricing models. Such a fixed economic model cannot effectively incentivize community developer teams to make contributions.

The modular DePIN infrastructure is dedicatedly designed to address the aforementioned issue. As shown in Fig. 11, the entire DePIN infrastructure is owned by the community and each module of which could be built by multiple community developer teams.

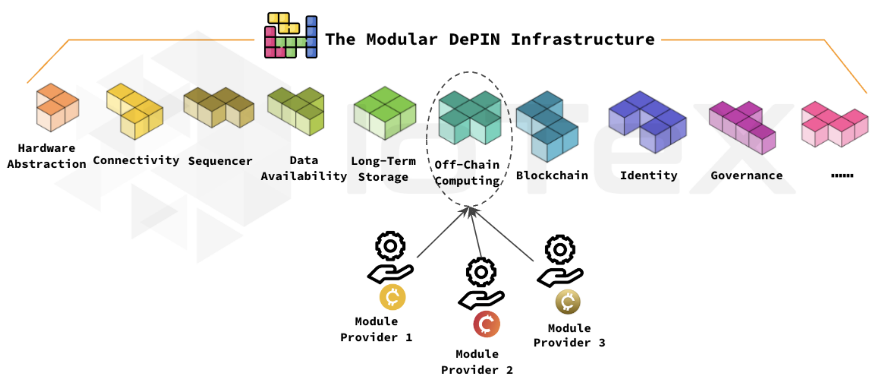

Fig. 11. The Diversified Economy in the Modular DePIN Infrastructure

A salient feature of the modular DePIN infrastructure is the module-specific economy that allows each developer team to design its own economic model for incentivizing its community members and customers in the most effective way. The module-specific economy provides strong incentives and great flexibility for developer teams growing their own communities and working together to achieve the common goal of serving DePIN application developers simultaneously.

6.2 The Modular DePIN Infrastructure Flywheel

Once the cold start has been achieved, DePIN projects should enter a dynamic equilibrium that is often referred to as the *flywheel effect*. The modular DePIN infrastructure is comprised of a number of infrastructure modules built by multiple developer teams, which leads to a hierarchical and cascaded flywheel.

Module-Level Flywheel. Each infrastructure module follows a module-level flywheel as shown in Fig. 12.

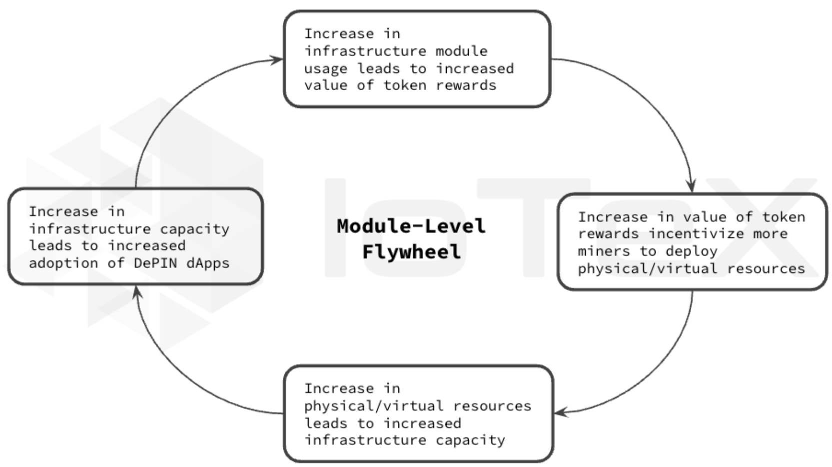

Fig. 12. The Module-Level Flywheel for a Modular DePIN Infrastructure

The above module-level flywheel is self-explainable, which describes how the token value of a DePIN infrastructure module is accrued by moving the flywheel continuously.

dApp-Level Flywheel. Each DePIN dApp is built upon a number of infrastructure modules, which follows a dApp-level flywheel as shown in Fig. 13.

The above dApp-level flywheel is self-explainable, which describes how the token value of a DePIN dApp is accrued by moving the flywheel continuously as well as its impact on multiple module-level flywheels. Fig. 14 clearly illustrates the cascaded relationship among DePIN dApps and infrastructure modules. Multiple flywheels of infrastructure modules are going to move whenever the flywheel of a DePIN dApp moves.

6.3 Building DePIN Infrastructure Modules with Restaking

Depending on the technology strategies of developer teams, each infrastructure module could be built by growing its own node operator community or leveraging the validators of some existing Layer-1 blockchain via restaking. Restaking-based approach adds and additional dimension with respect to the tokenomics design.

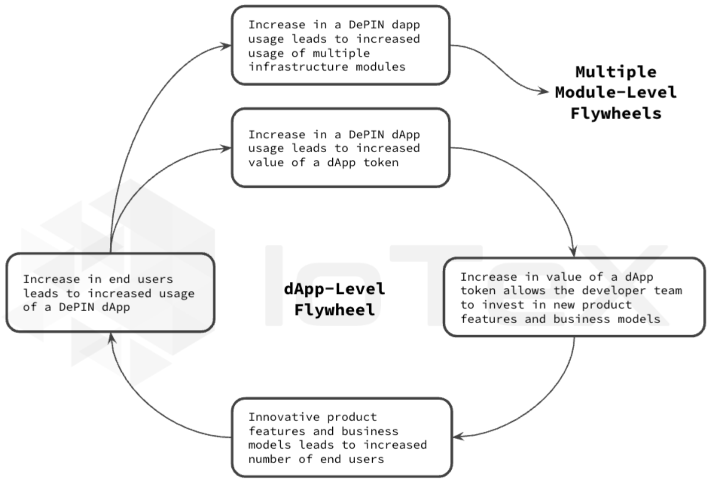

Fig. 13. The dApp-Level Flywheel for a DePIN Project Built upon the Modular Infrastructure

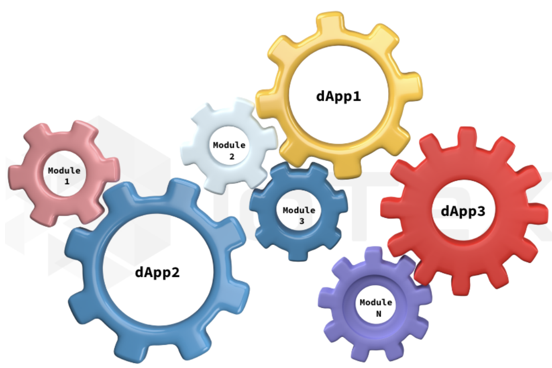

Fig. 14. The Cascaded Relationship among DePIN dApps and Infrastructure Modules

7 The Modular DePIN Infrastructure Adoption and Investment Landscape

In this section, we point out some pioneer DePIN projects that is going to build their applications on top of a modular DePIN infrastructure and summarize the current landscape of venture capital investments from the modular DePIN infrastructure perspective.

7.1 The Modular DePIN Infrastructure Adoption

While the modular DePIN infrastructure thesis is still at its early stage, a number of pioneer DePIN projects are exploring this new concept and planing for the future adoption. These projects cover a wide range of industry sectors such as smart home, smart city, AI, automotive, and cybersecurity, as shown in Fig. 15.

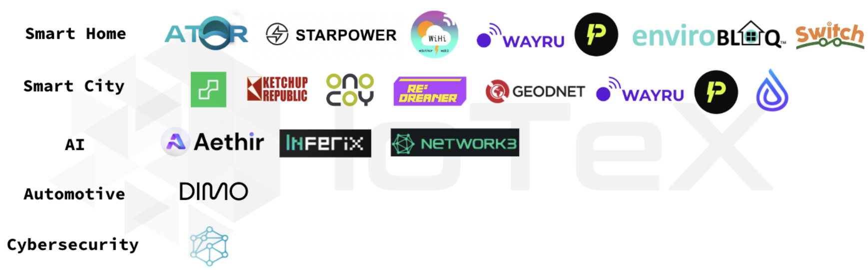

Fig. 15. Adoption of the Modular DePIN Infrastructure by Pioneer DePIN Projects

More DePIN projects at different maturity stages are expected to join the evolution of the modular DePIN infrastructure in this year.

7.2 The Modular DePIN Infrastructure Investment Landscape

We summarize the investment portfolio of venture capital funds from the perspective of the modular DePIN infrastructure in Fig. 16.

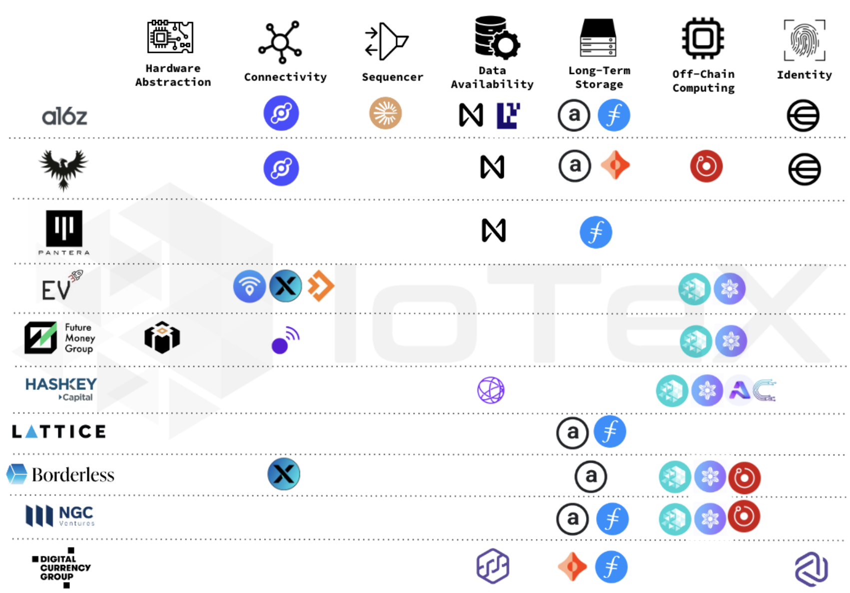

Fig. 16. The Venture Capital Portfolio on the Modular DePIN Infrastructure

It is clear to see that a majority of venture capital funds go to the projects that build the connectivity, data availability, long-term storage, and off-chain computing modules in the modular DePIN infrastructure currently. Such an investment landscape is expected to continuously evolve with new DePIN projects breaking into the market. Considering the explosive growth of DePIN projects recently, the modular DePIN infrastructure has great investment potential as the fundamental basis of building emerging DePIN applications.

8 Outlook

With the increasing number of Web3 startups joining the DePIN revolution and the amount of investments in the DePIN thesis, the DePIN sector is going to become more mature in 2024 with respect to technology stack and tools, ecosystem and community growth, as well as real-world adoption. The proposed modular DePIN infrastructure thesis aims to address the key technical challenges faced by many DePIN builders. We expect that the DePIN community can work together closely to realize the first community-owned modular DePIN infrastructure that can be used by a wide range of existing and emerging DePIN projects.

Appendix

The modular DePIN infrastructure is the foundation to empowering existing and emerging DePIN applications. The following DePIN projects (in alphabetical order) are either developing infrastructure modules or exploring an instantiation of the modular DePIN infrastructure for empowering their applications.

Aethir [47] has built distributed GPU-based compute infrastructure for enterprise use cases. Aethir makes it easier for GPU infrastructure providers to scale, and simpler for buyer to access GPU worldwide.

ATOR [89] is building the largest global anonymous-routing ecosystem, leveraging a decentralized privacy protocol, on-chain incentives and signature hardware to rapidly scale the network.

DATS [90] DATS boosts Web3 security by conducting cybersecurity audits using hacker-inspired tactics and Distributed High Power Computing (D-HPC) to defend against complex cyber threats.

DIMO [5] is an open and user-controlled IoT protocol and network. It connects drivers, developers and manufacturers on a shared network with common state, developer tools, payment rails and more.

dTelecom [91] is a decentralized Real-Time Communication (RTC) that allows anyone to contribute spare bandwidth power and earn rewards through the $DTEL token. It provides affordable and and efficient RTC resources for adding audio/video/chat solutions to customers' apps without the overhead of traditional in-house and cloud solutions.

Helium [21] is a decentralized, blockchain-based wireless infrastructure project that allows individuals and organizations to deploy and operate wireless networks through token incentivization. It leverages the Solana Blockchain for its foundation. The primary token powering the network is HNT, while IOT and MOBILE tokens are used to facilitate the LoRaWAN and 5G networks, respectively.

Ketchup Republic [92] tokenizes real-world spaces and actions utilizing the Proof of Engagement (PoE) mechanism. It offers essential support for a wide range of applications, including Local Life Services, SocialFi, and GameFi, by transforming engagement in the physical world into tokenized rewards and incentives.

Network3 [93] is building a dedicated AI layer2 for developers worldwide, which is going to offer model optimization, compression, federated learning and confidential computing for efficient and scalable AI deployment.

Onocoy [94] is building out a network of RTK (Real-Time Kinematic) stations to provide high-precision positioning for all. The onocoy system is community-owned and borderless, aiming to be a indispensable utility covering the globe.

RE:DREAMER Lab [95] is building a data exchange layer for tokenizing real-world assets (RWA) by combining real asset oracles, the Redeem Protocol, ERC-6672 NFT standard, and a Decentralized B2B Network.

Starpower [96] is pioneering the energy internet, akin to Uber, by linking millions of energy devices globally to virtual power plants (VPPs) and more, in a market worth over $100 billion.

Textile [97] is building Tableland, an open source, permissionless cloud database built on SQLite, as well as Basin, scalable subnets for fast and secure data storage powered by the Filecoin network.

WiHi [98] is decentralizing weather monitoring and forecasting, democratizing access to data and enhancing accuracy of forecasts. Transitioning to a web3 framework holds the promise of breaking down silos and making data gathering more efficient, participatory, and broader geographically.

References

1. C. Lovely, What are Decentralized Physical Infrastructure Networks (DePIN)?, IoTeX, https://iotex.io/blog/what-are-decentralized-physical-infrastructure-networks-depin/, 2023.
2. S. Kassab, Navigating the DePIN Domain, Messari, https://messari.io/report/navigating-the-depin-domain, 2023.
3. S. Sengupta and T. Jain, Exploring The Design Space Of DePIN Networks, Multicoin Capital, https://multicoin.capital/2023/09/21/exploring-the-design-space-of-deping-networks/, 2023.
4. M. Chennana, M. Ryan, N. Kumar, and S. Khan, Enable Analytics and Insights for Telecom Networks, https://aws.amazon.com/blogs/industries/enable-analytics-and-insights-for-telecom-networks/, 2023.
5. DIMO. https://dimo.zone/.
6. Hivemapper. https://hivemapper.com/.
7. WeatherXM. https://weatherxm.com/.
8. Helium, https://www.helium.com/.
9. Nodle, https://www.nodle.com/.
10. Wicrypt, https://wicrypt.com/.
11. Render Network, https://rendernetwork.com/.
12. Akash Network, https://akash.network/.
13. io.net, https://io.net/.
14. ioConnect - A Universal Embedded SDK for Connecting Smart Devices to Web3, https://github.com/machinefi/ioConnect.
15. PSA Certified Crypto API, https://arm-software.github.io/psa-api/crypto/1.2/.
16. Decentralized Identifiers (DIDs) v1.0 - Core architecture, data model, and representations, https://www.w3.org/TR/did-core/.
17. Verifiable Credentials Data Model v2.0, https://www.w3.org/TR/vc-data-model-2.0/.
18. DIDComm Messaging v2.1, https://identity.foundation/didcomm-messaging/spec/v2.1/.
19. DePHY, https://dephy.io/.
20. Nodle, https://www.nodle.com/.
21. Helium, https://www.helium.com/.
22. Drop Wireless, https://dropwireless.io/.
23. Wicrypt, https://wicrypt.com/.
24. WiFi Map, https://www.wifimap.io/.
25. Roam, https://weroam.xyz/.
26. Wayru, https://www.wayru.io/.
27. Karrier One, https://karrier.one/.
28. Helium Mobile, https://hellohelium.com/.
29. World Mobile Token, https://worldmobiletoken.com/.
30. Streamr, https://streamr.network/.
31. Espresso Systems, https://www.espressosys.com/.
32. Metis, https://www.metis.io/.
33. Astria, https://www.astria.org/.
34. Radius, https://www.theradius.xyz/.
35. EIP-4844, https://www.eip4844.com/.
36. Celestia, https://celestia.org/.
37. Near, https://near.org/data-availability.

38. Textile, https://linktr.ee/textileio.
39. Polygon Avail, https://www.availproject.org/.
40. EigenLayer, https://www.eigenlayer.xyz/.
41. Filecoin, https://filecoin.io/.
42. Arweave, https://www.arweave.org/.
43. ScPrime, https://scpri.me/.
44. Ceramic, https://ceramic.network/.
45. io.net, https://io.net/.
46. Destra Network, https://www.destra.network/.
47. Aethir, https://www.aethir.com/.
48. The Render Network, https://rendernetwork.com/.
49. Akash, https://akash.network/.
50. Inferix, https://inferix.io/.
51. Risc0, https://www.risczero.com/.
52. Succinct, https://succinct.xyz/.
53. ICME, https://www.icme.io/.
54. Nexus, https://www.nexus.xyz/.
55. Delphinus Lab, https://delphinuslab.com/.
56. Fluent, https://fluentlabs.xyz/.
57. Cysic, https://cysic.xyz/.
58. Ingonyama, https://www.ingonyama.com/.
59. Circom, https://docs.circom.io/.
60. ZoKrates, https://zokrates.github.io/.
61. Aligned, https://alignedlayer.com/.
62. Nebra, https://www.nebra.one/.
63. Oasis Network, https://oasisprotocol.org/.
64. Toki, https://toki.finance/.
65. Taiko, https://taiko.xyz/.
66. Automata, https://www.ata.network/.
67. Secret Network, https://scrt.network/.
68. Phala Network, https://phala.network/.
69. W3bstream, https://w3bstream.com/.
70. Ethereum, https://ethereum.org/en/.
71. Solana, https://solana.com/.
72. Polkadot, https://polkadot.network/.
73. IoTeX, https://iotex.io/.
74. Polygon, https://polygon.technology/.
75. Cosmos, https://cosmos.network/.
76. Eclipse, https://www.eclipse.xyz/.
77. Peaq, https://www.peaq.network/.
78. BNB Smart Chain, https://www.bnbchain.org/en/bnb-smart-chain.
79. Web3 ID, https://www.dock.io/web3id.
80. PolygonID, https://www.polygonid.com/.
81. zkPass, https://zkpass.org/.
82. Worldcoin, https://worldcoin.org/.
83. ENS Domains, https://ens.domains/.
84. Tally, https://www.tally.xyz/.
85. Commonwealth, https://commonwealth.im/.
86. Tezos, https://tezos.com/governance/.
87. Snapshot, https://snapshot.org/.

88. oSnap, https://docs.uma.xyz/developers/osnap.
89. ATOR, https://www.ator.io/.
90. DATS Project, https://datsproject.io/.
91. dTelecom, https://dtelecom.org/.
92. Ketchup Republic, https://x.com/ketchuprepublic.
93. Network3, https://network3.ai/.
94. Onocoy, https://www.onocoy.com/.
95. RE:DREAMER Lab, https://www.redreamer.io/.
96. Starpower, https://www.starpower.world/.
97. Textile, https://linktr.ee/textileio.
98. WiHi, https://www.wihi.cc/.

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