

Mycelium Testbed: A Comprehensive Platform for Decentralized Physical Infrastructure Networks (DePIN)

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Abstract—Decentralized Physical Infrastructure Networks (DePINs) leverage blockchain technology to enable the construction and operation of real-world physical infrastructure networks in a trustless and programmatic manner. However, the inherent challenges faced by DePINs, such as infrastructure deployment, network management, and ensuring a seamless end-user experience, hinder their full potential. To address these challenges, this research paper introduces the Mycelium Testbed, the world's first and only DePIN Testbed, designed to facilitate the development, testing, and showcasing of decentralized network technologies. This paper provides an overview of DePINs, explores the need for Testbeds in the DePIN ecosystem, outlines the design considerations and implementation details of the Mycelium Testbed, highlights its features and capabilities, discusses the role of Testbeds as incubators and accelerators, and concludes with the impact and significance of the Mycelium Testbed.

I. INTRODUCTION: LEVERAGING BLOCKCHAIN FOR DECENTRALIZED PHYSICAL INFRASTRUCTURE NETWORKS

A. DePINs: Definition and Key Principles

DePINs can be defined as networks that utilize blockchain technology and crypto-economic protocols to enable globally distributed individuals to collectively build, maintain, and operate physical networks in a trustless, permissionless, and programmatic manner. These networks encompass a wide range of physical infrastructure, including but not limited to mobility networks (e.g., vehicles), energy networks (e.g., solar panels and batteries), wireless networks (e.g., hotspots and routers), and cloud networks (e.g., servers).

B. Key Components of DePINs

DePINs are characterized by four criteria that work synergistically to enable their decentralized and efficient operation:

- **Physical Infrastructure:** DePIN networks always leverage distributed physical infrastructure of some kind.
- **Off-chain Oracles:** DePINs leverage oracle systems to determine the contribution of a given operator and programmatically assign a reward value to their contribution.
- **Blockchain Ecosystem:** DePINs leverage blockchain technology to manage trustless distribution of rewards

via smart contracts that interface with off-chain infrastructure and distribute tokens to the network operators.

- **Token Incentives:** Rewards systems of DePINs leverage token rewards to incentivise continued network operation in a permissionless manner. While some DePINs choose to operate their own L1 blockchain, most choose to leverage a token standard on an existing L1.
- **DePIN Network Participants:** In a DePIN network, two key types of participants interact to create a symbiotic ecosystem. Supply-side participants (operators) are the users who purchase, install, verify and maintain DePIN infrastructure, and are rewarded in token incentives. Demand-side participants (consumers) are users who leverage the infrastructure or data served by a DePIN, adding value and increasing revenue on the network.

C. Conclusion

The emerging DePIN model has proven its potential to compete with legacy industries and disrupt existing incentive models, resulting in lower costs and explosive network growth.

II. DEFINITION OF A DEPIN TESTBED

A. Definition and Purpose of a DePIN Testbed

A DePIN Testbed can be defined as a controlled and simulated environment specifically designed to facilitate experimentation, validation, and testing of decentralized physical infrastructure networks. It serves as a platform for researchers, developers, and other network stakeholders to evaluate the feasibility, performance, and effectiveness of DePIN implementations, as well as refine and optimize various aspects related to infrastructure deployment, coverage validation, network protocols, token incentives, and governance mechanisms. The primary purpose of a DePIN Testbed is to provide a controlled and realistic environment that enables researchers and practitioners to overcome the challenges associated with real-world deployments of decentralized physical infrastructure networks.

B. Role of Testbeds in Facilitating Network Development and Innovation:

DePIN Testbeds offers a range of benefits and serves multiple purposes, including:

- **Experimentation and Validation:** A Testbed allows researchers and developers to conduct operational experiments and validate their ideas, hypotheses, and solutions in a controlled setting. It provides a safe space to test new protocols, algorithms, and technologies before deploying them in real-world scenarios, helping to identify potential issues and refine designs.
- **Performance Evaluation:** Testbeds allow for the evaluation of key performance metrics, such as throughput, latency, scalability, and reliability, under different network conditions. This enables stakeholders to assess the effectiveness of their DePIN implementations and make informed decisions regarding network optimization and resource allocation.
- **Infrastructure Deployment Simulation:** Testbeds simulate the process of infrastructure deployment, mimicking the challenges and considerations involved in the real world. Researchers and practitioners can experiment with various deployment strategies, assess the impact of different factors, and optimize resource allocation for achieving optimal coverage and quality of service.
- **Token Incentive Mechanism Design:** Testbeds provide a platform for testing and refining token incentive mechanisms, which play a crucial role in motivating participants to contribute to the DePIN network. By simulating token rewards, distribution, and governance processes, researchers can assess the effectiveness of different incentive models and iterate on their designs.
- **Security and Privacy Assessment:** Testbeds allow for the evaluation of security and privacy measures within the DePIN ecosystem. By simulating attacks, vulnerabilities, and privacy concerns, stakeholders can identify potential risks and develop robust security frameworks to safeguard the network and its participants' data.
- **Standardization and Composability:** Testbeds facilitate the exploration and development of standards and protocols for interoperability between different DePIN networks. They provide an environment to test and refine communication protocols, data exchange mechanisms, and interoperability frameworks, enabling seamless collaboration and integration between various networks.

III. WHY DEPIN NEEDS TESTBEDS

A. Challenges Faced by DePINs in Infrastructure Deployment and End-User Experience

Decentralized Physical Infrastructure Networks, or DePINs, face distinct challenges due to their inherent reliance on individual (decentralized) network implementation. This fundamental dependency entrusts network participants with infrastructure deployment and management while requiring sufficient deployer participation to achieve viable coverage. Simultaneously, DePINs strive to provide end-users with an exceptional experience to showcase the effectiveness of their decentralized network or hardware solution. Without the ability to dictate or guarantee the extent of deployment coverage or the quality of the end-user experience, DePINs struggle to demonstrate their full potential, diluting network growth and adoption.

B. Addressing Challenges Through Testbeds

DePINs need a way to quickly and efficiently incentivise deployment at scale in a way that reduces setup time and operator error and enables effective network testing and operation.

IV. BUILDING THE MYCELIUM TESTBED

A. Establishing the Core Host Network

In most cases, the first step to building a DePIN Testbed is the establishment of a network of "Hosts" or distributed locations where operators have permission to deploy infrastructure. The Mycelium Host Network was built with the intent to onboard a range of different kinds of reliable Host locations, such as homes, apartments, businesses and special case deployments such as cell phone towers. It is the duty of the Testbed operator to identify technical and resource requirements of the intended deployment type to determine the architecture of the core Host network.

B. Deployment Types

Each DePIN requires a unique set of resources for optimal operation in a Testbed environment. Historically, the term "resources" has been used in the context of blockchain networks to describe the technical specifications of operating a protocol such as compute and bandwidth. While these resources are still crucial to the operation of DePINs, additional resources are necessary. DePIN specific resources can include elevation, coverage density and range, regional topography, roof access and physical device access.

C. Host Management Infrastructure

In order for DePIN Testbeds to scale effectively, systems need to be in place to record and manage relevant information and operational statistics. Examples of data relevant to DePIN Testbed operators include inventory management, token rewards, deployment information, host contact information and site resources. The Mycelium Testbed leverages a custom-built CRM to record, track and generate operational reports based on real-time information, paired with a publicly available mobile application for Hosts to manage services, report issues and update personal information.

D. Outside Participation

In design considerations of DePIN Testbeds, there is an outsized opportunity for outside involvement and participation. While outside influence is not a core function of Testbeds, it can be a massive catalyst for growth if leveraged appropriately, largely depending upon the community demographics. A core feature of the Mycelium Testbed is its community involvement aspects, embodying the core belief that the most beneficial Testbeds will be those that are most involved in communities. Ideally, community participation begins as an effort to get people excited about helping the Testbed operator, and continually foster growth to the point where the community becomes the primary Testbed Operator.

E. Demand-Side Usage and Network Growth

DePIN deployments within Testbeds possess an embedded benefit in acting as local coverage zones, with the ability to turbocharge network operations. Optimally deployed coverage can be used to display effectiveness and efficiency of network operation at scale, providing the ability to layer on composable DePINs. Because of this effect, adding and filling in gaps in DePIN coverage becomes easier as more infrastructure is deployed.

V. MYCELIUM TESTBED FEATURES AND CAPABILITIES

A. Extensive Geographical Coverage and Host Locations

Mycelium Networks is operating the world's first and only DePIN Testbed sporting a network of 300+ Host locations across 25+ cities and three counties, covering over 1620 square miles in Northwest Arkansas.

B. Network Composability

The Mycelium Testbed was designed with a unique focus on composability. The ability to “stack” or layer different types of hardware and different network protocols is key to the success of a DePIN Testbed due to decreased operational expenditures and increased ease of access at participating Host locations. This model also increases token rewards at each location, and makes enhanced use of infrastructure such as electricity, bandwidth and conduit mounts. This allows for an enhanced and exponential-in-nature deployer rewards model, replacing the more common linear growth experienced in other token reward systems.

C. Successful Application Deployments

Mycelium has successfully deployed various applications, with prime deployments at the Walmart Amphitheater, Walton Art Center, and the Ledger Building in Bentonville. Alongside these premier locations, the Testbed also encompasses a large volume of scattered locations, creating density and redundancy.

D. Support for Local Business Onboarding

Mycelium’s commitment extends beyond network deployment and operation. Mycelium assists local businesses in the Testbed with onboarding and solutions architecture leveraging DePINs, providing practical applications ranging from cold chain solutions in restaurants and bars to asset tracking for horseback riding. While Mycelium Networks is not in the business of deploying IoT solutions, the team offers support and expertise to partner businesses, assisting with sensor selection, onboarding and managing data integrations. This strategy is akin to creating fertile ground for the next wave of downstream projects, creating an environment where new solutions companies can create thriving businesses.

E. Public Builders Program for Innovative Applications

Mycelium has also launched a public builders program aimed at fostering and developing solutions leveraging DePIN technology and datasets in new applications. Mycelium Builders have created enterprise grade weather stations, low-power smart-home systems and are currently building an autonomous hydroponic vertical farming MVP leveraging the Helium LoRaWAN Network. In creating the Builders Program, Mycelium Networks hopes to empower the next wave of solutions businesses in educating talented students and local entrepreneurs.

F. Recognition and Achievements

Mycelium has continued to demonstrate growth during the economic downturn, which has impacted nearly every facet of decentralized infrastructure, through the establishment and effective use of existing tokenomic systems in a functional region of coverage. Notably, Mycelium is involved in an active partnership with Layer-1 blockchain network, IoTeX, to help drive network incubation, growth and real-world testing within the Testbed.

VI. TESTBEDS AS INCUBATORS AND ACCELERATORS

A. Supporting Network Development and Innovation

DePIN Testbeds have the ability to provide significant contributions to network development and innovation through an enhanced acceleration of the DePIN Flywheel. Coined by Messari Analyst, Sami Kassab, the DePIN flywheel is a novel concept that outlines how network effects drive demand in order to create higher incentives for operators of DePIN protocols. When DePIN infrastructure is concentrated in a single area, it has the potential to turbocharge the existing DePIN Flywheel, which relies on direct-to-consumer activities. Concentration of infrastructure creates community incentive to deploy and operate DePIN projects in areas where the base infrastructure layer has already been built out, such as an area with ubiquitous Helium LoRaWAN Testbed-operated coverage being optimal for community deployment of WeatherXM weather stations which leverage LoRaWAN for data offload.

B. Encouraging Collaboration and Knowledge Sharing

DePIN Testbed operators have a unique responsibility to encourage community awareness and involvement in the networks that comprise their specific Testbed. Through education, interested parties can help to catalyze Testbed network effects, in some cases with guidance from the operator in optimal deployment practices. In an ideal scenario, educated individuals work to provide complimentary coverage by deploying infrastructure to fill gaps created by the Testbed operator. In an inverse scenario, Testbed operators who act in a prohibitive manner towards other operators create a metaphorical self-inflicted wound in their loss of otherwise useful coverage in the region. In the case of the Mycelium Testbed, Mycelium began as the dominant operator in the Northwest Arkansas region, possessing 60% - 80% of DePIN coverage, but later shifted to 30% - 50% of provided coverage after regional incentives and community education became better aligned.

C. Fostering Industry-Academia Partnerships

Mycelium Networks is located less than one mile from the University of Arkansas. As the Mycelium Host Network has expanded, the Mycelium team has garnered attention from University of Arkansas faculty and staff regarding the Testbed and its implications to both the campus and the Northwest Arkansas region as a whole. Mycelium Team members have worked with university personnel to educate staff and outline use cases surrounding the permissionless DePIN technology deployments in the Testbed. A core component of the Mycelium Networks mission is education regarding benefits and tangible benefits of DePINs. Mycelium Networks CEO, Rishi Mittal, regularly guest lectures in undergraduate and graduate level courses offered by the Blockchain Center of Excellence (BCoE), helping to engage students and generate interest around DePIN technology. Mycelium Networks is also a proud sponsor of the BCoE RazorBlock Hackathon Annually, presenting use cases leveraging DePIN tech for use cases such as campus safety and asset tracking and protection.

VII. CONCLUSION

A. The Significance of the Mycelium Testbed in Advancing DePINs

The impact of the Mycelium Testbed within the region is significant. The Testbed's presence is felt through events such as the NWA Tech Summit, local Web3 meetups, guest lecturing at the University of Arkansas, and annual sponsorship of blockchain hackathons. Mycelium Testbed achievements have been recognized with accolades such as the Innovator of the Year award from the Fayetteville Chamber of Commerce. While these achievements serve as a testament to local influence, it is worth noting that the Testbed model was architected and is supported by an organization willing to fully back and showcase capabilities, with an overarching goal of advancing the adoption of decentralized networks.

B. Future Directions and Potential Research Avenues

Moving forward, Mycelium Networks intends to continue to advance the boundary of the role that a DePIN Testbed can play in ecosystem, network and community dynamics. Mycelium plans to explore a model of Testbed endorsement, sponsorship and dedicated, protocol-specific testing zones. Mycelium hopes to architect a model for introducing exclusive relationships between projects and manufacturers and Testbed operators. Finally, the Mycelium team hopes to showcase the exponential effect of composability on token rewards, network effects, data served, rewardable data and geographically concurrent deployments.

C. DePIN Industry Outlook

Presently, the Mycelium Testbed serves as the only living example of a fully functional DePIN testing ground. In this application of DePIN technology within a concise footprint, the Mycelium Testbed has effectively exemplified a new model for locally concentrated network deployment, operation, ownership and growth that radically challenges principles of

traditional DePIN deployment. Moving forward, Mycelium envisions that the primary focus of DePIN Testbed operations will be focused on the deployment of solutions, in contrast to networks, empowering a more open, fair, composable and decentralized future.

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