WiHi: A Noëtic Weather Service on Solana

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1 Overview

Weather affects everyone. Inherently linked to agricultural production, transportation, and people's day-to-day life on Earth, the importance of forecasting weather is evident in the fact that the World Meteorological Organization (WMO) is one of the oldest international organizations on the planet (est. 1873).

According to the National Weather Service (NWS), the yearly demand for weather data alone is around $13B with only $2.5B being satisfied as of 2017 [15]. Meeting the remaining demand is cost prohibitive even for government entities like the NWS, let alone commercial weather companies that rely on the NWS for raw meteorological data as inputs for their weather prediction services. Moreover, the public data offerings from the NWS are reaching their limits due to increasing demand and a lack of investment in infrastructure [2]. This already limits the quality of weather prediction and the fact that better weather data is siloed means there is much room for improvement.

A conservative estimate of the revenues resulting from the improvement in the area of weather prediction is roughly $1.23B, the outstanding notional of listed weather derivatives on the CME as of 2020 [18]. The major buyers of weather forecasts are the insurance, agriculture and logistics industries, who look for both longer-term, daily forecasts, and shorter-term, minute-by-minute *nowcasts*. To realize high quality forecasting and nowcasting, it is not enough to rely on measurements from the currently established meteorological stations and computation intensive fluid dynamics simulations. We also need high-quality weather data from remote geographic locations, because weather is affected by events in far-away places.

Weather forecasting is an active area of research, with consistent improvement being achieved from year to year. Weather forecasting depends on two components: monitoring and modeling. Weather monitoring refers to the process of using sensors to measure environmental variables corresponding to the weather such as, for example, wind speed and relative humidity. Weather modeling refers to the process of constructing a set of mathematical rules, based on ordinary and partial differential equations, that describe the behavior of weather.

Current efforts in weather research include development of methods for obtaining higher fidelity data feeds from the Earth's lower atmosphere, especially from geographically remote areas such as, for example, the oceans and poles. Methods to do this include the development of ground-based LIDAR stations, as well as aircraft- and ship-mounted LIDARs [12]. With regards to weather modeling, it would be desirable to construct a weather model that is generally applicable to the entire globe. Currently, there exist multiple models over multiple geographic regions, such as the NAM (North American Mesoscale) [6], applicable to North America, and ECMWF (European Centre for Medium-range Weather Forecasts) [4], applicable to Europe.

Overall, weather research is heavily funded by taxpayer money via national and supra-national funding agencies. This is the preferred model of funding technology with delayed, long-term impact on the general well-being of society. It is opposed to the private investment model, which has a shorter-term outlook. This is not to say that investment in weather technology is exclusively a long-term effort. In the weather business, improved forecasting results in shorter term benefits for various industries such as, for example, agriculture, transportation, insurance and, perhaps most significantly, finance and insurance – where good weather prediction can lead to better responsiveness in the pricing of, for example, weather derivatives, since weather has a direct impact on various parts of the supply chain.

In recent years a new, tokenomic financing model has emerged, different from the conventional public and private models. The token-based model has its roots in cryptocurrency and distributed computing. It uses cryptotokens as a currency that serves as communication of value to participants in the distributed network. Cultivated and managed properly, such distributed communities can strike a balance between incentivization for long-term build-out and short-term value delivery. In the context of weather, there is an opportunity to found an organization that will incentivize the improvement of weather science, while ensuring it is in line with the desires of the market.

We therefore propose the establishment of WiHi, a Noëtic Weather Service on Solana. WiHi will tokenize and democratize weather forecasting, leading to improvement in humanity's understanding of weather and climate while delivering improved value to consumers of weather forecasts. Specifically, WiHi works by providing payment for improving WiHi weather forecasts, and charging for its forecasting service.

WiHi derives value via a burn-and-mint, where the WiHi token is earned for providing useful services to the network and consumed in a one-way burn that mints direct credits, used in paying for forecast data. Useful services include the provision of weather data via sensors that are configured to solely provide data to the WiHi network (for weather monitoring) and the development of superior models (for weather modeling). Measuring the usefulness of data provision is done algorithmically, with tokens being earned directly in proportion to the improvement in weather forecast. The automated determination of value is a type of useful-work algorithm [10], *i.e.*, an algorithm proving that useful work was done in creating a currency. The approach to incentivizing better modeling is more conventional, with grants being issued to scientists and engineers willing to improve the WiHi model.

WiHi incentivizes the build-out of a world-wide weather monitoring service. A key differentiator of our approach is that the amount received for the data is commensurate with the quality of the data, which depends on three things: 1) the amount of improvement made to prediction and 2) the amount of direct revenue earned for WiHi from the particular weather data. To measure 1), the network determines the improvement to the prediction over what was known prior; to measure 2) WiHi will publish bounties on the blockchain, for certain regions that correspond to areas in which weather data is being paid for by a customer.

With WiHi, all weather data is valuable, because weather can be affected by events that occur in remote places. Nevertheless, it is sometimes important to know the weather in a certain region due to direct economic value. For example, measuring wind speed on the West Coast of the United States is important for predicting air quality on the East Coast. In measuring the impact of data on quality to the business bottom line, WiHi incentivizes the best distribution of sensors possible.

The cost of devices is currently prohibitive to allow for investment without spreading the risk. Devices range from cheap (around $100) to expensive (around $100,000). WiHi expects that, as in the case of Bitcoin and Helium, the network will initially be comprised of cheaper devices and, as the network grows, individuals or groups of investors will be incentivized to invest in higher quality devices.

WiHi is uniquely positioned to execute this mission and become the world's premier weather forecasting system. The founding team is comprised of engineers and entrepreneurs with expertise in estimation theory, blockchain development, and tokenomics. More importantly, the team has performed a demonstration of its solution in the real world, the results of which are presented in the presentation accompanying this white paper. The demonstration consists of three Intellisense Systems weather stations set up in Torrance, California, and connected to the WiHi network, set up to earn WiHi tokens. The data from stations, treated as ground truth, earned in proportion to the amount that it improved prediction, with the station providing more improvement earning a higher amount.

2 Market Opportunity

The demand for better weather forecasting ranges from direct to indirect. Direct demand relates to the needs of private industry and includes demand from agriculture, transportation, insurance, and financial sectors. Indirect demand is societal, related to day-to-day life and, more importantly, the monitoring of climate change and staving off a climate emergency.

Weather forecasting and basic infrastructure. According to the National Weather Service (NWS), the annual demand for weather data alone is around $13B with only $2.5B being satisfied as of 2017. Meeting the remaining demand is cost prohibitive even for government entities like the NWS, let alone commercial weather companies which themselves rely solely on publicly available meteorological data, provided by the NWS, as inputs to their weather prediction services. The public data offerings from the NWS are reaching their limits due to a combination of increasing demand and a lack of investment in infrastructure [2]. By enabling accurate weather data and forecasts, WiHi can empower people to make informed decisions about a particular geographic location. For example, as extreme weather events become more common due to climate change, insurers have raised premiums related to adverse-weather events to the point of unaffordability and in a growing number of cases, stopped offering insurance altogether [17]. WiHi forecasts have the potential to lower insurance costs as adverse weather events become more predictable.

Climate monitoring. Monitoring the Earth's climate is necessary for enforcing climate agreements between countries and for enforcement of cap-and-trade efforts such as, for example, carbon credit schemes. While it is estimated that environmental monitoring will be a $26B market by 2028 [13], the value of globally traded carbon permit markets in 2021 grew to a record of $851B [3]. A mature WiHi network, accurately monitoring climate variables along with performing accurate weather forecasting, would be able to capture some of the value from the regulation-induced market.

Weather derivatives. Weather derivatives are a market-based approach to weather forecasting. Demand for weather derivatives has steadily increased and appears to be correlated with increased variability in weather [11]. In 2020 alone, the total notional value of weather futures and weather options contracts were $750M and $480M, respectively, on the CME exchange [18]. Weather derivatives are used by a wide range of market participants from insurance companies to energy companies to utilities and even governments to hedge their exposure to adverse weather events. Because weather is always changing, weather derivatives have value in enabling users to reduce financial loss from unpredictable adverse events. However, weather derivatives are unhedgable from the perspective of a derivative seller, since there exist no contracts that the seller can use to reduce risk and the seller, in most instances, must increase premiums in the price of weather derivatives. The WiHi protocol has the potential to capture a significant amount of the value currently traded in weather derivatives by providing higher accuracy in weather forecasts that reduce the uncertainty around weather events and therefore the need for premia in weather derivatives.

Agriculture. In 2021, the National Center for Environmental Information estimated that extreme weather damages in the US cost $150B [5]. Compared to the estimated farm income of $117B [1], extreme weather events have resulted in a net loss for the farming industry as a whole. WiHi's accurate forecasting can prevent these types of losses and capture the savings by providing the farming industry and ability to take preventative measures in order to minimize losses and increase the robustness of the food supply.

Transportation. The USDOT estimates that extreme weather events cause an estimated $3.5B a year in financial costs and an estimated 32.6B vehicle hours lost in time [7]. Accurate weather and climate forecasts have the potential to bring about not only financial but human impact. For example, different from other industries affected by weather, extreme weather events require changes in operating procedures in order to maintain the safety of the worker. Here, accurate forecasts not only have the potential to save time and money, but for the transportation industry, the potential to save lives as well. Similarly, accurate climate modeling and forecasts can positively impact human lives by providing accurate forecasts of the change in the environment due to climate and enabling decision makers to unequivocally carry out preventative measures. For example, raising 221 of the world's most active seaports by 2 meters in order to ensure their uninterrupted operation in light of rising sea-levels would require 49 million metric tons of concrete, costing $60B [9]. However, to the best of our knowledge, no seaport has planned nor plans to take preventative steps since there is no accurate forecast of when and where such changes to the environment will occur. Accurate climate forecasts can help transportation companies take the appropriate preventative measures to ensure their continued operation.

Insurance. As extreme weather events become increasingly prevalent and commonplace, insurers have taken on heavily losses, to the tune of $77 globally in the first half of 2021 [16]. While the institution of insurance exists to protect against economic losses incurred due to unexpected events, as adverse weather events become more common, the cost of insuring will become exorbitant for insurers and unaffordable for consumers [17], leading to a poor outcome for both parties. Accurate weather and climate forecasts can help mitigate damage from adverse weather events, lowering insurance premiums. This increased transparency benefits both parties as insurers can require customers to utilize services that prevent debilitating losses affecting the insurers' ability to pay out other premiums, while consumers can be more informed of whether they are at risk against adverse weather events and make necessary adjustments.

3 WiHi: A Noëtic Weather Service

The WiHi network consists of a weather forecasting algorithm and a digital currency incentivization mechanism, both running on the Solana blockchain. The forecasting algorithm consists of 1) a set of dynamical systems models, modeling the weather over certain geographic areas and whose inputs are weather sensor measurements; and 2) a data assimilation algorithm, which corrects modeling error using data obtained from weather sensors. The digital currency mechanism is a program that runs on Solana and issues WiHi tokens as determined by the data assimilation algorithm; specifically, the algorithm compares the current prediction against the sensor measurements and rewards sensors whose readings result in the best benefit for the network. As opposed to the token program, the forecasting and digital assimilation algorithms run as oracles.[1]

3.1 Forecasting algorithm and data assimilation

There exists a variety of weather forecasting models, and their performance varies based on the geography for which they are specialized. In North America, the NAM model is used for short-term weather prediction; in Europe, the ECMWF model is used. At this time, regional weather models perform better than general, global weather models and therefore any attempt at high-quality, short-term forecasting must take into account the region for which a forecast is being requested. The above discussion notwithstanding, we provide a mathematical description of the WiHi approach using a single model for convenience. Suppose, then, there exists a dynamical system of the form,

$$x_{k+1} = f(x_k) + g(x_k)w_k, \tag{1a}$$

$$y_k = h(x_k) + v_k, \tag{1b}$$

where x_k is the vector of *system states*, w_k is the vector of *unknown inputs* (usually just noise), y_k is the vector of *measured outputs*, and v_k is the vector of *measurement errors*. The goal of forecasting is to determine the state vector x_k from a model of the dynamics f, h and measurement vector y_k at past times $k = 0, -1, -2, \ldots$. This type of forecast is performed multiple times a day using publicly available information from weather stations placed around the globe. The system itself is complex as it needs to make trade-offs between signal noise filtering and signal fidelity. The WiHi network consists of a set of sensors whose data is only available to the network. Let the output of these sensors be given by,

$$\bar{y}_k = h(x_k) + \bar{v}_k, \tag{2}$$

and let $\hat{x}_k$ be the forecast based on (1) and $\hat{y}_k = h(\hat{x}_k)$; and let $\hat{\bar{x}}_k$ be the forecast based on (1)-(2) and $\hat{\bar{y}}_k = h(\hat{\bar{x}}_k)$. The result $\hat{x}_k$ is the baseline forecast and the result is $\hat{\bar{x}}_k$ is the modified forecast, *i.e.*, after data assimilation.

Token reward

Let $\bar{y}_k^i$ denote the i-th component of $\bar{y}_k$, which corresponds to data obtained from some sensor i. To determine the contribution of sensor i to model improvement, we compare the measurement $\bar{y}_k^i$ to the prediction $\hat{y}_k^i$, *i.e.*, the prediction lacking assimilation from WiHi.

Rewards are distributed on a regular basis, currently the five-minute epoch, which is the period at which the model updates. The reward total is equal to R tokens per epoch,[2] so each sensor i earns,

$$\frac{|\bar{y}_k^i - \hat{y}_k^i|}{\sum_j |\bar{y}_k^j - \hat{y}_k^j|} R, \tag{3}$$

[1]This design is current but should be changed to run as a program on Solana.

[2]Subject to deflation, *e.g.*, reward halving

for its owner.

Market-based incentive. In the future, the reward will need to be modified from (3) to include an additional, market-based incentive. Customers paying for data will need to have a way to increase the reward for data that is important to them, perhaps via a bounty. Important to note is that customers themselves would not be able to determine better than the network which data was important to them, because weather in some unintuitive location may affect their desired forecast.

Model adaptation

The model (1) adapts with time. With every measurement from a sensor, the WiHi data assimilation algorithm calibrates and improves forecasts so that they better correspond to actual sensor readings. This means that the owner of a sensor placed at a desirable location would likely notice a large reward at the beginning of the sensor's operation, but see this reward drop as the model improves based on sensor readings. This implies that the WiHi network incentivizes investment into mobile sensing technology; mobile placement would allow a sensor to improve modeling for longer periods of time.

3.2 Tokenomics

The WiHi network implements a burn-and-mint, dual-token model as its incentive mechanism [14], comprised of the value token and the utility token. The value token compensates participants for improving the network; the utility token compensates the network for providing forecasts.

The reward mechanism for obtaining a value token was described in the previous section. Value tokens are minted after every epoch and are burned for utility tokens. Utility tokens in turn are used to purchase forecasts from the network and are set to a fixed fiat value, currently 0.1¢. The expectation is the the market forces would find the right value for the value token through trade on cryptocurrency exchanges. Utility tokens can only be minted into existence through burning and spent in exchange for forecasting services, so there is no reason to provide a method for their transaction – therefore utility tokens are not to be traded on the secondary market.

Value token

The tokenomics of value tokens directly incentivize improved weather data collection. Network participants provide value to the network by selling their data to be used in the creation of weather forecasts. They are in turn rewarded in proportion to the resulting model improvement. This leads to both an improvement in 1) weather sensor quality and 2) weather sensor placement. This is because better rewards is a result of both 1) better sensing data being provided to the network and 2) placement of sensors in remote areas. The first component drives value for incumbent weather sensor manufacturers. Weather manufacturers of high-quality devices, currently priced out of the retail market, would become more competitive if they were to offer integration with a reward scheme. The second component has the potential to offer new sources of income to other industries. For example, the current practice of obtaining highly valuable data from the oceans is via buoys and the program of Voluntary Observing Ships (VOS); instead of having the programs be voluntary, ships could be incentivized to provide weather data to WiHi in return for reward.

Utility token

Also known as a data credit, the utility token is used to purchase a forecast $\bar{x}_k$ over some region and time. Obtained solely via burning the value token, the utility token is fixed to a fiat amount of 0.1¢and the fees required for forecast access are negotiated with each customer separately, and pricing depends on type of forecast: timescale, accuracy, geographic distribution, types of data (*e.g.*, CO_2 levels and air quality), and so on.

3.3 Blockchain and oracles

In the current framework, forecasting is currently expensive both in terms of compute and storage. Solana blockchain cannot economically distribute the necessary computations pertaining to weather forecasting and data assimilation nor can it economically store weather data. We therefore use the Solana blockchain to:

1. Ensure trust between users contributing weather data and the network by associating the unique identifier[3] of a weather data collection device with a public key that denotes ownership of the weather data collection device on-chain. The on-chain program "Bookkeeper" derives a PDA for each data contributor and records a hash summarizing each batch of data received.

2. Implement the WiHi token and perform transfers.

The WiHi forecasting model is implemented as a centralized oracle and must be trusted. However, WiHi will eventually remove the need for trust in the computation of the model improvement by implementing ZKPs (Zero-Knowledge Proofs); the determination of model improvement will be encoded in a ZKP and wrapped in a program on the blockchain that can be invoked to ensure that rewards were determined correctly.

3.4 Organization

Science and, by extension, weather forecasting are not exercises of democracy, and neither is driving value to customers. Considerate planning is required to achieve alignment between product, science, and customer satisfaction. The WiHi organization is there to perform the task of guiding the broader community towards network improvement and better quality in forecasting. In particular, it is important to acknowledge the role of scientists in supporting WiHi. The development of weather forecasts is a multinational effort and assuming that WiHi could, and even should, compete with large public endowments is not realistic. WiHi therefore is designed to complement current efforts in weather science by providing grants to scientists wishing to work on the needs of WiHi as well the general science of weather forecasting, and to open-source weather forecasting algorithm development.

4 Current Status, Future, and Climate

Currently, the WiHi project has completed a demonstration of its capabilities [8]. The focus of design has been on improving weather forecasting as described in Section 3 of this white paper. In the future, a core element of WiHi should transition to monitoring of climate variables. As described in Section 2, there is a growing demand for accurate climate monitoring in the context of enforcing climate regulations. An accurate weather forecasting model could be transitioned to climate monitoring with the on-boarding of air quality sensors and similar technology, as well as modifying the WiHi forecasting models to include a broader spectrum of variables. This by itself should not be a difficult pivot to make given the relationship between climate and weather.

[3]Usually an IMEI

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